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Energy Production from Hardwoods Growing on Southern Pine Sites

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Southern Forest Experiment Station

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Summary

Hardwoods on pine sites are a virtually untapped source of biomass for conversion to energy. This resource is substantial; above-ground stems 5 inches and larger in d.b.h. total about 49.2 billion ft^3 amounting to about 888 million tons of wood and bark, ovendry. Complete-tree biomass, including branches and central root systems of these trees, and those too small to be surveyed, probably totals at least 100 billion ft^3,or 1,805 million tons, ovendry.

Direct combustion is the most promising process for converting such biomass to energy—principally in the form of heat for process steam. A wide array of burners is available, ranging from highly efficient domestic stoves to industrial systems such as fuel cell burners, inclined-grate furnaces, spreader stokers, suspension-fired burners, cyclonic furnaces, and fluidized-bed burners. Average heat of combustion (higher heating value) for ovendry stemwood of pine-site hardwoods is about 7,827 Btu per pound; bark and branchwood have slightly less heat content. Moisture content of pine-site hardwood stemwood averages about 73.5 percent of dry weight; that of bark averages 67.6 percent. As a replacement for natural gas (at $2 per million Btu) to generate steam, pine-site hardwoods have a fuel value of about $15 per green ton, and when used to replace oil the value is slightly higher.

Fuel costs, however, are only one consideration in the total economic picture. Wood-fired boilers cost more and are more expensive to maintain than oil- or gas-fired units. The key to economic success in use of wood for heat energy is development of harvesting systems that deliver wood to the plant fuel pile at low cost.

Gasification of wood is a versatile process that can lead to a number of energy-related products. After direct combustion, gasification with on-site combustion of the low Btu producer gas appears to be the best alternative for conversion of the pine-site hardwoods to heat energy. With the development of fuel cells, producer gas may be used in the future to generate electricity. Synthesis gas (the hydrogen and carbon monoxide components of producer gas) can be converted to many important fuels and chemicals, but none seem economically competitive when produced by this route until at least the end of the century, barring unforeseen disruptions in the world distribution system for oil.

Charcoal manufacture is a well established industry. Opportunities may exist for further development of plants that effectively use the off-gases.

Liquefaction processes yielding a wood oil are possible, but appear not economically competitive. Hydrolysis of wood and subsequent conversion of sugars and lignin to yield ethanol, furfural, and phenol, or to produce a yeast for protein supplement have yet to be proven economically competitive. Prehydrolysis products from waste streams of primary wood products plants have achieved some economic success.

In summation, wood fuel will be increasingly used by the forest products industry, however the industry will probably depend partially on gas and oil for

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as long as they are available; coal will supply perhaps one-fourth of the industry's fuel needs by the end of the century. Oil and gas will continue to be the primary feed stocks for organic chemicals through the turn of the century. For better chemical utilization of wood, research should focus on making the ligno-cellulosic complex accessible to chemical and biological action, increased use of cellulose and lignin as polymers, producing specialized chemicals, and catalyst research and development. Economic feasibility of all processes to convert forest residues into energy depends largely on the cost of wood; development of appropriate harvesting equipment is, therefore, the number one research priority.

CHAPTER 1

Introduction

The United States uses about one-third of the total energy produced in the world. Since the 1973 oil embargo, we have become aware that our energy sources are not inexhaustible; and, they are no longer cheap. We are compelled, therefore, to assess our energy needs for the future and to seek new sources.

The amounts of energy consumed today are very large and are therefore measured in millions of barrels per day oil equivalent or in quads. A barrel of oil has a heat content of 5.55 million British thermal units (Btu) (Exxon Company 1978). One quad is equal to 10^{15} Btu's or about 494,000 barrels of oil per day for a year, as follows:

$$1 \text{ quad} = \frac{10^{15} \text{ Btu}}{5.55 \times 10^{6} \text{ Btu/barrel} \times 365 \text{ days}} = 493{,}644 \text{ barrels/day}$$

The Department of Energy (1978) has projected that by 1990 the total consumption of energy by the United States could range from 100.7 to 109.4 quads per year.

In another projection of demand (Exxon Company 1978), the United States is forecast to increase its energy consumption from 38 million barrels per day oil equivalent (just under 77 quads annually) in 1977 to 51 million barrels per day oil equivalent (103 quads annually) by 1990. The assumptions made in this projection include the following: the growth rate of the gross national product will be just under 3.6 percent annually; environmental goals will be achieved at a rate comparable with economic growth; and oil imports will be available at a price that will increase at about the same rate of inflation.

Oil will remain the predominant fuel through 1990 (fig. 1-1). However, oil imports will have to increase from about 45 percent of the total oil supply in 1977 to about 57 percent of the supply in 1983 and then will decline slightly through 1990. Gas will have limited availability and will decline to about 17 percent of our energy base by 1990. Nuclear energy (which is limited to electric utility use) will increase to 10 percent of our energy base. Hydroelectric and geothermal energy have small growth potentials due to the limited number of sites where such energy is available.

Coal reserves in the United States are substantial. The Department of Energy estimates that the proven domestic reserve amounts to about 4,000 quads (fig. 1-2). However, logistical and technological gaps prevent us from fully using this potential now. Extensive research and development are underway to find methods for converting coal into fuels that are economically acceptable and environmentally clean. Coal usage is expected to grow from 18 percent of our energy base in 1977 to 27 percent in 1990.

Among potential sources, one that has generated considerable interest—mainly because it is renewable—is *biomass,* that is, living matter. For example, the U.S. Department of Energy is assessing the technical and economic feasibility of using intensively managed, short-rotation tree farms as a source of energy for the future.

Essentially, biomass is a form of stored solar energy. That is, green plants use sunlight as energy in *photosynthesis* to convert carbon dioxide (CO_2) and water (H_2O) to higher energy products, that is carbohydrates ($CH_2O)_n$ and oxygen (O_2). While carbohydrates are the principal organic products of photosynthesis, plants can produce other compounds such as hydrocarbons, fats, and proteins in the process (Calvin 1976, Bassham in press). Overall photosynthetic conversion efficiency for plants in the temperate zone ranges from 0.1 to 1 percent of the total available sunlight. Calvin (1976) envisions that eventually a synthetic system will be developed to simulate plant photosynthesis to produce renewable fuel.

Estimates of the annual storage of solar energy in the U.S. biomass system are as high as 80 quads a year (Falkehag 1977). The U.S. Department of Energy estimates 7 to 8 quads are produced annually in our forests (Del Gobbo 1978). Standing available forests contribute about 300 quads to the proven reserves of energy in the U.S. (fig. 1-2).

The equivalent of about 4 quads of our forests are harvested annually for lumber and paper products. These products are more valuable than fuel. However, the residues from these resources can be, and perhaps should be, utilized for energy.

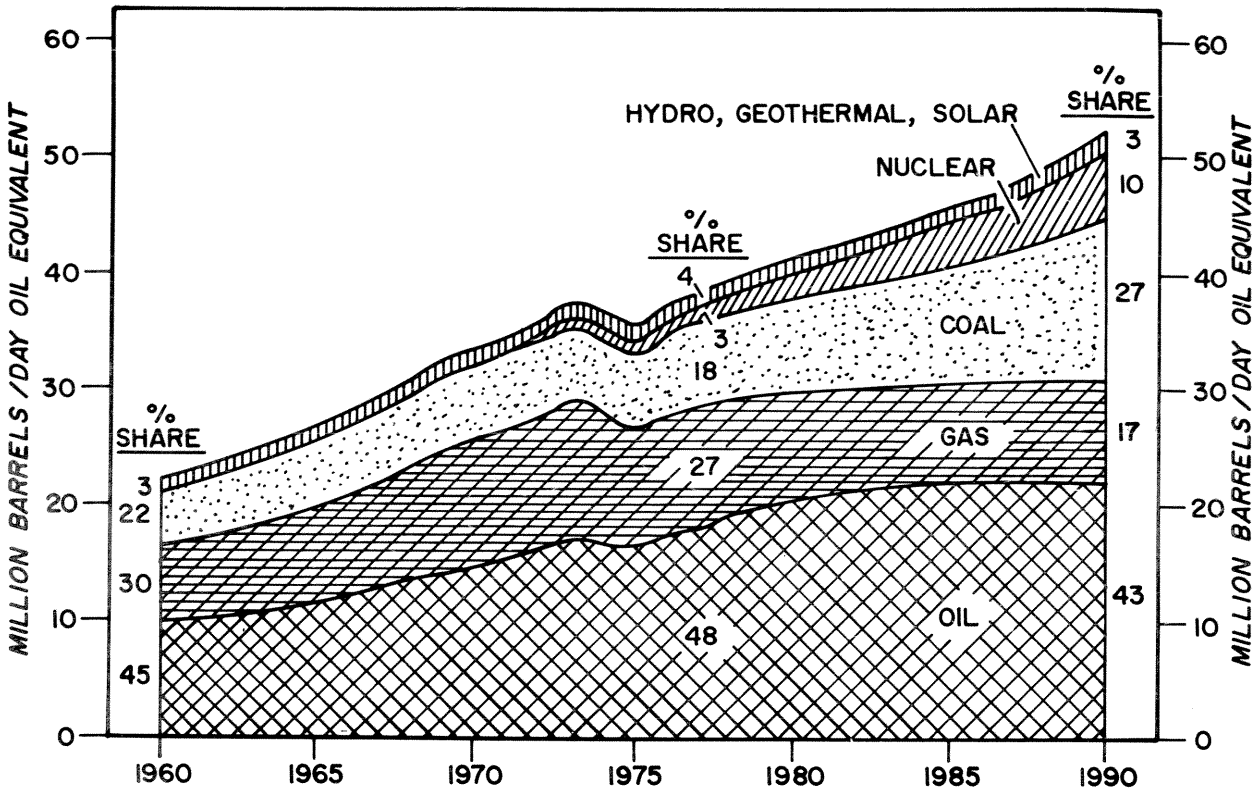


Figure 1-1.—*U.S. energy supply projected to 1990. Top line represents 100 percent of the energy supply which is broken down into contributing percentages from oil, gas, coal, and nuclear energy, and the group hydro, geothermal and solar energy (Drawing after Exxon Company, 1978.)*

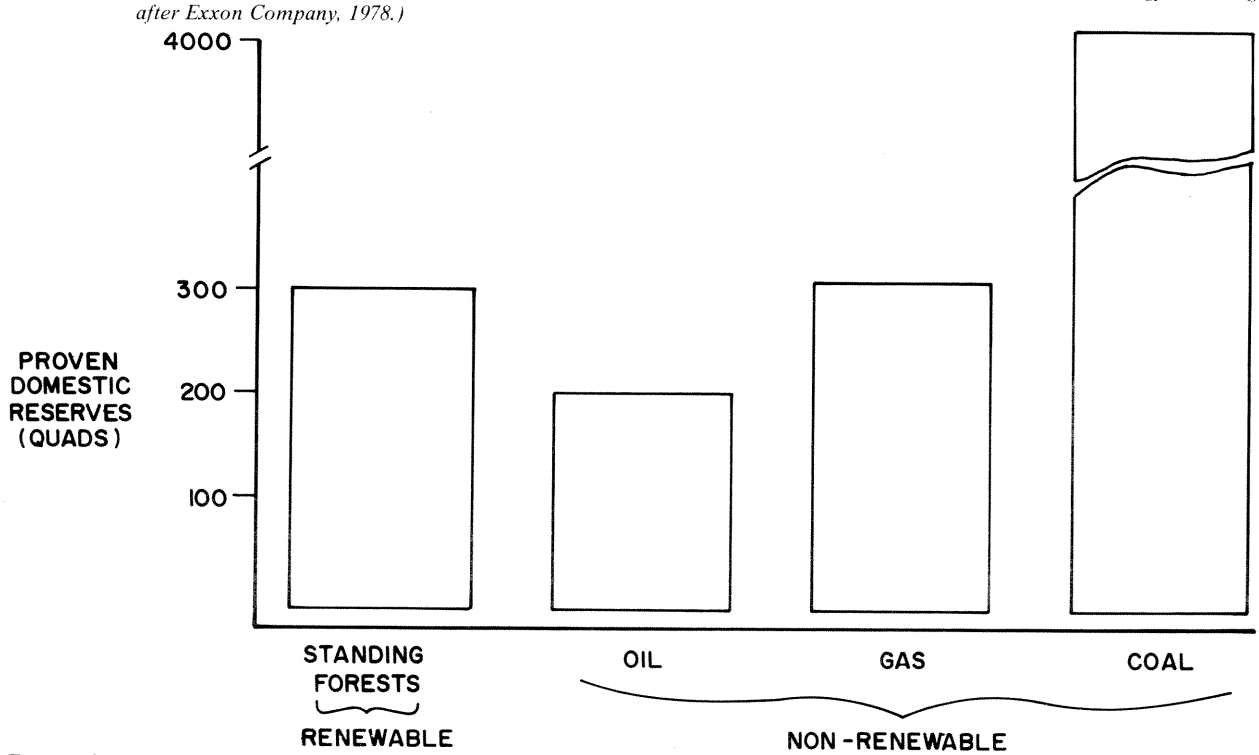


Figure 1-2.—*Proven reserves of energy in the U.S. Renewable reserves are considered to be 730 million acres of standing forests with an annual production of 7 to 8 quads. Oil, gas, and coal are the non-renewable resources. Coal is the largest reserve with about 4,000 quads of energy. (Drawing from Department of Energy.)*

The forest products industry already produces about 1 quad of energy from its residues. In the near term, an additional 0.5 to 1.0 quad could be realized from combined forestry and agricultural residues. The projected contribution of biomass to our national energy requirements by the year 2000 ranges from 3 to 8 quads (Del Gobbo 1978, Zerbe 1977). To aid in achieving this goal, the Department of Energy has established a Fuels from Biomass Program. Its objective is to develop technologies for the preparation, harvest, and conversion of renewable biomass into clean fuels, petrochemical substitutes, and other energy-intensive products (Del Gobbo 1978).

In the South, hardwoods growing on pine sites are a virtually unused source of biomass. Over the years attempts to use these hardwoods have been thwarted by the diversity of species, scattered occurrence, smallness and shortness of boles, branchiness of crowns, and prevalence of knots. Therefore, most of these hardwoods are destroyed during site preparation for pine—a destruction that is wasteful and costly (perhaps $85 per acre). Economic uses for these hardwoods would be desirable and at least two utilization schemes have been proposed (Goldstein et al. 1978, Koch 1978). In the energy self-sufficient Koch approach, a new harvesting and utilization system known as BRUSH (Biomass Recovery and Utilization with Shaping-Lathe Headrigs) could recover 67 percent of the tree biomass of all species as solid wood products. In the Goldstein et al. approach, entire hardwood trees are chipped in the woods. Such chips can be used for fuel, production of chemicals, or fiberboard.

In the chapters that follow, we will review the potential of using the pine-site hardwoods, or their residues from manufacturing processes, as a source for energy, fuels and chemicals. Conversion processes that are available or near at hand will be described, and potential uses and economics of the conversion products will be discussed.

CHAPTER 2
The Raw Material

2-1 The Resource

The total hardwood resource of the South recently was estimated at 113.7 billion ft^3 which amounts to 2,051 million tons of ovendry wood and bark. This resource, which is spread over 12 states, can be divided into that on southern pine sites and that on hardwood sites. Pine sites are defined as forested uplands, excluding those growing cove-type hardwoods, that support southern pine or show evidence, like stumps, of its former occurrence. Hardwoods on pine sites total about 49.2 billion ft^3 of wood (888 million tons of wood and bark, ovendry) or 43 percent of the total hardwood inventory (table 2-1).

How have pine sites become so heavily invaded by hardwoods? In most of the South, plant succession—the replacement of one plant community by another—climaxes with a hardwood forest (Billings 1938, Quarterman and Keever 1962). Establishment of pine stands requires the absence of heavy litter and freedom from competing plant cover; wildfires often provide these conditions and check the succession to hardwoods. However, man has largely excluded fire from the forest, thus favoring the shade-tolerant hardwoods.

About 90 percent of the total hardwood volume on southern pine sites is composed of 23 species or species groups representing 10 genera (table 2-2). The inventoried hardwoods (table 2-3) are only about one-half of the total hardwood biomass (excluding foliage) grown on these sites; the other half is in roots, stumps, and branches of inventoried stems and in trees smaller than 5 inches d.b.h.

Oaks comprise 47 percent of the 12-state volume of hardwoods on pine sites. Sweetgum and white oak are the leading species, each with an inventory of more than 6 billion ft^3.The hickories, third in abundance, are widespread, though on pine sites their quality tends to be poor. The five most abundant pine site hardwoods, sweetgum, white oak, hickory,

Table 2-1.—*Volume of all hardwoods on pine sites and hardwood sites in 12 Southern States (Christopher et al. 1976)*[1]

	All sites	Pine sites	Hardwood sites
	Million cubic feet		
Alabama	10,886	6,456	4,430
Arkansas	11,174	4,926	6,248
Florida	5,461	1,078	4,383
Georgia	12,999	6,600	6,399
Louisiana	9,879	3,085	6,794
Mississippi	8,416	3,827	4,589
North Carolina	17,074	6,838	10,236
Oklahoma	1,601	633	968
South Carolina	8,093	3,358	4,735
Tennessee	10,255	3,724	6,531
Texas	4,222	2,593	1,629
Virginia	13,651	6,118	7,533
	113,711	49,236	64,475

[1] From source data gathered during 1964-1974 on systematic sample plots 2 to 4 miles apart. The volume is expressed in cubic feet inside bark of trees from stump to a minimum 4-inch top diameter (outside bark) of stem. All trees 5 inches in diameter at breast height are included.

Table 2-2.—*The major hardwood species on pine sites*

Common name	Botanical name
Ash, green	*Fraxinus pennsylvanica* Marsh.
Ash, white	*F. ameriana* L.
Elm, American	*Ulmus americana* L.
Elm, winged	*U. alata* Michx.
Hackberry	*Celtis* spp.
Hickory	*Carya* spp.
Maple, red	*Acer rubrum* L.
Oak, black	*Quercus velutina* Lam.
Oak, blackjack	*Q. marilandica* Muenchh.
Oak, cherrybark	*Q. falcata* Michx. var. *pagodaefolia* Ell.
Oak, chestnut	*Q. prinus* L.
Oak, laurel	*Q. laurifolia* Michx.
Oak, northern red	*Q. rubra* L.
Oak, post	*Q. stellata* Wangenh.
Oak, scarlet	*Q. coccinea* Muenchh.
Oak Shumard	*Q. shumardii* Buckl.
Oak southern red	*Q. falcata* Michx.
Oak, water	*Q. nigra* L.
Oak, white	*Q. alba* L.
Sweetbay	*Magnolia virginiana* L.
Sweetgum	*Liquidambar styraciflua* L.
Tupelo, black	*Nyssa sylvatica* Marsh.
Yellow-poplar	*Liriodendron tulipifera* L.

Table 2-3.—*Species volumes on pine sites in the 12 southern states*

Species	Volume	Proportion of pine site hardwood volume
	Million cubic feet	*Percent*
Sweetgum	6,508	13.2
Oak, white	6,058	12.3
Hickory, spp.	4,173	8.5
Oak, southern red	3,994	8.1
Oak, post	3,444	7.0
Yellow-poplar	3,421	7.0
Tupelo, black	2,710	5.5
Oak, water	2,332	4.7
Oak, chestnut	2,102	4.2
Oak, black	1,949	4.0
Oak, scarlet	1,799	3.6
Maple, red	1,751	3.6
Oak, northern red	1,169	2.4
Oak, laurel	683	1.4
Elm, spp.	668	1.4
Oak, cherrybark	579	1.2
Ash, spp.	441	.9
Sweetbay	300	.6
Oak, Shumard	120	.2
Hackberry, spp.	57	.1
Other hardwoods	4,978	10.1
Total hardwoods	49,236	100.0

[1] Compiled from data of Christopher et al. (1976).

southern red oak, and post oak, and the seventh, black tupelo, are well represented in all 12 States. Yellow-poplar, scarlet oak, and chestnut oak are scarce or absent west of the Mississippi and in Florida. Black oak is plentiful except in Florida, Texas, Louisiana, and Oklahoma. Among other species making up 2 percent or more of the hardwood on pine sites, red maple is well distributed except in Oklahoma, water oak is scarce only in Tennessee and Oklahoma, and northern red oak is scarce in the Gulf States.

Many factors make using these hardwoods difficult. Trees are often scarred and defective from fires and from previous pine harvesting. They are slow growers because the sites are not right for them—trees 6 inches in diameter at breast height are typically 40 years of age (Manwiller 1974). They are short and crooked in bole. The low cubic content per stem, the highly variable species mix from stand to stand and even from site to site within stands, and the low volume per acre all combine to raise harvesting costs. Moreover, the value of the trees after harvest is low. Knots and other defects, short lengths, and small diameters preclude any hope of sawing quality lumber in conventional lengths. Not least among the problems is that of maintaining a species mix suitable for a manufacturing operation (Barber 1975).

Offsetting these disadvantages are some advantages. The resource is distributed throughout the southern pinery and therefore is available near many potential consumers. Because the volumes are substantial, they can supply a market of almost any realizable size—and at a variety of locations. A supply will always exist because on many sites hardwoods replace southern pines in natural succession, and certain sites, such as areas bordering intermittent streams in uplands, will remain in hardwoods for environmental reasons. Stumpage cost is low, thus leaving much of the final product value for harvest and manufacture. New industries based on these hardwoods can be located in depressed rural areas where labor is readily available, and local communities are frequently eager to help in plant establishment. Finally, factories utilizing these hardwoods can be energy self-sufficient (Barber 1975).

Improved utilization of hardwoods from all sites should hasten the time when wood production can be maximized by concentrating hardwood management on sites best suited for hardwoods and pine production on lands best suited for pines. Hardwood sites intermingled with pine lands will permit a desirable pattern of diversity in most areas. Moreover,

substantial acreages suitable for high production of either hardwoods or pine are available; these lands can be allocated to either species group as needed to balance demands, not only for industrial wood products, but for wildlife habitat, recreational areas, visually pleasing landscapes, and water management.

2-2 Physical and Chemical Characteristics

To assess the energy potential of pine-site hardwoods, it is necessary to know their specific gravity, moisture content, heat content, and chemical makeup.

Stemwood specific gravity (based on ovendry weight and green volume) ranges from 0.40 in yellow-poplar to 0.67 in post oak. Bark, which constitutes about 18.8 percent of above-ground biomass (foliage excepted) in 6-inch trees ranges in specific gravity from 0.34 in winged elm to 0.64 in blackjack and northern red oaks (table 2-4).

Moisture content of stemwood averages 73.5 percent of ovendry weight (42 percent wet basis); bark averages 67.5 percent moisture content on a dry basis and 40 percent on a wet basis (table 2-4). Yellow-poplar stemwood has highest moisture content at 125.8 percent of ovendry weight (56 percent on a wet basis).

Heats of combustion of stemwood, stembark, branchwood, and branchbark all range from 6,840 to 8,123 Btu per ovendry pound (table 2-5). The averages are as follows:

Tree portion	*Heat of combustion* (higher heating value)
	Btu/ovendry pound
Stemwood	7,827
Branchwood	7,784
Stembark	7,593
Branchbark	7,632

About 50 percent of the wood and bark of these hardwoods is comprised of the element carbon, from

Table 2-4.—*Specific gravity, moisture content, and green wood weight of stemwood and bark from 6-inch hardwoods on southern pine sites*

Species	Percent of total volume[1]	Stemwood specific gravity[2]	Stembark specific gravity[2]	Stemwood moisture content[3]	Stembark moisture content[3]	Weight of bark-free green stemwood
				Percent		*Pounds/cu. ft.*
Ash, green	0.9	0.561	0.407	47.4	75.9	51.6
Ash, white		.582	.397	47.5	68.4	53.6
Elm, American	1.4	.536	.395	75.5	86.9	58.7
Elm, winged		.623	.341	65.6	76.0	64.4
Hackberry	.1	.525	.601	72.6	55.5	56.5
Hickory, true	8.5	.643	.522	51.5	72.9	60.8
Maple, red	3.6	.496	.535	69.9	74.4	52.6
Oak, black	4.0	.620	.612	69.2	56.2	65.5
Oak, blackjack	< .1	.638	.642	74.2	43.6	69.4
Oak, cherrybark	1.2	.633	.622	66.6	54.1	65.8
Oak, chestnut	4.2	[4]	[4]	[4]	[4]	[4]
Oak, laurel	1.4	.582	.630	74.4	57.4	63.3
Oak, northern red	2.4	.605	.644	69.7	55.7	64.1
Oak, post	7.0	.659	.498	65.6	48.9	68.1
Oak, scarlet	3.6	.622	.618	69.4	55.6	65.7
Oak, Shumard	.2	.625	.644	69.1	52.2	65.9
Oak, southern red	8.1	.609	.601	70.1	52.9	64.6
Oak, water	4.7	.587	.628	73.6	54.4	63.6
Oak, white	12.3	.665	.543	61.9	58.1	67.2
Sweetbay	.6	.437	.440	100.8	102.1	54.8
Sweetgum	13.2	.453	.369	120.4	89.3	62.3
Tupelo, black	5.5	.500	.428	90.0	69.8	59.3
Yellow-poplar	7.0	.395	.390	111.7	125.8	52.2
Other hardwoods	10.1	—	—	—	—	—
	100.0					

[1] Data from Christopher et al. (1976)

[2] Basis of ovendry weight and volume when green. Data from Manwiller, F. G. (in press). Wood and bark specific gravity of small diameter pine-site hardwoods in the South. Forest Products Journal.

[3] Dry weight basis. Data from Manwiller (1975).

[4] Data not available.

Table 2-5.—*Heat of combustion of ovendry wood and bark of 23 southern hardwoods*[1,2]

Species	Stemwood	Branchwood	Stembark	Branchbark
	Btu per ovendry pound			
Ash, green	7,695	7,727	7,472	7,606
Ash, white	8,033	8,013	7,695	7,816
Elm, American	7,770	7,857	6,840	6,904
Elm, winged	7,917	7,869	7,019	6,889
Hackberry	7,882	7,867	7,147	7,141
Hickory, true	8,183	7,931	7,586	7,259
Maple, red	7,846	7,829	7,595	7,384
Oak, black	7,680	7,692	7,642	7,847
Oak, blackjack	7,739	7,739	7,766	7,907
Oak, cherrybark	7,848	7,737	7,582	7,655
Oak, chestnut	[3]	[3]	[3]	[3]
Oak, laurel	7,828	7,653	7,897	7,806
Oak, northern red	7,791	7,776	7,879	7,926
Oak, post	7,889	7,845	7,191	7,728
Oak, scarlet	7,798	7,673	8,041	7,894
Oak, Shumard	7,789	7,745	7,970	7,913
Oak, southern red	7,919	7,839	7,983	7,798
Oak, water	7,876	7,833	7,930	7,918
Oak, white	7,676	7,507	7,328	7,574
Sweetbay	7,736	7,802	7,822	7,886
Sweetgum	7,667	7,690	7,200	7,214
Tupelo, black	7,867	7,814	7,788	8,176
Yellow-poplar	7,774	7,811	7,696	7,666
Average value	7,827	7,784	7,593	7,632

[1] Higher heating value
[2] F. Manwiller, data on file at the Southern For. Exp. Sta., Pineville, La.
[3] Data not available.

30 to 44 percent is oxygen, and about 6 percent is hydrogen. Together, ash and nitrogen amount to about 1 percent of wood weight; ash content in bark is more than that in wood (table 2-6).

The proximate analyses for different hardwood species also fall within a rather narrow range of values (table 2-7). In general, when wood and bark are burned, 75 to 80 percent will burn in the gaseous state while about 20 to 24 percent will burn as fixed carbon (Arola 1976).

Summative chemical analyses of stemwood of 18 of the principal pine-site hardwoods are given in table 2-8. Percentages of the componenets range as follows:

Component	*Percent*
Cellulose	33.8 - 48.7
Hemicellulose	23.2 - 37.7
Lignin	19.1 - 30.3
Extractives	1.1 - 9.6
Ash	.1 - 1.3
	100

Table 2-6.—*Typical ultimate analysis for hardwood species*[1]

	Wood	Bark
	Percent	
Carbon	50.8	51.2
Oxygen	41.8	37.9
Hydrogen	6.4	6.0
Nitrogen	.4	.4
Ash	.9	5.2

[1] Data from Arola (1976).

Table 2-7.—*Typical proximate analysis for hardwoods*[1]

	Volatile matter	Fixed carbon[2]	Ash[2]
	Percent		
Wood	77.3	19.4	3.4
Bark	76.7	18.6	4.6

[1] Data from Arola (1976).
[2] Differs from value in ultimate analysis due to different purpose and method of determination.

Table 2-8.—*Summative chemical analyses of principal hardwoods that grow on southern pine sites* (unpublished data from H. L. Hergert, ITT Rayonier, New York, N.Y.)

Species	Site[1]	Cellulose[2]	Hemicellulose[3]	Lignin[4]	Extractives[5]	Ash[6]
			Percent			
Ash, white	G	48.7	23.5	23.3	5.4	0.3
Ash, white[7]	T	39.5	29.1	24.8	6.3	.3
Elm, American[8]	G	42.6	26.9	22.4	1.9	.8
Elm, American[7]	G	38.0	32.5	24.7	4.6	.3
Elm, American[7]	T	41.9	29.7	25.6	2.4	.5
Hickory, mockernut	T	43.5	27.7	23.6	5.0	.4
Hickory, mockernut (?)	G	37.7	29.2	23.0	9.0	1.1
Hickory, pignut	T	46.2	26.7	23.2	3.4	.6
Maple, red	G	39.9	28.2	23.0	8.6	.3
Maple, red	T	40.7	30.4	23.3	5.3	.3
Oak, black	T	39.6	28.4	25.3	6.3	.5
Oak, blackjack	T	33.8	28.2	30.1	6.6	1.3
Oak, chestnut	T	40.8	29.9	22.3	6.6	.4
Oak, northern red	T	42.2	33.1	20.2	4.4	.2
Oak, post	G	37.7	29.9	26.1	5.8	.5
Oak, post	?	40.3	28.6	25.4	5.1	.5
Oak, scarlet	T	43.2	29.2	20.9	6.6	.1
Oak, southern red	G	40.5	24.2	23.6	9.6	.5
Oak, southern red	?	43.9	27.6	23.0	5.2	.3
Oak, water	G	41.6	34.8	19.1	4.3	.3
Oak, white	G	43.7	24.2	24.3	5.4	1.0
Oak, white	T	41.7	28.4	24.6	5.3	.2
Sweetbay	G	44.2	37.7	24.1	3.9	.2
Sweetgum[8]	G	42.8	30.1	25.7	1.1	.3
Sweetgum[9]	G	43.4	31.0	23.7	1.6	.3
Sweetgum	T	40.8	30.7	22.4	5.9	.2
Tupelo, black	G	44.9	23.2	28.9	2.6	.4
Tupelo, black	T	42.6	27.3	26.6	2.9	.6
Yellow-poplar	T	39.1	28.0	30.3	2.4	.3

[1] G indicates southeastern Georgia; T indicates eastern Tennessee.

[2] 99 percent of glucan percentage minus half the mannan percentage.

[3] Glucomannan plus acetyglucuronoxylan, plus aribinogalactan, plus pectin.

[4] Klason lignin, insoluble and soluble (by ultraviolet spectrum of filtrate, corrected for furfural and hydroxymethylfurfural).

[5] Extracted in succession with petroleum ether, ethyl ether or chloroform, 95-percent ethanol, and hot water.

[6] Ashed at 550°C.

[7] Single tree; dimensions not recorded.

[8] 20 trees.

[9] Single tree, 18 cm diameter, 39 years old.

CHAPTER 3
Direct Combustion

Today, as in the past, the most common way to use wood and bark for energy is to burn it for heat. In the United States the use of wood for fuel peaked about 1875 and has dramaticcally declined with the availability of fossil fuels (Corder 1973). Internationally, however, about half of all harvested wood is still used for fuel[1]. And, with the depletion of fossil fuels, there is renewed interest in using wood and bark as fuel.

[1] Saeman, J. F. Energy and materials from the forest biomass. Institute of Gas Technology Symp. on Clean Fuels from Biomass and Wastes. (Orlando, Fla., Jan. 1977.)

3-1 Wood as Fuel

Heating value, ultimate analysis, proximate analysis, moisture content, and size are some of the important characteristics that influence the value of wood as a fuel. Some of these characteristics will not vary significantly, while others, such as moisture content and size, can vary greatly. Often, fuel preparation will be required to minimize variations and to provide a more homogeneous material for efficient combustion.

The Combustion Process—*Combustion* is the rapid chemical combination of oxygen with the elements of a fuel that will burn (Babcock and Wilcox Co., 1972). Chemically it is an oxidation process that results in the release of heat energy. The major

combustible elements in wood are carbon and hydrogen (table 2-6). The complete oxidation of carbon forms carbon dioxide (CO_2), and heat energy; complete oxidation of hydrogen (H_2) yields water (H_2O) and heat energy.

$C + O_2 \rightarrow CO_2 + 14{,}100$ Btu/lb of C (3-1)

$2H_2 + O_2 \rightarrow 2H_2O + 61{,}100$ Btu/lb of H_2 (3-2)

Combustion of wood is not always complete, which results in the release of lesser amounts of carbon monoxide (CO), hydrocarbons, and other substances.

The burning of wood can be divided into three consecutive stages. In the first stage the moisture is evaporated to dry the wood, which requires about 1,100 Btu per lb of water. In the second stage, the temperature of the fuel rises to the point where volatiles are driven off and combusted. In the third stage, the fixed carbon (carbon remaining after the volatiles are driven off) is combusted as fast as oxygen can be brought in contact with it (Fernandes 1976).

In most combustion processes, air is the source of oxygen. For the purpose of calculating the amount of air required for combustion, air can be considered to be 23.1 percent oxygen and 76.9 percent nitrogen by weight. Thus, for every lb of oxygen required, 4.32 lb of air must be supplied. As carbon has an atomic weight of 12 and oxygen has a molecular weight of 32, we can see from equation 3-1 that 12 pounds of carbon require 32 pounds of oxygen to produce 44 pounds of carbon dioxide (molecular weight 44). To burn 1 lb of carbon will require 2.67 lb of oxygen. By similar calculations, it can be shown that 8 lb of oxygen are required to burn 1 lb of hydrogen (equation 3-2). The amount of air required to burn a fuel can be calculated from its ultimate analysis. The average hardwood contains about 50.8 percent carbon, 41.8 percent oxygen, and 6.4 percent hydrogen (table 2-6). The nitrogen and ash do not play a significant role in the combustion calculations and can be left out. In calculating the minimum air required to burn wood, the percentage of elements can be based on any weight; here let us use 1 lb of wood.

The oxygen required to burn the carbon = 1 lb wood (0.508 lb C/lb wood) (2.67 lb O_2/lb C) = 1.36 lb O_2

The oxygen required to burn the hydrogen = 1 lb wood (0.064 lb H/lb wood) (8.00 lb O_2/lb H) = 0.512 lb O_2

Thus, total oxygen required = 1.87 lb.

The molecular structure of the average hardwood is already 41.8 percent oxygen (table 2-6). This oxygen as well as oxygen from air will be involved in the formation of CO_2 and H_2O and must be accounted for in the combustion calculations. Thus, the oxygen already in 1 lb of wood = 0.418 lb. The oxygen needed from the air = total oxygen required − oxygen already in wood = 1.87 lb. − 0.42 lb = 1.45 lb. Therefore, total air required = (1.45 lb O_2) (4.32 lb air/lb O_2) = 6.26 lb air.

This minimum amount of air is called *theoretical air* and does not depend on the moisture content of the wood. In theory, combustion of wood generally requires about 6 lb air per lb of wood (Wiley 1976). In practice, *excess air* is provided to ensure complete combustion. This usually runs from 25 to 150 percent over the theoretical air.

We have seen how the ultimate analysis can be used to calculate the air required for burning wood. The proximate fuel analysis is an indication of the relative amounts of volatile material that will be evolved and burned in the second stage of the combustion process. The amount of carbon left after the volatiles leave is called the fixed carbon. The fixed carbon burns in the solid state. Seventy-seven percent of the average hardwood will burn as volatile matter and 19 percent will burn in the solid state as fixed carbon (table 2-7). This kind of analysis can suggest the best locations for combustion air inlets in a furnace.

Moisture Content and Available Heat—The *heat of combustion* for wood can vary considerably with chemical content. Resin, waxes, lignin, and such compounds with high carbon and hydrogen contents have higher heating values than carbohydrates which have a high oxygen content. Softwoods, because they generally have a higher resin and lignin content, have a higher heat of combustion than hardwoods. For example, loblolly pine stemwood has a heat of combustion of 8,600 Btu per ovendry lb (Howard 1973), while pine-site hardwoods average 7,827 Btu per ovendry lb of stemwood and about 7,593 Btu per ovendry pound of stembark (table 2-5).

Heats of combustion are determined with an oxygen bomb calorimeter. Values obtained are somewhat higher than those recovered in practice because the calorimeter is closed and the products of combustion are contained. Thus, on cooling, water vapor is condensed and releases its heat of vaporization. In an industrial furnance, this heat is normally lost to the atmosphere. The heat of combustion measured by a bomb calorimeter is called the *higher heating value.* The *lower heating value* is obtained by subtracting the heat of vaporization of the water formed in combustion. The average lower heating value for pine-site hardwoods is 7,261 Btu per lb for stemwood

and 7,027 Btu per lb for stembark.

There are two ways to express moisture content of wood. The ovendry method is most commonly used by people in the forest products industry.

$$\text{M.C. (dry)} = \frac{\text{(weight of water)}}{\text{(weight of ovendry wood)}} \times 100 \quad (3\text{-}3)$$

People in the field of fuels and combustion and most engineers use the wet basis moisture content.

$$\text{M.C. (wet)} = \frac{\text{(weight of water)}}{\text{(total weight of wood and water)}} \times 100 \quad (3\text{-}4)$$

A material that is half water and half wood would have M.C. (dry) = 100 percent and M.C. (wet) = 50 percent. The two moisture contents can be converted by the following formula:

$$\text{M.C. (wet)} = 100\ \text{M.C. (dry)}/[100 + \text{M.C. (dry)}] \quad (3\text{-}5)$$

$$\text{M.C. (dry)} = 100\ \text{M.C. (wet)}/[100 - \text{M.C. (wet)}] \quad (3\text{-}6)$$

In keeping with most of the literature referenced, the wet basis moisture content will be used in the following discussion unless otherwise noted.

The economic value of a fuel will depend both on its heating value and moisture content. High moisture content is detrimental in two ways. First, it reduces the *available heat* of the fuel. The higher heating value of a fuel does not change with increasing moisture content, but the available heat does change (equation 3-7) because there is simply less fuel per unit weight (table 3-1, Ince 1977).

$$\text{Available heat} = \text{(percent wood)} \times \text{(higher heating value)} \quad (3\text{-}7)$$

High moisture content also reduces furnance efficency, because heat energy is lost up the stack in vaporizing the moisture in the wood. Vaporization of fuel moisture is the first stage in combustion; thus heat energy must raise the moisture temperature from ambient (70°F) to the boiling point (212°F). Additional heat energy is required to vaporize the water to steam at 212°F. Heat energy is also lost in raising the steam temperature to that of the furnace stack gases. Steam tables can be readily used to calculate the amount of energy required to heat and evaporate water. For example, if the stack temperature is 500°F, the calculated heat energy lost in changing the water at 70°F to steam at 500°F and 14.7 psi is 1,250 Btu/lb of water (Wiley 1976).

Table 3-1.—*Available heat versus moisture content for pine-site hardwoods*[1]

Moisture content	Available heat (Higher heating value)
Percent (wet basis)	*Btu/lb*
0 (ovendry)	7,827
10	7,044
25	5,870
42	4,540
50	3,914

[1] Average value for stemwood (table 2-5).

Fuel Preparation—High moisture content, bulkiness, dirt, and heterogeneous size are the undesirable properties that come with using some wood fuels. As with refined petroleum fuels, wood can be upgraded in value for various burning situations (Johnson 1975). Wood-burning furnaces, for example, are designed to burn chip size or smaller material. This permits automation in feeding and more efficient burning. But of course the size of pieces can range from slabs and logs to sawdust and shavings. To reduce and size wood for easier handling and burning, it usually is passed through an attrition mill or *hog*. In a typical hammer hog (fig. 3-1), large pieces enter at the top and are forced down and through spaced bars by the rotating action of hammers. The size of the particles leaving the hog depends on speed of the hammers and clearance between the hammers and the spaced bars. Optimum particle size depends on the burner. In some grate-type furnances, for example, an excess of fines and sawdust inhibits efficient combustion.

Hogged fuel is wood waste having no higher recovery value than that of fuel; such fuel contains no municipal refuse (Johnson 1975). Under this broad definition, which is in common use today, a fuel would not have to be passed through a hog to be called hogged fuel. Common hogged fuels include sander dust, shavings, sawdust, bark, log yard cleanup, clarifier sludge, forest residuals, and fly carbon.

Boiler tests have shown that drying hogged fuel produces the double benefit of increased steam generation efficiency and reduced emissions (Johnson 1975, Hall et al. 1976). Most furnaces designed for wet wood operate best if weight of water does not exceed that of wood, that is, if moisture content is 50 percent or less on a wet basis. At moisture contents exceeding 60 percent, most furnaces operate poorly, if at all.

Wood fuel can be dried in several ways. Mechanical pressing squeezes water out with simple equipment that requires no heat. Moisture content can be reduced to 50-55 percent by this method (Porter and Robinson 1976). Air drying is slow but can reduce the moisture content to about 20 percent and if climate permits, even less. Perhaps solar dryers will be

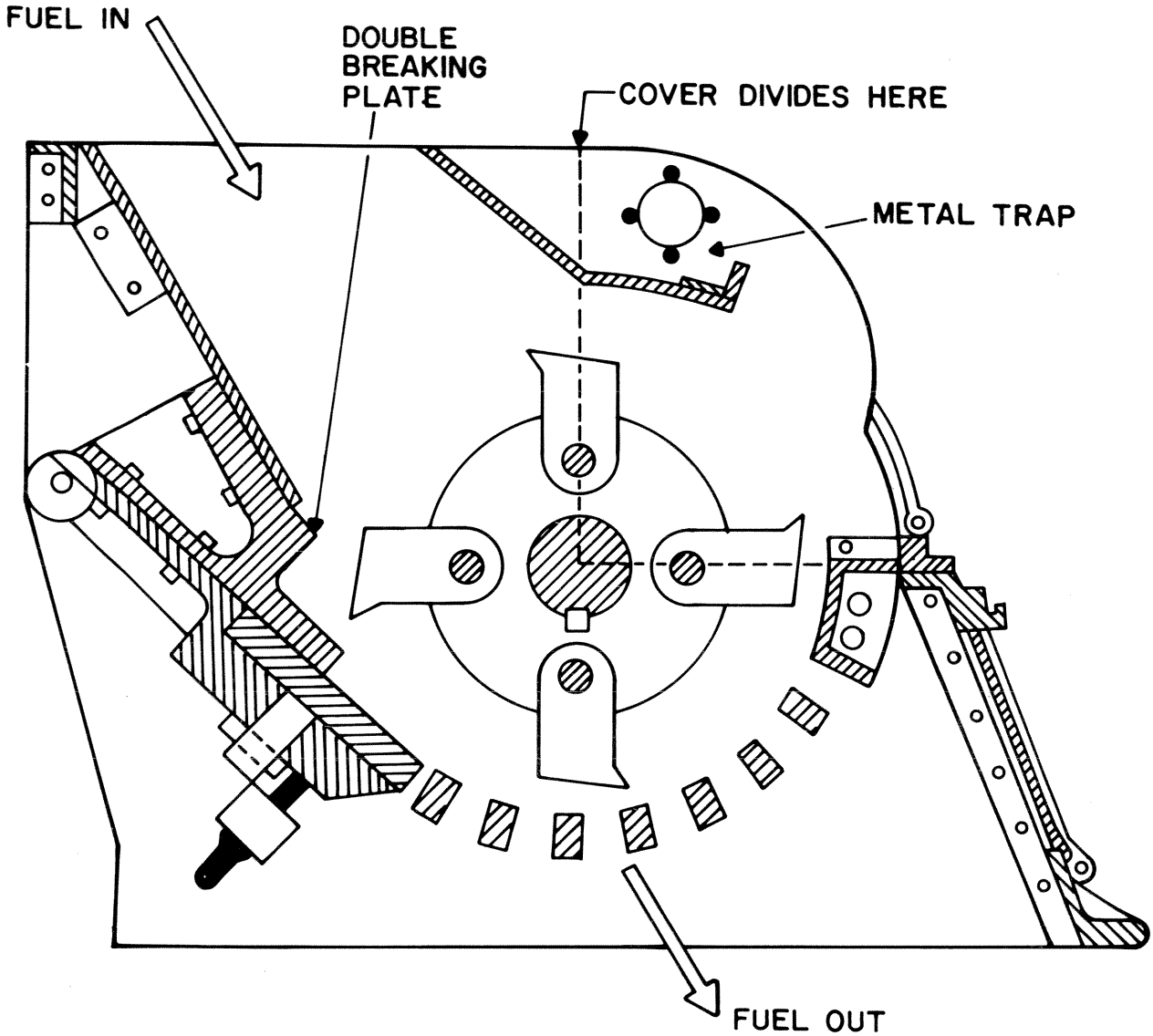


Figure 3-1.— *Transverse section through a typical hammer hog. (Drawing after Fernandes 1976.)*

developed for this purpose. Today, fuel dryers which use hot gases are in widespread use. The most common type is the rotary drum. Other types of fuel dryers, such as the hot hog and hot conveyor system (Johnson 1975) have not been as successful[2]

In a typical *rotary drum dryer system,* fuel that is to be dried is first screened to remove and rehog oversized pieces. Hot gases and the fuel enter one end of the drum or cylinder and are brought into contact with each other by cylinder rotation and horizontal gas flow (fig. 3-2). An induced-draft fan draws the hot gases through the dryer, and this gas pushes the dried fuel toward the outlet end of the dryer. Two- to four-inch pieces can be adequately dried in 20 minutes or less. Fuel is separated into different sizes at the dryer outlet. Airborne fines go to the cyclone separator with the gas flow (Thompson 1975, Johnson 1975).

Rotary drum dryers are suited for handling large quantities of wet fuel. The inlet temperature can go as high as 1600°F if the moisture in the fuel is high enough to absorb the heat without scorching the wood. However, one must be careful to prevent the formation of blue haze. Blue haze, a major environmental concern for the forest products industry, is caused by distillation of organic material such as terpenoids into the air while drying wood. Douglas-

[2] Personal communication with David C. Junge, Oregon State University, Corvallis.

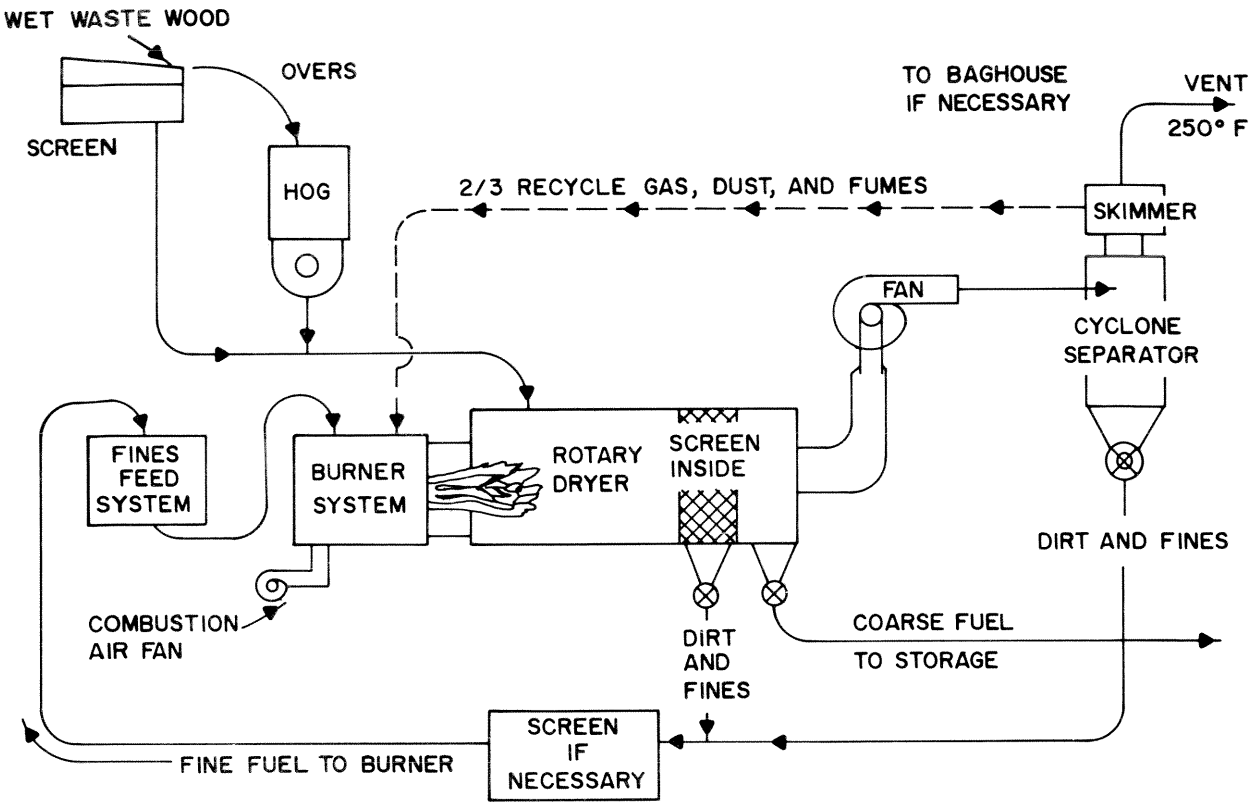


Figure 3-2.—*Typical rotary dryer system. (Drawing after Johnson 1975.)*

fir dried above 750°F creates blue haze. We do not know the optimum drying conditions for pine-site-hardwoods.

Bulkiness of wood fuel can be circumvented to some extent by compressing it into more dense material of various shapes and sizes. Such compressing makes storing, handling, and shipping easier and promotes uniform burning.

There are several ways to densify wood for fuel. Compression baling can reduce wood residue volume to one-fifth its loose bulk while squeezing out 12 to 15 percent of its moisture (American Hoist & Derrick 1976). Most of the densified products can be formed by compressing the residue in a die under heat and pressure. Apparently the key to success is to break down the elasticity of the wood or bark. If the elasticity is not sufficiently destroyed, the densified form will not have permanence (Hausmann 1974). It is possible that polyphenolic compounds (especially in bark) play a role in successful densification. The compounds may act as natural binding agents or glues when subjected to heat and pressure. Fire logs for home use can employ a wax or other binder (Braun 1975).

The technology for densifying particulate wood and bark has been around for over 50 years (Sprout Waldron and Co. 1961, Hausmann 1974, Currier 1977, Farnsworth 1977). The famous "pres-to-logs" used for hand-firing fireplaces and stoves were first made about 1933. In the 1950's machines were developed to extrude wood residue rods suitable for fueling coal stoker furnaces. Generally, the rods are about 1 inch in diameter and can be cut to desired lengths. In 1959 a company in Tennessee first pelletized bark for fuel. These oak bark pellets were used with coal to fire a steam boiler and reportedly gave burning rates equivalent to soft-coal. Since the late 1960's extensive research on pelletization of wood and bark residues for fuel and other uses has been carried out by Currier (1977) at Oregon State University and Steffensen (1973) at Georgia-Pacific.

Pelletization can be accomplished with standard agricultural pellet mills (Currier 1977). The product is generally 3/16- to 1/2-inch in diameter and 1/2-inch long. The compression ratio in pelletizing is usually about 3 to 1. Because of their uniform density, fuel pellets are easier than hogged fuel to meter into a furnace and can be burned at more closely controlled rates. Wet fuel cannot be pelletized unless it is first dried, however, and part of such fuel

must be used to dry the material to be pelletized. Because of this, those industries that have dry wood wastes, such as furniture and cabinet manufacturers, may find pelletizing most economically attractive.

A company in Alabama pelletizes sawdust and bark after pre-drying it in a rotary dryer fired by some of the pelletized product. The pellets are sold to a power plant. Estimated total investment is about one-half million dollars including land. The pelletizer sells for around $32,000. Similar estimates of cost have been reported by Farnsworth (1977). A company in Oregon markets pelletized Douglas-fir bark (Blackman 1978). Reportedly, the product sells for about half the price of coal of equivalent Btu's. Plant operations use the equivalent of 12 percent of the energy contained in the pelletized product.

Residues—Ash and incompletely combusted carbon are the solid residues from burning wood. In boiler furnaces, where high burning temperatures are achieved, slag and clinker are formed from the melting and fusion of ash. Analysis of the ash from the 23 pine site hardwoods is underway at the Southern Forest Experiment Station. Studies of other species indicate that wood ash is composed primarily of calcium oxide (ÇaO) and silica (SiO_2) and contains small percentages of alumina (Al_2O_3), iron oxide (Fe_2O_3) and magnesium oxide (MgO) (table 3-2).

Wood ash generally has been considered inert (Hall et al. 1976), but this may not be chemically true. In at least one case, wood ash has been shown to be an effective catalyst in the gasification of wood (Feldman 1978).

Increased use of wood for fuel might make ash disposal a problem (Hall et al. 1976). Perhaps ash could be used as a soil conditioner to break up clay, and the alkalinity of ash could help raise the pH of acid soil. If supplemented with nitrogen compounds ash also has the potential to be used as a fertilizer. One mill in central Louisiana uses clinkers for roadbed surfaces around the plant.

Table 3-2.—*Chemical composition of wood ash*[1]

Component	Percent by weight
SiO_2	33.8
Al_2O_3	2.6
TiO_2	.2
Fe_2O_3	1.6
CaO	56.5
MgO	4.7
Na_2O	.5
K_2O	.1
	100.0

[1] Data from Babcock and Wilcox Company (1972).

Emissions—Both gaseous and particulate emissions occur when wood is burned (table 3-3). Carbon dioxide and water vapor (equations 3-1 and 3-2) combined with nitrogen and oxygen from the combustion air comprise 98-99 percent of the total material emitted from an efficient combustion process.

In terms of potential air pollution, the United States Environmental Protection Agency (EPA) is concerned with the amounts of particulate matter, sulfur dioxide, carbon monoxide, nitrogen oxides, and unburned hydrocarbons that are emitted into the atmosphere. In wood combustion, sulfur dioxide emission is negligible, and carbon monoxide and hydrocarbon emissions present no problems in most situations. The situation with nitrogen oxides is less certain, and particulate emissions from wood-fired boilers require attention.

When combustion is poor, hydrocarbon[3] emissions are increased. In extreme cases, these emissions may be 55-85 lb/ton of fuel (Junge and Kwan 1974). High hydrocarbon emissions could present a twofold pollution problem. First, polycyclic aromatic compounds can be produced through the incomplete combustion of solid carbonaceous fuels such as coal (Hall et al. 1976). Certain polycyclic aromatic compounds are suspected carcinogens. However, it is not certain to what extent these compounds occur in the incomplete combustion of wood. The second problem is the production of peroxy compounds that react with sunlight as part of the complex process resulting in photochemical smog. Formation of carcinogenic compounds or photochemical smog should not be problems in wood burning if combustion is efficient (Hall et al. 1976).

Nitrogen oxides (NO and NO_2) are instrumental in smog formation. At present, the automobile engine

[3] The term hydrocarbon is poorly defined as it is used in the literature and is sometimes used to denote oxygen-containing organic compounds as well as hydrocarbons.

Table 3-3.—*Emissions from combustion of hogged fuel (Junge 1975a)*

Gases		Particulate matter
Nitrogen, Carbon dioxide, Oxygen, Water vapor	98-99% of total	Inorganic flyash Fixed carbon Traces of metals and salts
Carbon monoxide		
Unburned hydrocarbons		
Sulfur dioxide		
Oxides of nitrogen		
Inert gases		

is by far the largest source of nitrogen oxides. In high concentrations, these compounds not only harm life but destroy material as well. Fortunately, the ambient concentration of nitrogen oxides is low enough in most areas that emission control for them from wood burning should not be required. However, if the need arises, modification in the combustion process rather than the use of a cleaning device at the stack would be necessary (Hall et al. 1976).

Particulate emissions can be controlled by any of four basic devices. These are cyclone separators, scrubbers, baghouse filters, and electrostatic precipitators (Junge 1975a). Most wood-fueled boilers are equipped with cyclone separators; however, some are equipped with scrubbers.

Comparison to Fossil Fuels. — The higher percentages of oxygen in the molecular structures of wood and bark gives them lower heating values than coal and oil (table 3-4). In comparison with coal, wood has a low ash content and little or no sulfur. The chief drawback of woody fuels is their naturally high moisture content and bulkiness.

Arola (1975) has a graph (fig. 3-3) that is a useful tool for comparing the cost of heat or steam produced from wood-based and fossil fuels (See below for an example of how to use the figure.)

The graph has three sets of lines which correspond to three classes of fuel considered: (1) oil; (2) coal, bark, wood, and municipal solid refuse; and (3) gas. A fourth set of lines represents efficiency values to allow for losses when converting heat energy to steam. Heating values used for the solid fuels are "as fired," that is, the available heat at the moisture content (wet basis) as fired (equation 3-7).

Figure 3-4 is an example of how to use the graph (Arola 1975).

Given: The fuel is bark which costs $10/wet ton and has a higher heating value of 9,000 Btu/lb when ovendry. Process efficiency is 65 percent. The bark is fired at 50 percent moisture content (wet basis).

Problem: What is the cost of steam?

Solution: Available heat at 50 percent moisture content is 4,500 Btu/lb, i.e., (1.00 - 0.50) x 9,000 Btu/lb. From the $10/ton point along the upper scale at bottom of chart, extend a line vertically to the 4,500 Btu/lb point for bark (interpolation required). Extend a horizontal line from this intersection to the 65 percent efficiency line and then a vertical line to the top of the graph to read the cost of steam.

Answer: About $1.70/million Btu.

3-2 Industrial Burning Systems

Today industrial wood burning furnaces are commonly incorporated into boiler systems to produce steam. Nearly 1700 such wood fired boiler systems are in operation in the United States (Environmental Protection Agency 1977). They range in size from shop-fabricated units, with steam capacities up to about 100,000 pounds per hour, to large field-erected units that can generate up to 600,000 pounds of steam per hour on hogged fuel (U.S. Forest Service 1976, Bliss and Blake 1977). Wood-fired boilers that produce 15,000 to 100,000 pounds per hour of steam are the most common recent installations (Hall et al. 1976). In some furnace systems the hot combustion gases produced are used to direct-fire kilns and dryers without the intermediate step of steam generation. In addition, certain furnaces could be used to drive gas turbines whose exhaust heat could then be

Table 3-4.— *Ultimate analyses and heating values of some fossil fuels compared with hardwoods*

	Coal[1]		Hardwood[2]		Residual fuel oil[1]
	Western	Pennsylvania	Wood	Bark	
	Percent				
Ultimate analysis					
Hydrogen	6.4	5.0	6.4	6.0	9.5 - 12.0
Carbon	54.6	74.2	50.8	51.2	86.5 - 90.2
Oxygen	33.8	7.1	41.8	37.9	—
Sulfur	.4	2.1	—	—	.7 - 3.5
Nitrogen	1.0	1.5	.4	.4	—
Ash	3.3	10.1	.9	5.2	.01- .50
Heating value, Btu/lb	9,420	13,310	7,827[3]	7,593[3]	17,410 -18,990

[1] Data from Hall et al. (1976).
[2] Data from Arola (1976).
[3] Data from table 2-5.

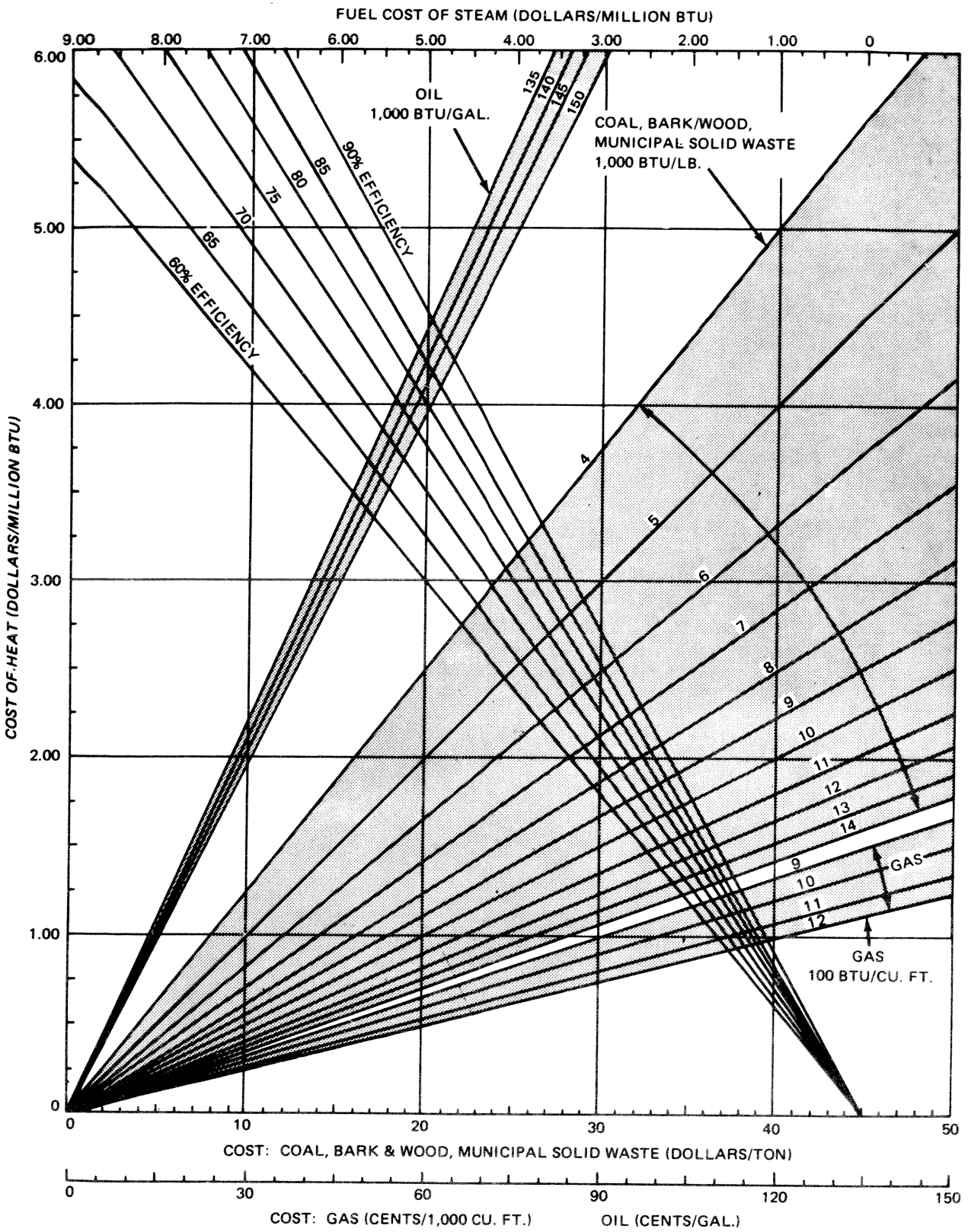


Figure 3-3.—*Graph to compare fuel value for wood-based and fossil fuels. (Drawing after Arola 1975.)*

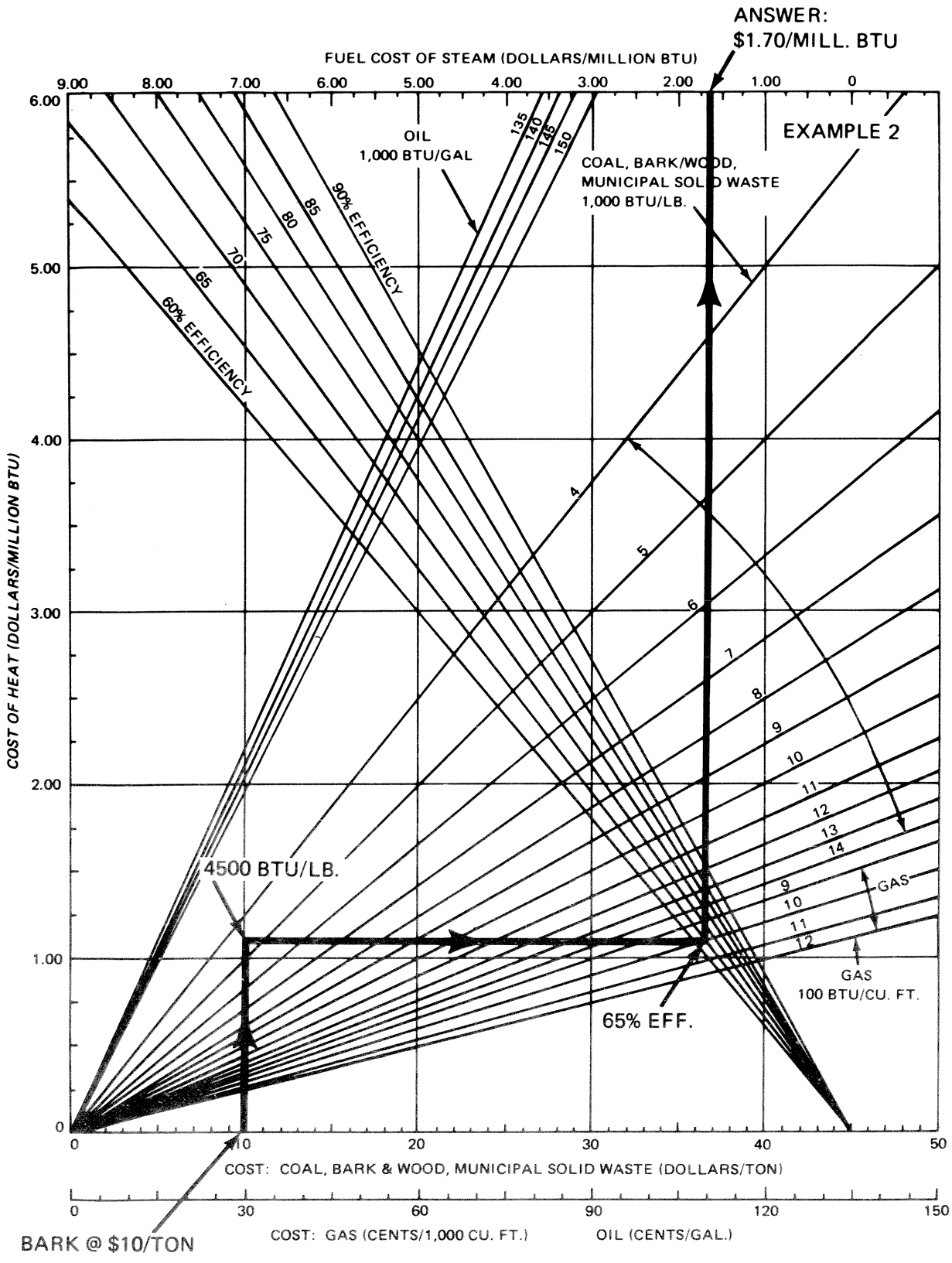


Figure 3-4.—*Example of how to use the fuel value comparison graph. (Drawing after Arola 1975.)*

used in a conventional boiler to produce added steam power.[4]

Basically there are two classes of furnace design in use for wood burning—grate burners and suspension burners. Dutch ovens, inclined grate furnaces and spreader stokers burn the fuel on a grate, either in a pile or spread into a thin bed. In suspension burning, the fuel is supported by air during its combustion. Within these two classes of furnace design are a variety of furnace types which can differ markedly in basic operation. This variety is due largely to the various forms that wood fuel can take. Innovative engineers have created a diversity of furnaces designed for particular circumstances.

Dutch Ovens.—Historically, Dutch ovens (fig. 3-5) provided steam for many industries in this country. They are now considered obsolete for new installations, because they are expensive to maintain and respond poorly to load changes.

The Dutch oven is a two-stage refractory (firebrick-lined) furnace. Fuel is fed through a chute in the oven roof and forms a conical pile on the grate in the oven or primary furnace. Here the fuel is dried and partially combusted. The system is designed so that there is insufficient air for complete combustion in the primary furnace. Combustible gases emerge from the fuel pile and pass into the secondary furnace, or combustion chamber, where air entering through the overfire air ports completes combustion. On their way to the stack, the hot combustion gases pass through water-carrying heat exchangers to generate steam. Removal of ash is done by either manual rake-out or dumping grates. Combustion rates of about 600,000 Btu per ft^2 of grate per hour have been attained with air and wood having 45 percent moisture content, but combustion rate drops off rapidly above that level. Excess air at the stack is usually between 30 and 40 percent (Babcock and Wilcox 1972, Junge 1975a).

Fuel Cell Burners.—Fuel cell burners (fig. 3-6) are an adaption of the Dutch oven design; drying and gasification of the fuel occur in the primary furnace, and combustion is completed in the secondary furnace. Fuel is metered into the primary furnace, which is a vertical, refractory-lined cylinder with a water-cooled grate. Here the fuel is partially combusted, and the volatiles pass into the upper chamber where burning is completed. Boilers of this type are common in the western United States, where they are used for kiln-drying lumber. They generally have capacities of 10,000 to 30,000 lb of steam per hour when operated at pressures below 150 psi. Dryers have to be incorporated when fuel moisture content is above 50 percent (Junge 1975a, Corder 1973).

A new variation of a fuel cell furnace is the wet cell burner (Anonymous 1978). This unit employs a cyclonic-type furnace for the upper, secondary combustion chamber (fig. 3-7). Hogged fuel with a moisture content up to 65 percent is metered by a hydraulic ram at a rate controlled by Btu demand. The hydraulic ram then forces the fuel up through

[4] H. G. Hagen. 1977. Wood fueled combustion cycle gas turbine power plant. 38 p. Paper presented at the California Energy Comm. Energy-From-Wood-Workshop.

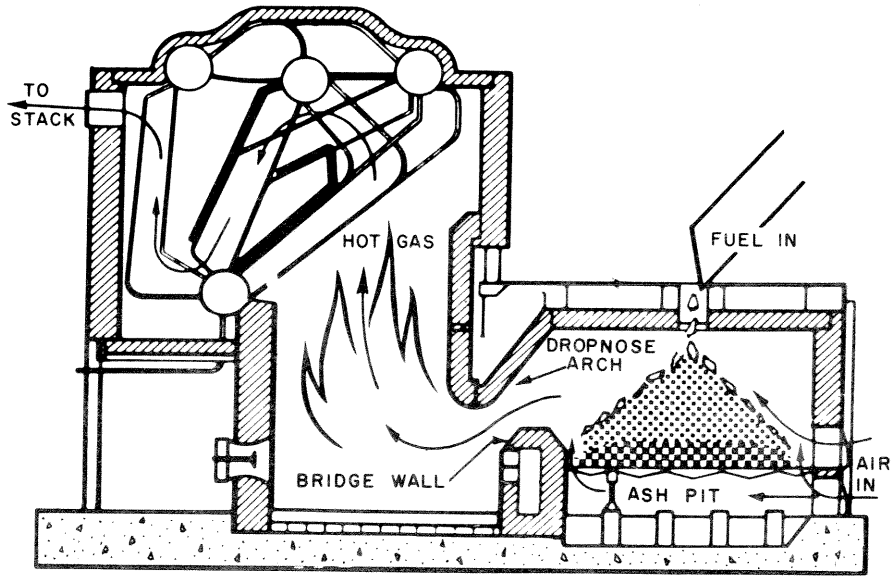


Figure 3-5.—*Dutch oven furnace and boiler. (Drawing after McKenzie 1968.)*

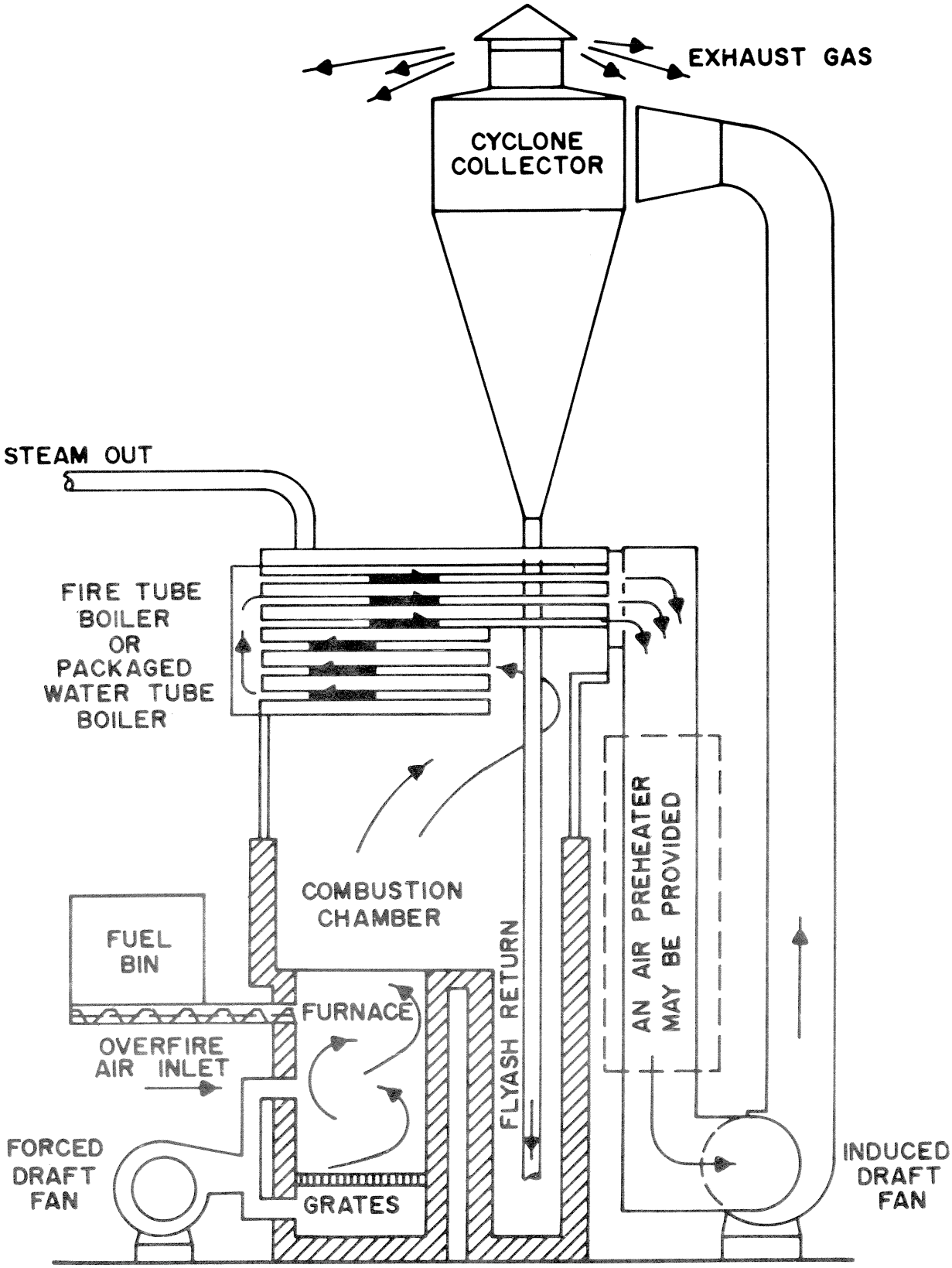


Figure 3-6.—*Fuel cell furnace system. (Drawing after Junge 1975a.)*

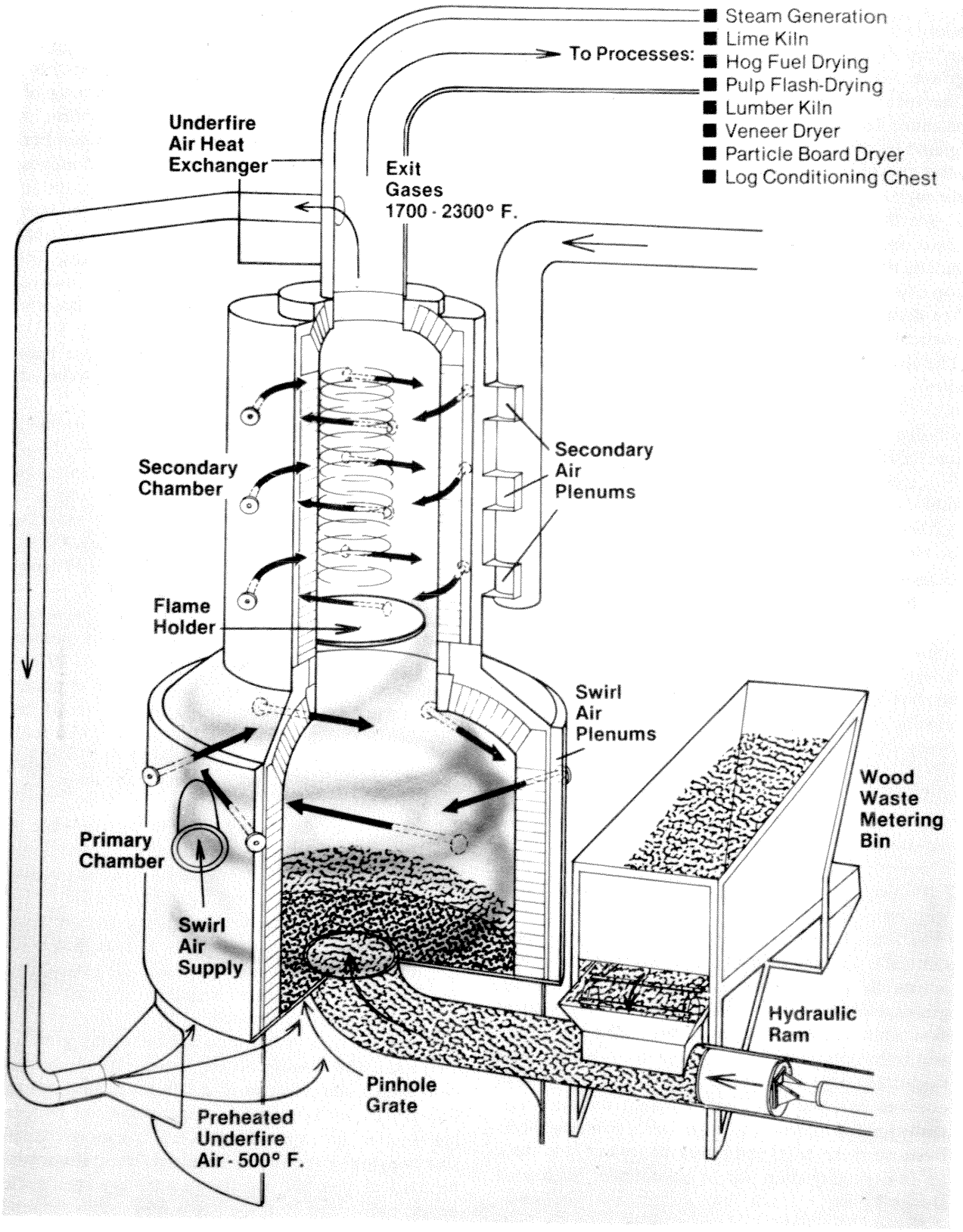


Figure 3-7. — *Wet cell burner. (Drawing from Hugh Dwight Advertising.)*

a large-diameter cylinder under the base of the burner, depositing the fuel through an opening in pinhole grates that form the floor of the lower chamber. The fuel forms a slightly conical pile over the grate as more fuel is pushed up from below. The pile is ignited by an automatic gas burner which shuts down after the pile is burning. Preheated air is forced up through the pile as well as through swirl air plenums above the pile. However, insufficient air for complete combustion is maintained so that the fuel is mostly dried and gasified. Swirling air-flows near the top of the primary combustion chamber subject the hot distillates to a scrubbing action that separates particulates to the outer wall by centrifugal action. The fixed carbon particulates complete oxidation as they are swept away. As the volatiles rise to the upper combustion chamber, they are met by cooler air that is vortexing downward. This action mixes and combusts the gases in a cyclonic air flow. Excess combustion air is limited to 10-15 percent by this mechanism. Exhaust gases leave the burner at 1,700 to 2,300°F and can be used to fire a boiler or be blended with cooler air to use in kilns and dryers.

Inclined Grate Furnaces.—This type of furnace usually has a water-cooled grate and water-cooled furnace walls (fig. 3-8). Fuel enters the furnace at the top of the grate and is dried as it slides down to the lower horizontal section where it is burned. Ash is removed intermittently through discharge doors. Inclined grate furnaces are one of the more popular types of furnaces in Europe (Astrom and Harris 1975).

Spreader Stokers.—The spreader stoker is probably the most commonly used wood and bark burning furnance (Fuller 1976, Bliss and Blake 1977). These furnaces can burn large amounts of wood and bark alone or in combination with coal, oil, or gas with little difficulty.

In spreader stokers, fuel is spread either pneumatically or mechanically into an even thin bed across the grates. When the fuel is added above the grate, smaller particles and volatiles burn in suspension while the large pieces of fuel fall to the grate and burn in the fuel bed. Flames from the particles suspended above the grate radiate heat that aids in combustion of the fuel bed. Furnace walls are normally lined with heat exchange tubes (water walled). Because there is no refractory to reflect heat back to fuel, combustion air is sometimes preheated (Junge 1975a).

Figure 3-9 shows a closeup sectional view of a travelling grate spreader stoker with front ash discharge; in figure 3-10 the stoker is attached to a large steam generator. Fuel is conveyed continuously and distributed into the furnace through an air-swept spout. High-pressure overfire air jets provide turbulence to aid the suspension burning of small particles and volatiles. Air for combustion in the fuel bed is admitted from the plenum chamber through holes in the grate bars. The fuel bed moves with the grate at a rate adjusted to allow complete combustion of the fuel before the ash is dumped into a hopper. Other types of grate are also used with spreader stoker furnaces (Fuller 1976). These include a vibrating-grate where the fuel bed moves toward the ash hopper as the bed is intermittently vibrated by an eccentric drive mechanism (fig. 3-11). In dumping-grate stokers (fig. 3-12) the grate bars are rotated 90° to dump the ash into a combined ash hopper-air plenum.

Spreader stokers can burn hogged fuel containing 45 to 50 percent moisture at 1 million Btu per hour per ft^2 of grate area while using 35 to 45 percent excess air. However, most boilers in operation use more than 75 percent excess air.[5] Spreader stokers are used with boilers that generate from 25,000 to 600,000 lb of steam per hour (Babcock and Wilcox Co. 1972, Corder 1973, Bliss and Blake 1977).

Suspension-Fired Boilers.—Suspension firing of wood and bark in large boiler furnaces is similar to the firing of pulverized coal (Hall et al. 1976). Most often bark hogged to a small size and pneumatically injected into the furnace is the fuel. If injection is high enough in the furnace and the fuel particles are small enough, then the fuel will be completely combusted before it falls out of the combustion zone.

In the system shown in figure 3-13, turbulence is provided by high velocity, tangentially injected flows of preheated air through nozzles at various heights in the furnace. This is also called tangential firing (Fernandes 1976). In tangential firing, the air flows create spinning air masses or fire circles that hold the fuel particles in suspension while they burn (fig. 3-14). Figure 3-15 shows an actual photograph of the fire circle in a boiler furnace.

In the suspension burners, a small dump grate is located at the bottom of the furnace to catch and burn larger fuel particles that fall out of suspension (Fernandes 1976). Usually, suspension-fired boilers are simpler than spreader stokers, but more extensive hogging of the fuel is required. Bark alone can be used as fuel but usually an auxiliary fuel, such as oil, pulverized coal, or gas is co-fired in suspen-

[5] Personal communication with David C. Junge, Oregon State University, Corvallis.

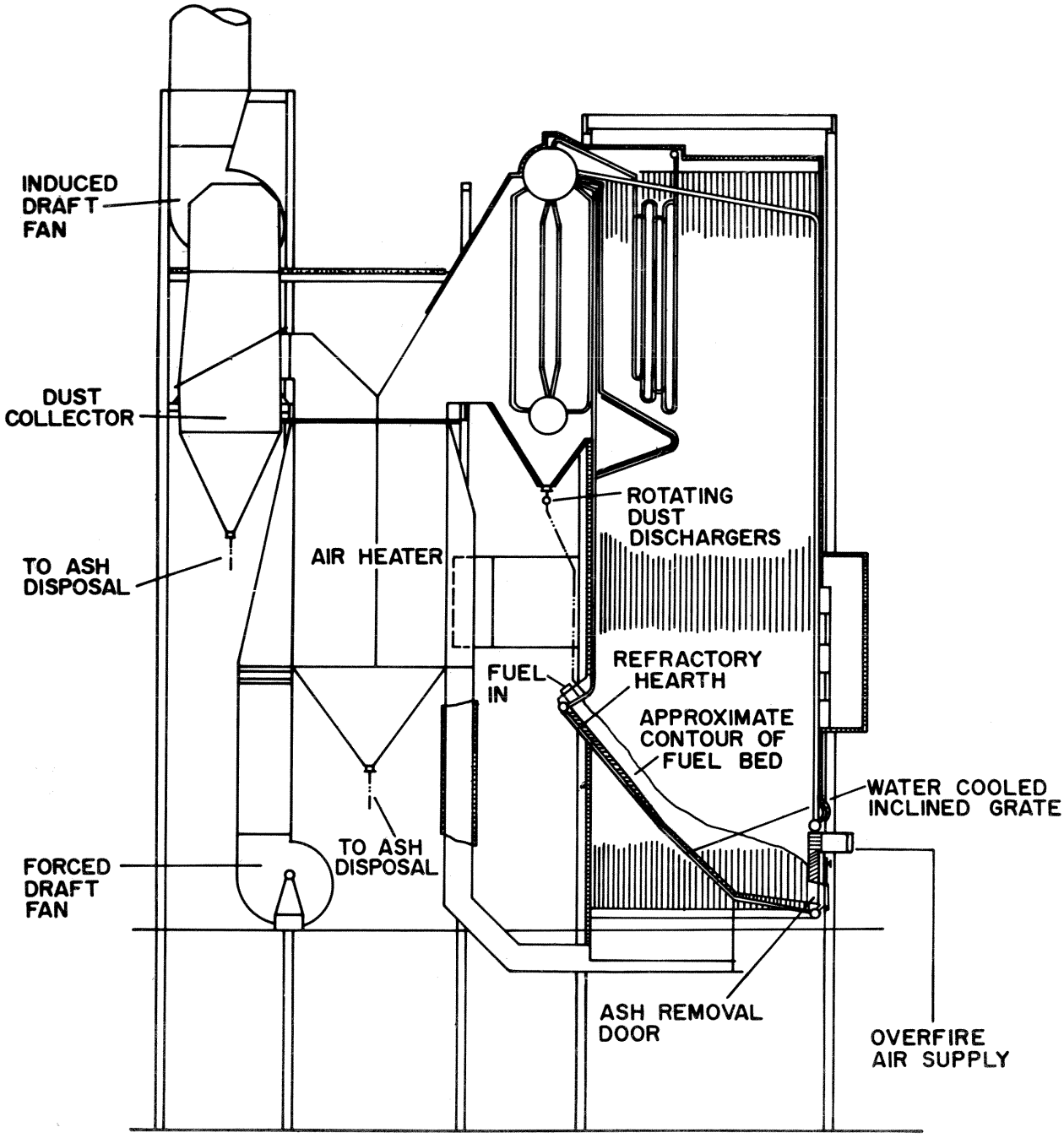
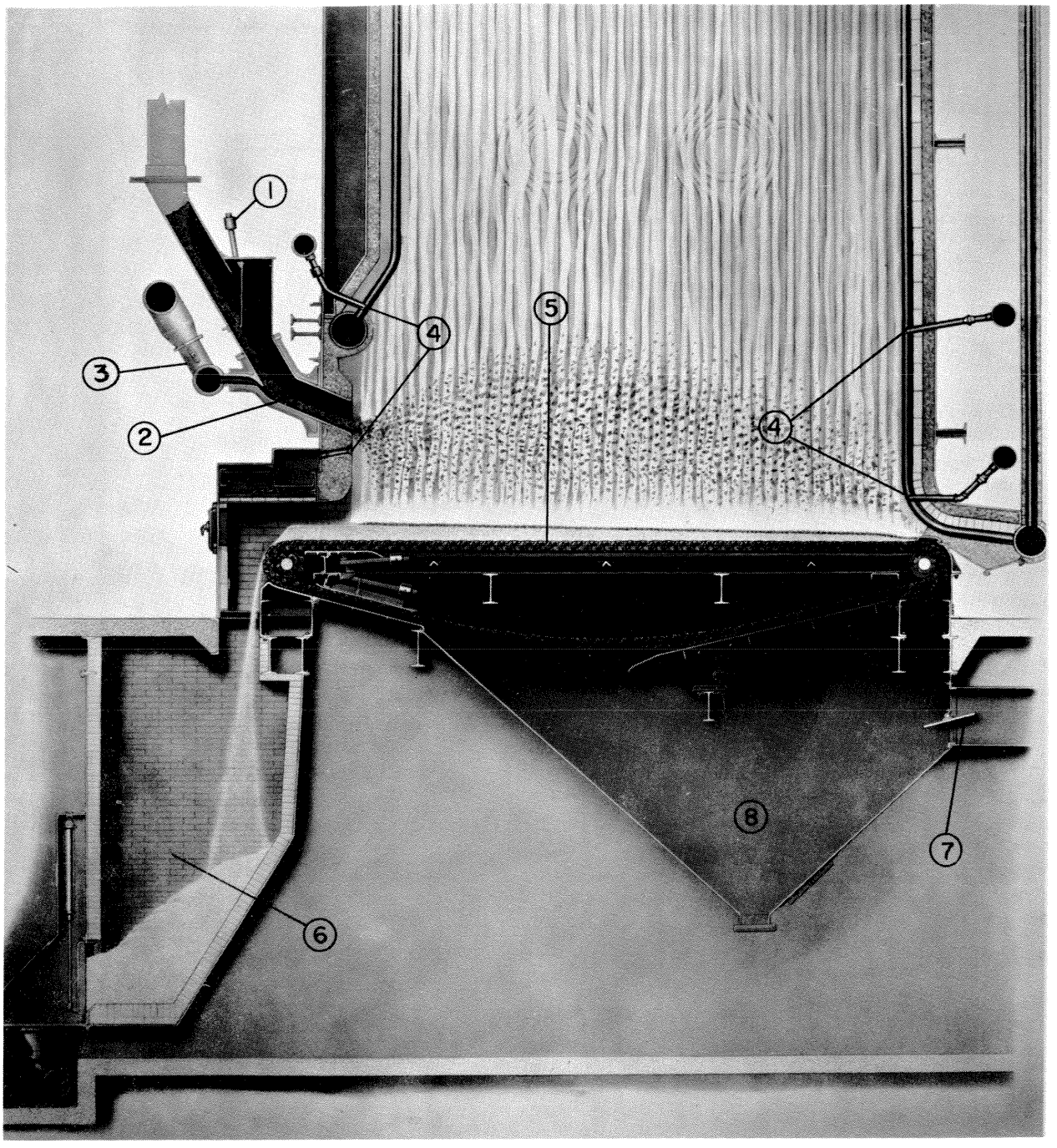


Figure 3-8.—*Inclined grate furnace system. (Drawing after Corder 1973.)*

sion with the bark. Auxiliary fuel nozzles are usually located immediately above and below the bark nozzle. Suspension fired boilers are often large units, some capable of generating over 500,000 lb of steam per hour (Hall et al. 1976).

Cyclonic Furnaces.—Cyclonic furnaces also burn fuel in suspension. In early water-cooled models, cyclone burners were fueled with wood and bark in combination with coal (Fuller 1976). Today, refractory lined models are commonly used and do not require auxiliary fuel except at startup.

In the horizontally mounted cyclonic burner, a drumlike combustion chamber is closed at one end (fig. 3-16). Hot combustion gases are discharged from the opening in the other end called the choke. Combustion air is forced by a blower through the



1. BALANCED DAMPER ASSEMBLY
2. AIR SWEPT FUEL DISTRIBUTOR SPOUT
3. ROTARY AIR DAMPER
4. HIGH PRESSURE OVERFIRE AIR JETS
5. TRAVELLING GRATE
6. ASH HOPPER
7. BLAST GATE
8. AIR PLENUM

Figure 3-9.—*Sectional view of a traveling grate stoker with front ash discharge. (Drawing from Detroit Stoker Company.)*

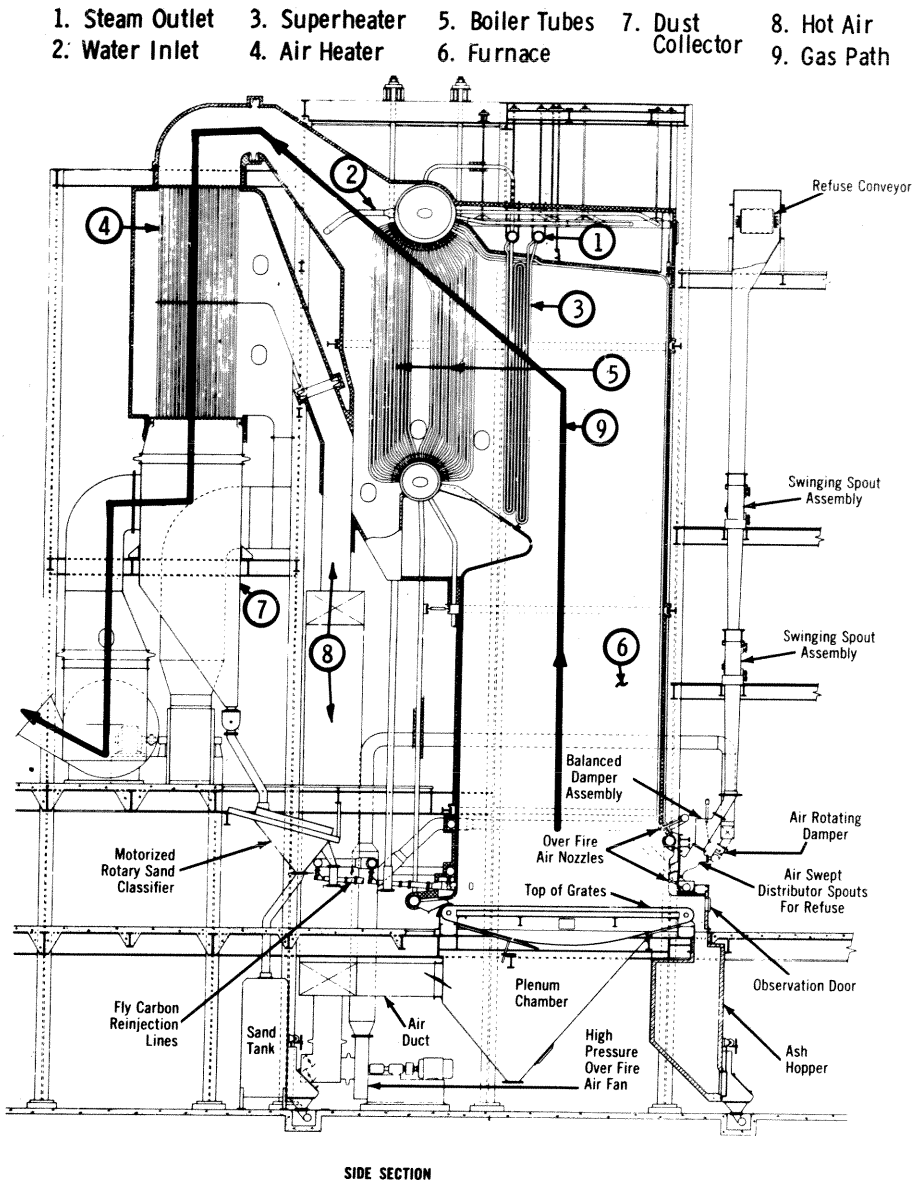


Figure 3-10. — *Components of a typical large steam generator equipped with a spreader stoker. (Drawing from Detroit Stoker Company.)*

air manifold into tuyeres which admit the air tangent to the inner surface of the combustion chamber. The airflow pattern created is a double cyclonic action. Fuel is injected tangentially into the burner with a stream of high velocity air. Mixing of the fuel and air takes place around the periphery of the burner as they traverse toward the choke. Both the high turbulence of the cyclonic airflow and time in the burner contribute to complete combustion as long as proper temperatures are maintained. Excess air can vary from 60 to 130 percent depending on the installation (Levelton and O'Connor 1978).

Fuel wood for this system must be dry (15 percent moisture content) and sized (1/8-inch or less). The fuel is metered from a bin to a mixing tee and then into the high velocity air stream for injection into the burners. An auxiliary burner is required for start-up and additional controls and components can be added for automation. A recirculation system can be incorporated to burn the volatile hydrocarbons associated with the blue haze produced by some veneer dryers (Cherewick 1975, Neild and Weyer 1975). A trap can be added to the basic burners for automatic removal of slag and grit.

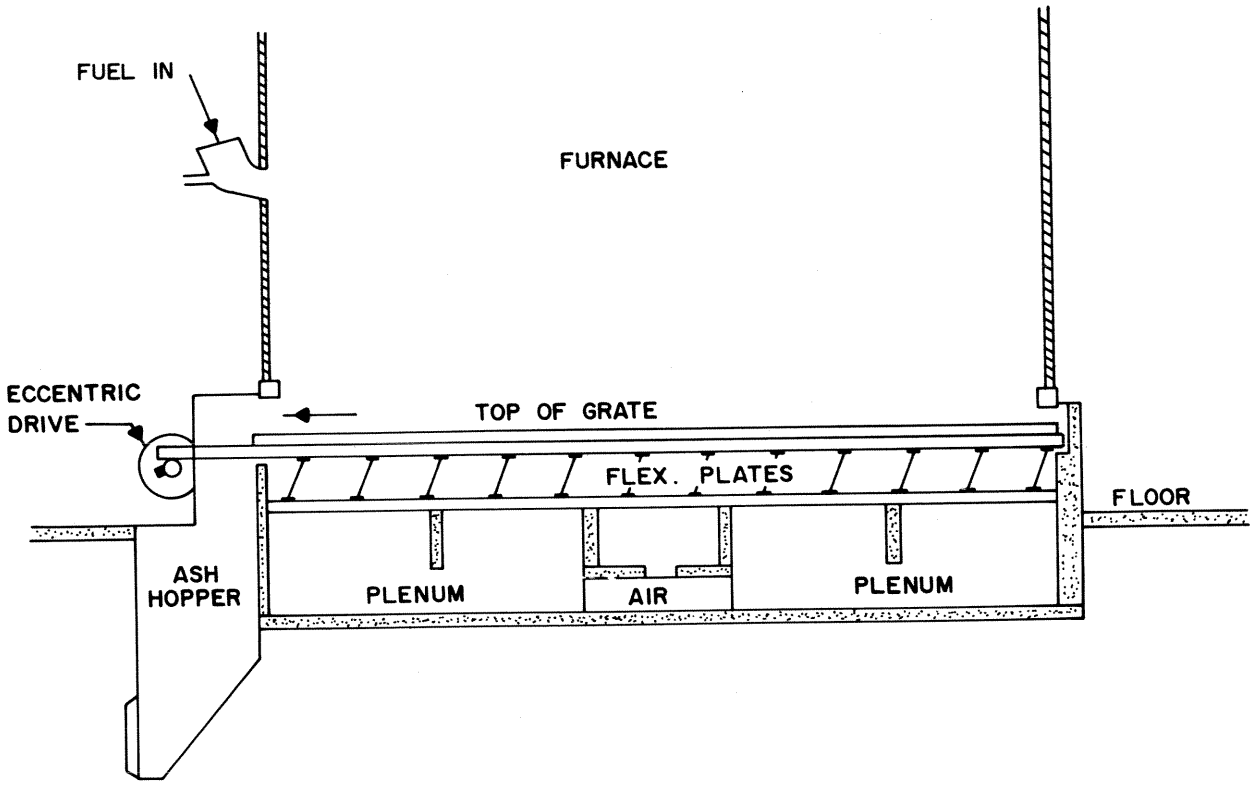


Figure 3-11.— *Vibrating grate stoker. (Drawing after Fuller 1976.)*

Capacities range from 5 to 60 million Btu per hour. Applications for this type of burner include direct firing of lumber kilns, rotary and veneer dryers, and boilers.

Fluidized Bed Burners.—Particles such as sand contained in a vessel can be fluidized by passing a stream of gas upward through them with a certain velocity (Bryers and Kramer 1977, Wiley 1978). When the particles are fluidized, the bed has a hydrostatic head, and light objects float on its surface, while heavy ones sink. Individual particles undergo a high degree of mixing by moving about in the bed.

Particle size determines the rate of gas flow needed to effect fluidization. With a low rate of gas flow the bed of particles behaves as a porous medium, allowing the gas to pass through. As the rate of flow is increased, the point of incipient fluidization is reached where the pressure drop across the bed equals the weight per unit area of the bed. At this point, the particles start to float on the gas flow. Increasing the gas flow gives no further rise in the pressure drop across the bed. The extra flow passes through the bed as bubbles, and when 3-5 times the minimum fluidization velocity is reached, the bed resembles a violently boiling liquid. On fluidization the bed may expand from 1½ to 2 times its original static depth.

Fluidized beds have been used for many years in the petroleum and mining industries for catalytic and ore reactors (Keller 1975). More recently, they have been adapted to combustion systems. Because of the large particle surface area in the fluidized bed, rapid heat transfer occurs between gas and solids. As the fluidized bed has high thermal inertia, fluctuations in heat input are dampened. This permits combustion of wet and low-quality fuels that vary in heating value. The mineral olivine has been found to be a suitable bed material as it is inert to combustion temperatures up to 2000º Bed material wears out by attrition and forms fines that are blown out of the system with the fluidizing gas flow.

Fluidized-bed burners may be used with existing boilers or water tubes can be inserted into the bed or placed in the wall of the burner. The hot combustion gases can also be used for direct heat drying applications (Bryers and Kramer 1977, Wiley 1978). A modified gas turbine cycle coupled to a fluidized bed burner has also been proposed. Such a system will fit into future mill energy needs by providing a higher ratio of electric power to steam power while

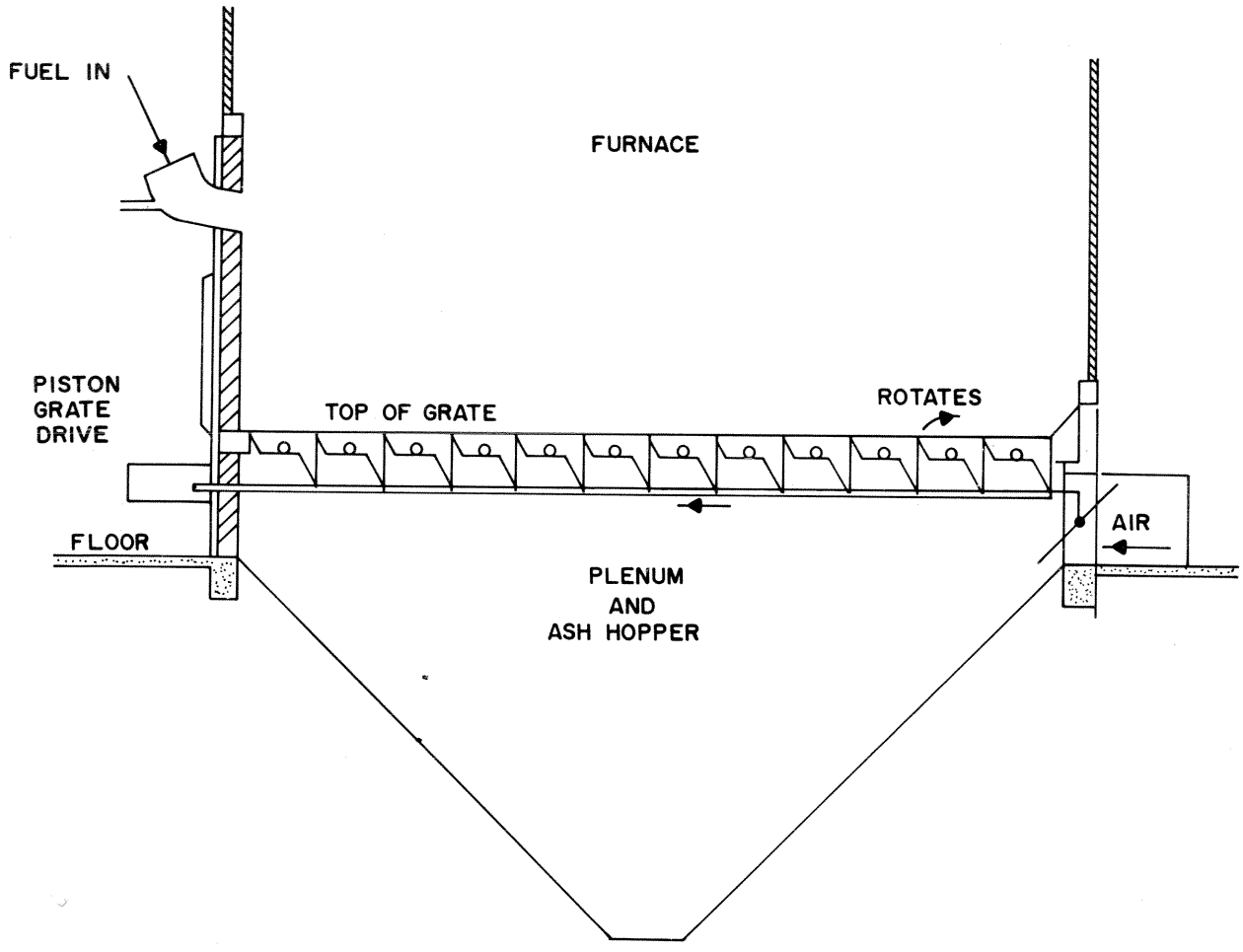


Figure 3-12.—*Dumping grate stoker. (Drawing after Fuller 1976.)*

utilizing a variety of low-grade fuels (Moody 1976).

In the fluidized-bed burner shown (fig. 3-17), the bed is preheated from 700 to 750°F with a non-fluidized airflow for startup. Then, a small amount of fuel spontaneously ignites as it is added to the bed. Once a flame is established, the bed is fluidized by increasing the airflow and then fuel feed is started. As combustion becomes self-sustaining, the temperature of the bed will rapidly rise into the operating range of 1,000 to 1,800°F. Preheat burners can then be turned off and no auxiliary fuel is required.

Fuel moisture contents can be up to 65 percent. Exhaust gas temperatures are normally up to 2,200°F and bed temperatures around 1,750°F. The largest units being constructed will handle 250 tons per day of hogged fuel and generate 55,000 lb of steam per hour. It is not expected that large units comparable to the spreader stokers will be built in the near future (DeArmond et al. 1975, Keller 1975).

Jasper-Koch Burner.—The Jasper-Koch burner (fig. 3-18) takes a new approach to suspension burning. The unit is designed to burn wet wood or bark efficiently in a small furnace that costs less than grate-type furnances of comparable capacity.

As we have said, bark or sawdust that is half water by weight burns very poorly and must be partially dried before combustion occurs. This drying can take place in a separate dryer before burning, in a pile on the floor of the furnace combustion chamber, or in an integral dryer that passes through the combustion zone. The Jasper-Koch burner works on the latter principle.

In the Jasper-Koch design, the combustion chamber is an annular space between two concentric vertical cylinders; particulate fuel burns in suspension in this chamber (fig. 3-19). In the commercial prototype, a stainless steel inner cylinder 29 inches in diameter with walls 1/4-inch thick houses a vertical downfeeding screw that introduces fuel into the bot-

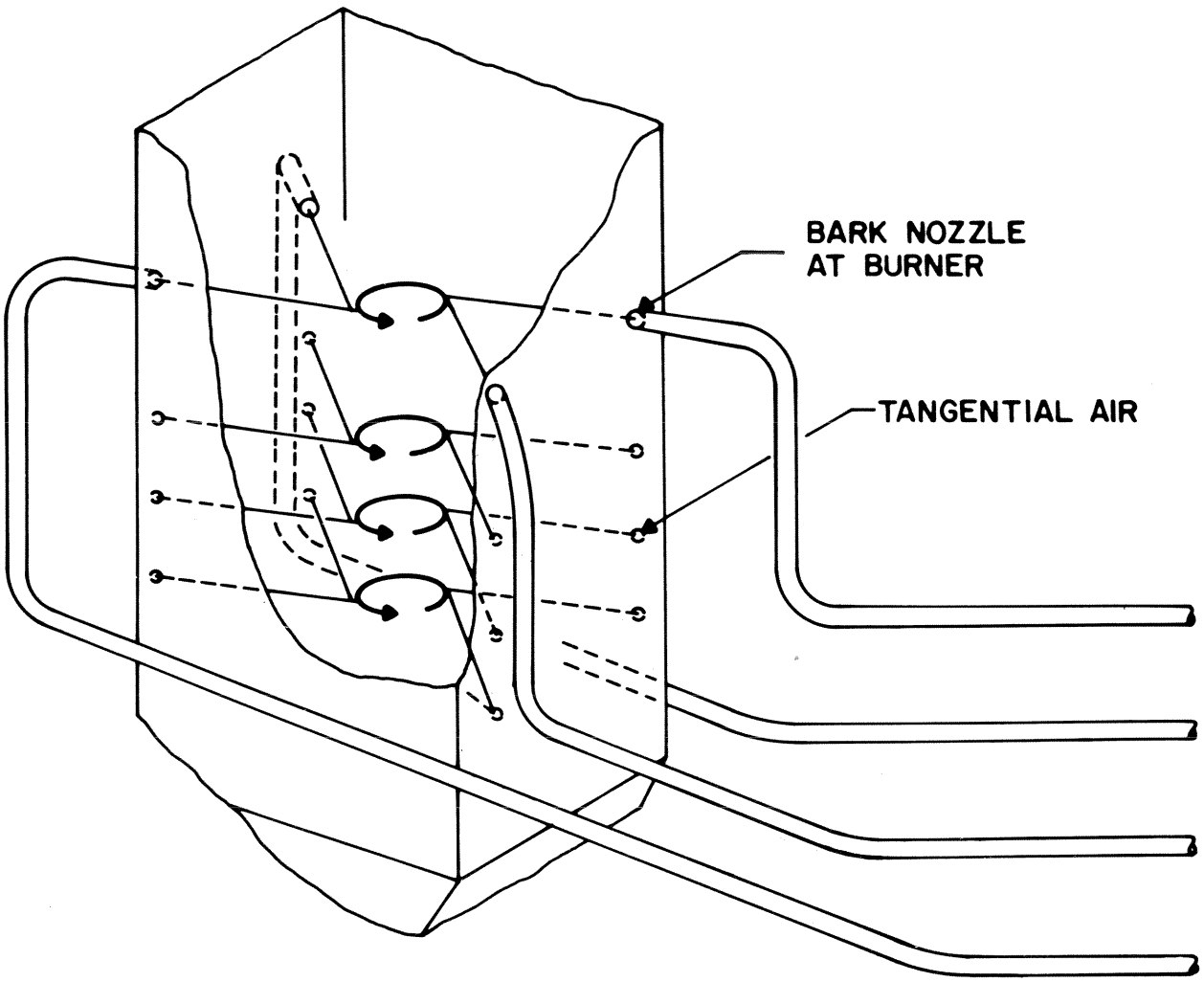


Figure 3-13.—*Schematic of a suspension firing system used in large boilers. (Drawing after Fernandes 1976.)*

tom of the chamber. The outer stainless steel cylinder that confines the upward-moving combustion gases is 49 inches in diameter and has walls 1/4-inch thick. The fuel is partially dried (nearly ovendried) in its 15-minute transit to the combustion zone.

Surrounding the outer cylinder, along the entire 7-foot-high burning zone, is a heat exchanger that preheats air to about 500°F and introduces it at high velocity (1,000-1,300 fpm) into the bottom of the burner. This air conveys fuel particles upward into the combustion zone, where the temperature is about 1,600°F. A 30 hp blower is required for the preheated air to assure proper airflow and velocity.

The burner has neither grate nor fuel bed. Combustion occurs throughout a zone in which particles are suspended in the air stream. The outer cylinder is flared at the top of the combustion zone. Since the inner cylinder has constant diameter, the flare increases flow area for upward-moving combustion gases slowing their velocity. This causes particulate matter (other than fine ash) to fall back into the burning zone for continuous recirculation until completely burned. Neither the laboratory model nor the commercial prototype formed slag since combustion temperatures do not exceed 1,800°F. Ash formed during combustion is discharged upwards along with hot combustion gases for later separation. The burner is equipped with a gas jet of one million Btu/hour capacity to facilitate startup.

The nonuniformity of fuel particle size is a problem for designers of wood burning furnaces. Most grate-type furnaces operate best with particles of pulp-chip size and cannot tolerate more than 50 percent sawdust or fines in the fuel mixture. Because

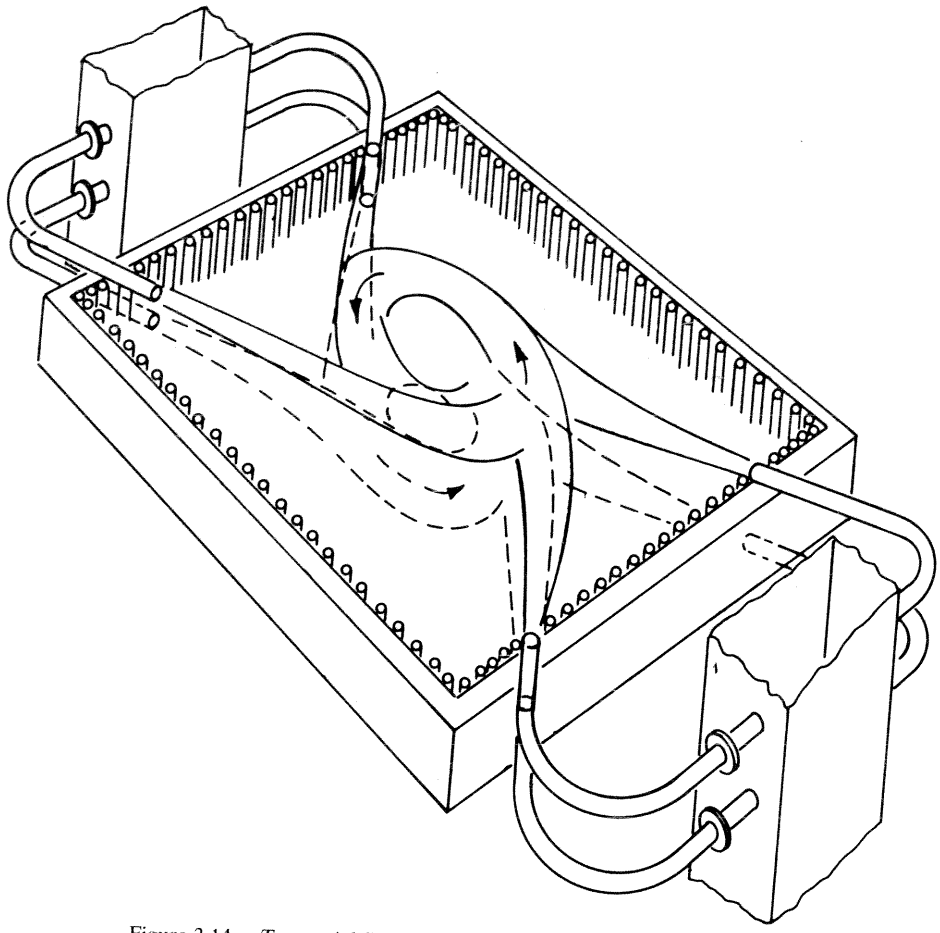


Figure 3-14.— *Tangential firing concept. (Drawing after Fernandes 1976.)*

wood particles can be hammermilled to smaller size, but cannot be increased in size (unless pelletized), the operators of grate-type furnaces have difficulty with an oversupply of fines and sawdust.

In the suspension burner, small particles are needed. Tests on the prototype have shown that the burner runs well with particles sized through the screen of a hammermill hog. Heat of combustion of the fuel was 8,500 Btu per ovendry pound. Ash contents ranged from 1 to 4 percent of dry weight, and moisture content as admitted to the infeed screw was 53 percent (wet basis).

3-3 Steam and Electrical Generation

Steam delivery from boilers can be expressed as kilo Btu's per hour, boiler horsepower, or pounds per hour (Miller 1976). *Kilo Btu* means 1,000 Btu and is a term commonly used by engineers.

Operators of small steam generating units sometimes express steam delivery in *boiler horsepower* (BoHP), a unit that bears no relationship to engine horsepower. Boiler horsepower was more commonly used in past decades when small steam plants were used to drive machinery. Boiler horsepower is the energy required for the evaporation of 34.5 lb of water per hour to saturated steam at 212°F at atmospheric pressure. The equivalent amount of heat energy in Btu's is 33,480 Btu/hr.

The amount of wood required to generate 1 BoHP can be calculated if boiler efficiency and fuel moisture content are known. The average green pine-site hardwood with 42 percent moisture content has an available heat of 4,540 Btu/lb (table 2-8). If we assume a boiler efficiency of 63 percent, then 11.7 lb per hour of green wood would be required to produce 1 BoHP:

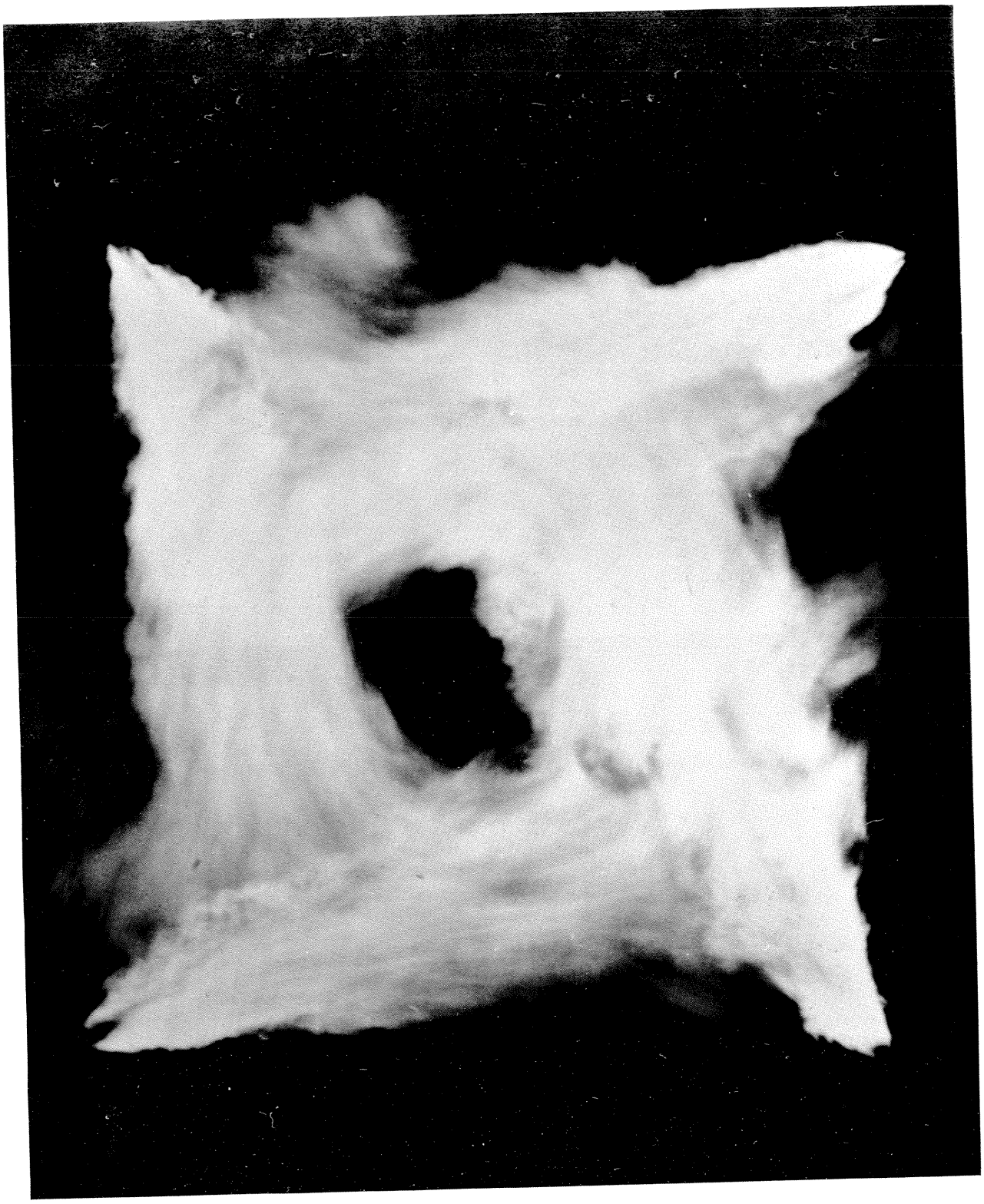


Figure 3-15.—*Photograph of fire circle produced by tangential firing inside a large boiler. (Photo courtesy of Combustion Engineering, Inc.)*

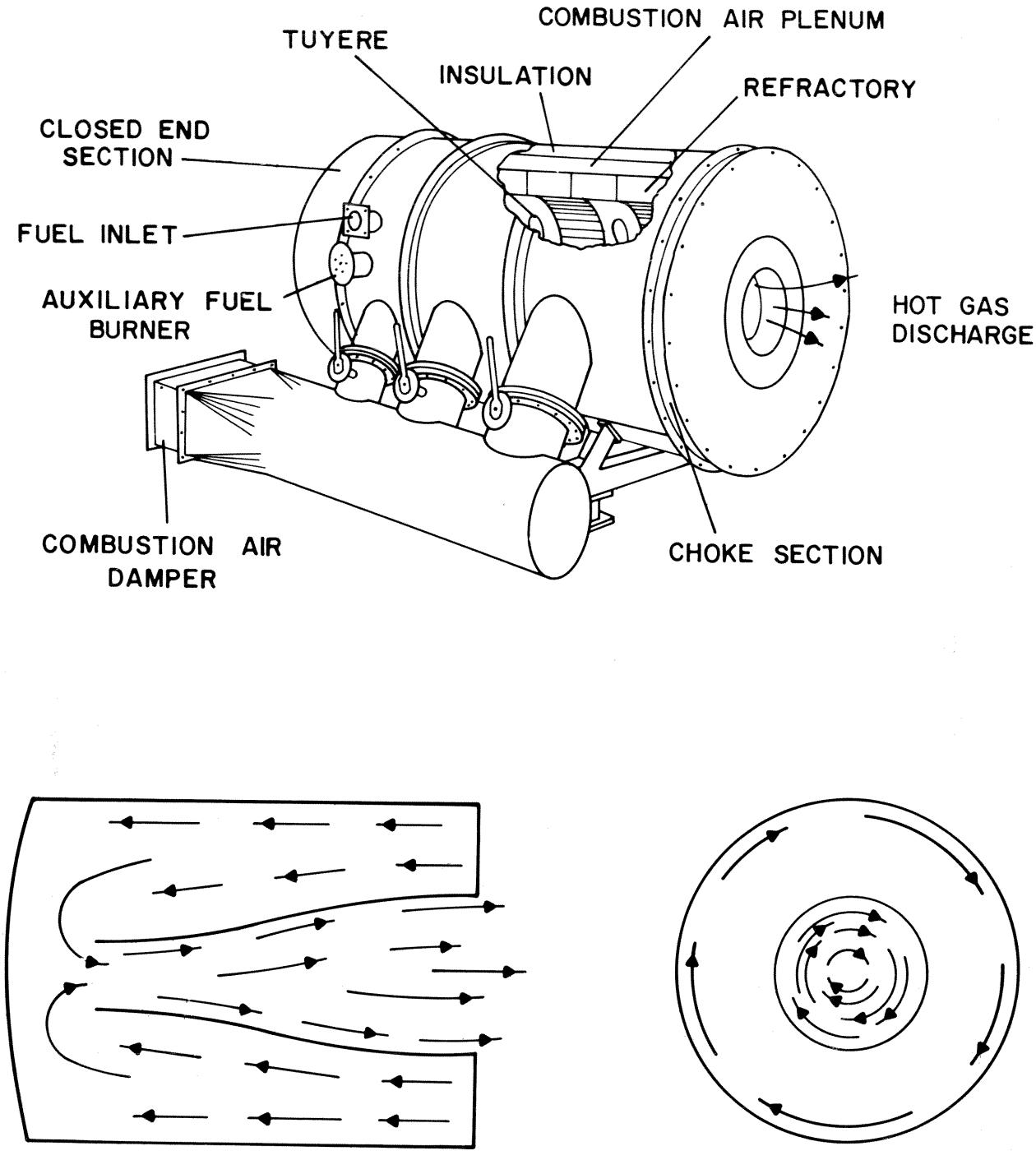


Figure 3-16. — *Cyclonic burner and airflow pattern in cyclonic burner. (Drawing from Energex Company.)*

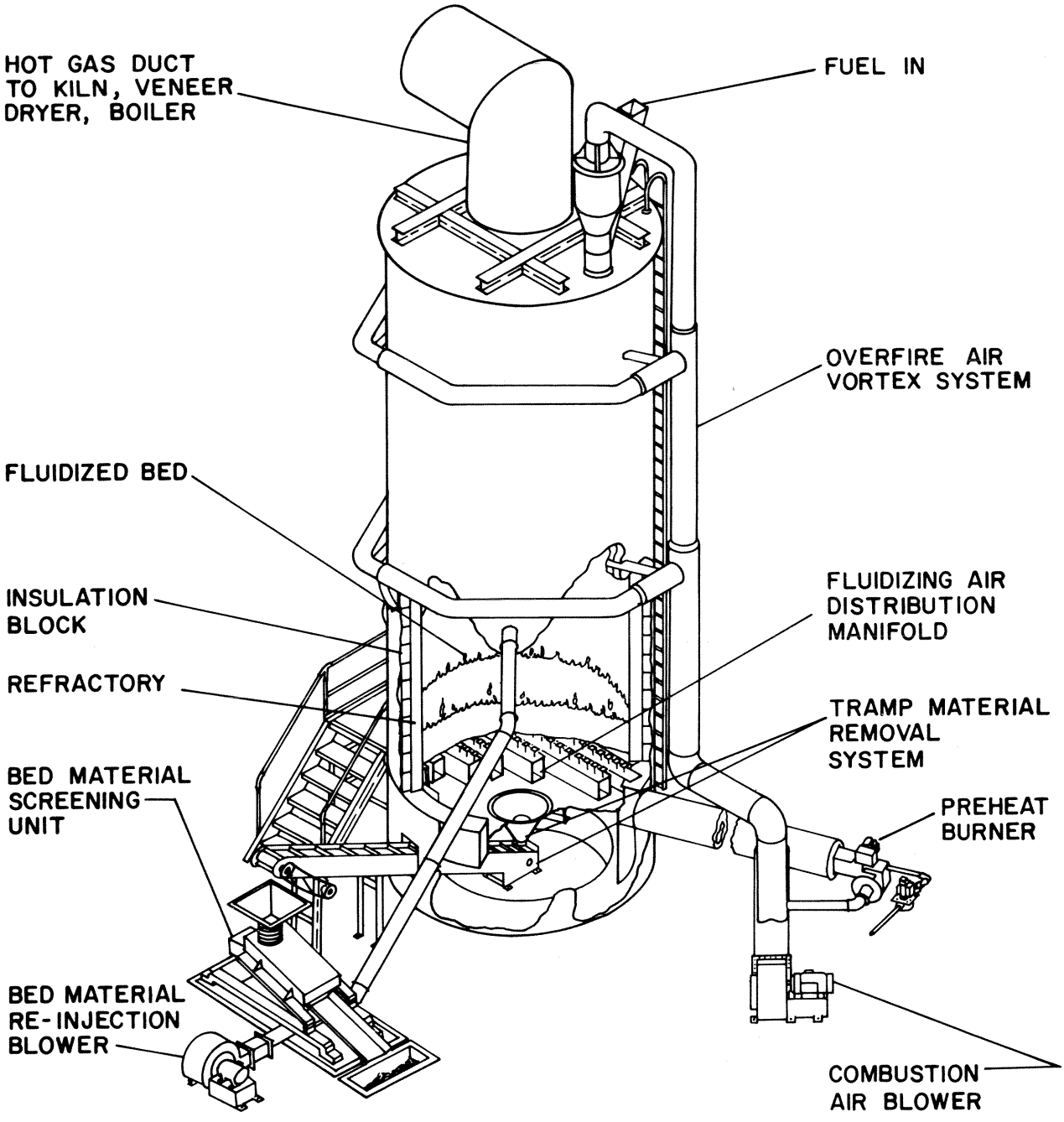


Figure 3-17.—*Fluidized bed combustion unit. (Drawing from Energy Products of Idaho)*

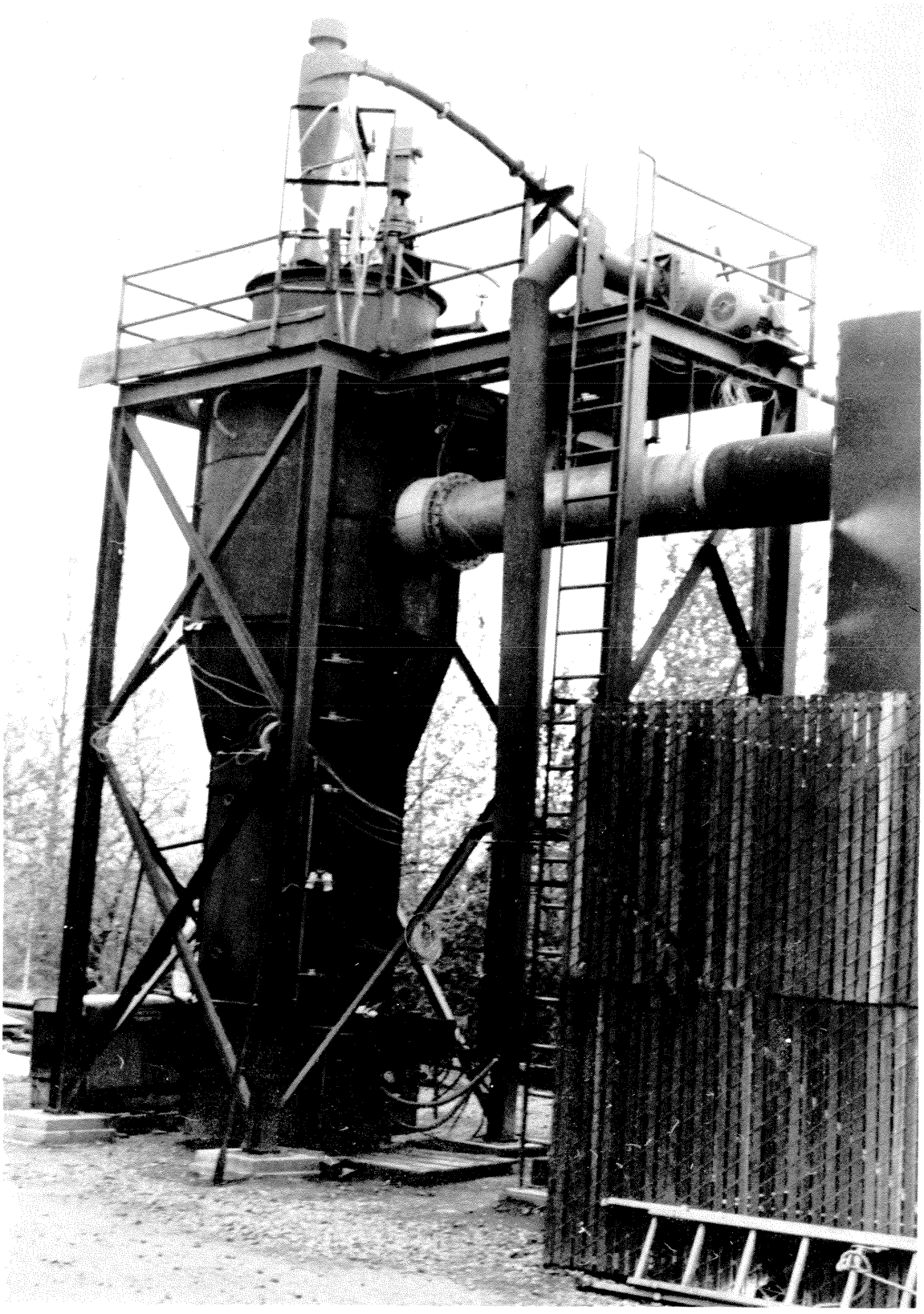


Figure 3-18.—*Photograph of the prototype of the Jasper-Koch burner.*

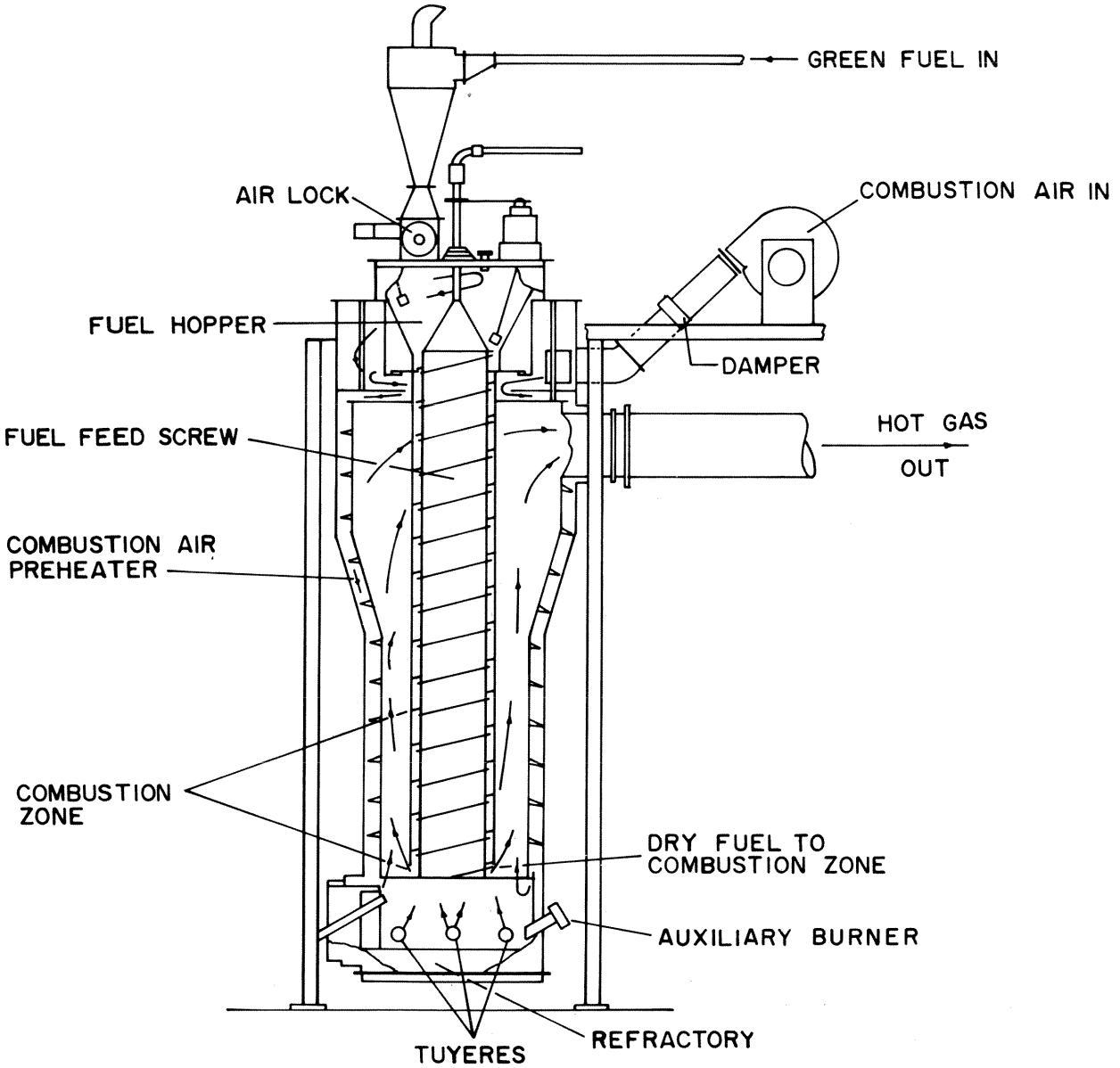


Figure 3-19.—*Cross sectional view of the prototype of the Jasper-Koch burner.*

$$1 \text{ BoHP} = \frac{33{,}480 \text{ Btu/hr}}{(\text{boiler efficiency})\ (\text{available heat of fuel, Btu/lb})} =$$

$$\frac{33{,}480 \text{ Btu/hr}}{(0.63)\ (4{,}540 \text{ Btu/lb})} = 11.7 \text{ lb/hr}$$

Today, in the forest products industry the most common expression of steam delivery is number of pounds of steam delivered per hour *(PPH).* The unit is not an absolute measurement as steam at different pressures and temperatures will have different amounts of energy. For example, steam at 165 psi absolute and 550°F contains heat energy of 1,118 Btu/lb more than feed water at 212°F. Under such a system, the amount of green pine-site hardwood (average available heat, 4,540 Btu/lb) required to deliver 50,000 lb of steam per hour with a boiler efficiency of 63 percent is equal to (50,000 lb steam/hr) (1,118 Btu/lb steam) ÷ (0.63) (4,540 Btu/lb wood), or 19,544 lb of wood per hour.

Overall *boiler efficiency* is expressed as energy output divided by energy input:

$$\text{Percent efficiency} = \frac{\text{output}}{\text{input}} \times 100 \quad (3\text{-}8)$$

This energy input equals the dry weight of fuel multiplied by the higher heating value of the fuel:

$$\text{Input} = m_f \times q_h \quad (3\text{-}9)$$

m_f = dry weight of fuel burned, lb/hr

q_h = higher heating value of fuel, Btu/lb

The output equals the steam generated multiplied by the difference in heat contents of the feed water and steam leaving the boiler:

$$\text{Output} = m_g (h_1 - h_2) \quad (3\text{-}10)$$

m_g = steam generated, lb/hr

h_1 = heat content of steam leaving boiler, Btu/lb

h_2 = heat content of feed water, Btu/lb

The instrumentation and procedures required to measure efficiency can become complicated. However, the process of calculating overall efficiency can be greatly simplified by assuming that everything going into the furnace comes out as mass or energy (Hughes 1976). Then, boiler output does not have to be measured and overall boiler efficiency can be expressed as:

$$\text{Percent efficiency} = \frac{\text{input} - \text{losses}}{\text{input}} \times 100 \quad (3\text{-}11)$$

Corder (1973) lists the sources of boiler heat loss as follows:

(a) moisture in fuel

(b) moisture formed from hydrogen in fuel

(c) dry stack gas loss

(d) incomplete combusion, radiation, and unaccounted sources.

In equation 3-11 the sum of (a) through (d) equals losses. Losses due to (a) through (c) can be readily calculated if the moisture content, ultimate analysis (table 2-6), and higher heating value (table 2-5) for the fuel are known. The ultimate analysis is required to calculate the amount of air needed for combustion. Corder (1973) estimates that item (d) accounts for a 4 percent heat loss, but the loss could be substantially greater in poorly insulated boilers.

A procedure outlined by Wiley (1976) was used to calculate overall boiler efficiency for pine-site hardwoods at various moisture contents (table 3-5). It was assumed that the furnace used 40 percent excess combustion air and that the stack gas temperature was 500°F (Corder 1973), values that might be expected for efficient burning of hogged fuel. The overall efficiency for green stemwood of average moisture content (42 percent wet basis, table 3-5) is 63 percent.

Table 3-5.—*Overall boiler efficiency versus pine-site hardwood moisture content*[1]

Heat loss from	Moisture content[2]			
	10%	25%	42%	50%
	Percent loss			
Moisture in wood[3]	1	5	12	16
Moisture from hydrogen in fuel[3]	9	9	9	9
Dry stack gases[3]	12	12	12	12
Incomplete combustion, radiation and unaccounted[4]	4	4	4	4
Total heat loss	26	30	37	41
Overall boiler efficiency	74%	70%	63%	59%

[1] Boiler operating with 40% excess air and stack temperature of 500°F.

[2] Wet basis.

[3] Calculated by Wiley's method (1976); average stemwood value of 7,827 Btu/lb used (Table 2-5).

[4] Estimated (Corder 1973).

High fuel moisture content is the most important factor in loss of boiler efficiency. The loss is a function of both the amount of moisture in the fuel and the stack gas temperature. Heat is lost both in vaporizing the water and in raising the temperature of the steam to that of the stack gases. At 50 percent moisture content, 16 percent of the fuel energy is lost up the stack (table 3-5). If the moisture content can be reduced to 10 percent, less than 1 percent of the fuel energy is lost and overall efficiency is 74 percent.

Evaporation of moisture formed from the combustion of hydrogen in wood also causes loss in boiler efficiency. One lb of dry wood with 6.4 percent H will produce 0.58 lb of water on combustion (equation 3-2). This results in a 9 percent loss in boiler efficiency.

Dry stack gas heat loss depends on both the amount of excess air and stack temperature. As excess air and stack gas temperature increase, heat loss increases (Corder 1973). When pine-site hardwoods are used as fuel, the loss is estimated at 12 percent with 40 percent excess air and 500°F stack gases. After the gases have passed through the steam-generating heat exchangers, heat can be salvaged from the gases by passing them through a second set of heat exchangers called economizers. Economizers can be used to predry incoming fuel and to preheat incoming combustion air.

The overall conversion efficiency for conventional steam generation of electricity from wood is about 25 percent (Benemann 1978, Love and Overend 1978). This estimate includes boiler efficiency, steam cycle efficiency, and auxiliary power requirements, all of which can vary. The amount of pine-site hardwood required to generate a kilowatt-hour (Kwhr)

can be calculated as follows. For green pine-site hardwood of 42 percent moisture content (wet basis), the available heat is 4,540 Btu/lb (table 2-8). As 1 Kwhr = 3,412 Btu,

$$1 \text{ Kwhr} = \frac{3{,}412 \text{ Btu}}{4{,}540 \text{ Btu/lb } (0.25)} = 3 \text{ lb green pine-site hardwood}$$

The amount of wood required to fuel electrical generating plants, assuming 25 percent conversion efficiency is as follows:

Electrical generating plant size	Amount of green pine-site hardwood required for fuel
5 MW	7.5 ton/hr
25 MW	37.5 ton/hr
250 MW	375 ton/hr
500 MW	750 ton/hr

Co-generation of steam and electricity from a boiler plant is becoming an accepted practice in the forest products industry (Pingrey and Waggoner 1978). It is not a new process, but interest in it has been renewed in recent years. In the 1920's, co-generation was common on the West Coast as it was the only way to obtain electricity for mill operations. As electricity from utilities became available, the electrical generation systems were shut down.

One method of co-generation that is becoming common is first to pass steam through a back pressure-type turbo-generator to produce electricity while using the exhaust from the turbo-generator for process steam in the mill. In this way the steam is used twice. Since there is no cooling water or cooling tower, the turbo-generator takes only the amount of energy out of the steam necessary to generate electricity, and the remaining energy is in the process steam. Exhaust pressures commonly vary between 25 psig to 200 psig depending on the usage.

Pingrey and Waggoner (1978) have estimated that in the United States the overall generating capacity of electrical generating plants using wood and wood derived fuels is about 4,500 MW (table 3-6). Many of the plants, however, use fossil fuels at the same time they are burning wood and wood derived fuels. For instance, it is estimated that on an annual basis, the pulp and paper industry burns 54 percent fossil fuels to generate electricity, while wood residues and pulping liquors supply the remaining 46 percent. On the other hand, solid wood products mills are estimated to use 98 percent wood fuel and only 2 percent fossil fuel.

Table 3-6.—*Estimated generating capabilities of electric generating plants in the United States that use wood and wood derived fuels*[1]

Producers	Generation capability
Pulp and paper mills	3,600 MW
Solid wood products	800 MW
Utilities	60 MW
Other[2]	40 MW
Total	4,500 MW

[1] Data from Pingrey and Waggoner (1978).

[2] Miscellaneous users of small wood fired plants which included a rubber plant, sugar mills, and a resort.

But outside the forest products industry, few wood-fueled electrical utilities are in operation. They are located in Eugene, Oregon; Libby, Montana; and Burlington, Vermont.

The Eugene utility has been using hogged fuel since the 1940's to generate electricity. The steam generated not only is used to run turbines, but is distributed to the central part of the city, where it is used to heat businesses and homes and provides process steam to plants such as laundries (Anonymous 1977).

3-4 Domestic Stoves and Fireplaces

High oil, natural gas, and electricity prices have renewed the public's interest in home and shop space heating with wood. Wood is readily available and improvements in woodstove design and devices to make stoves and fireplaces more efficient have come about with the renewed interest in wood burning (Shelton and Shapiro 1976, and Lew[6]).

Firewood for personal use is usually available free from both State and National Forests. Owners of small woodlots also sell culled hardwoods as domestic firewood. The pine-site hardwoods make excellent firewood for home use. They are more dense and burn less vigorously with a longer lasting fire than resinous softwoods. Oak is probably best as it gives the most uniform flames while producing hot and long lasting coals (U.S. Forest Service 1974).

Fireplaces generally are not very efficient (minus 5 to 10 percent) because much heat is lost up the chimney (Shelton and Shapiro 1976). One device to make fireplaces more efficient is a hollow grate through which air can be circulated. Glass doors with controlled air intakes can be placed on a fireplace to reduce the amount of air entering from the room. With reduced airflow the fire burns more slowly and less heat is lost up the chimney. In new fireplace installations, heat-circulating fire boxes can be incorporated behind the hearth.

[6] V. Lew, "Wood Burning Stoves," a staff report to the Fuels Office, Alternatives Division, California Energy Commission, June 14, 1978, Sacramento, California.

Wood burning stoves are considerably more efficient than fireplaces; efficiencies can range from 25 to about 70 percent[6]. Stove design is generally based on controlling combustion air and enhancing heat transfer to the room. Combustion air can be controlled with secondary air inlets, airtightness, and different airflow patterns through the stove. Secondary air, which is often provided in a secondary combustion chamber, is used to combust completely volatile gases produced from the burning wood. In airtight stoves, control over the amount of combustion air entering is accomplished by welding or cementing the stove sections together. Air leaks in non airtight stoves occur through cracks around the door and at other places where parts are joined. These leaks cause lost efficiency because the air entering is not involved in combustion and takes heat out through the chimney. The control over airflow gives airtight stoves longer burning times and causes them to use 25 to 50 percent less wood.

Many different wood stoves are on the market today. Most can be broadly categorized on the basis of the flow pattern of air through the stove (Shelton and Shapiro 1976). The five basic patterns are: up, diagonal, across, down, and "S" (figure 3-20).

In the updraft pattern the combustion air enters below the burning wood and travels up through the grate. Secondary air may be necessary above the wood for complete combustion of volatiles. Examples of updraft stoves include the pot-bellied stoves and the Shenandoah.

The diagonal flow pattern is found in the simple box stove. Air enters the stove at the bottom front of the combustion zone and travels diagonally through the burning wood, exiting at the top back corner. Secondary air inlets again may be supplied above the burning wood for more efficient combustion. Examples of this flow pattern include the Ashley 25HF, Fisher and drum stoves (Shelton and Shapiro 1976).

In the across pattern, air enters the stove at the bottom front but moves horizontally across the wood to exit at the lower back. Considerable turbulence occurs above the burning wood and volatile gases are forced through the hot coals or flames at the back of the combustion chamber. Secondary air is usually provided at this point. Stoves with both the across and downdraft flow patterns usually require a bypass damper to prevent smoke from entering the room when the stove door is opened. Many stoves using the across flow are airtight and have large fuel capacities so that refueling is not necessary for long periods (Shelton and Shapiro 1976).

In downdraft stoves, air enters the stove above the grate and passed down through the grate along with emerging volatiles produced from the burning wood. Secondary air can be provided at a number of points, often at the bottom of a baffle plate at the back of the stove. Combustion is then completed in a secondary chamber. This design is one of the better ones for efficient burning of wood. Downdraft stoves are usually airtight and can also operate for long periods between fueling (Shelton and Shapiro 1976).

Wood usually rests directly on the firebox floor in the S-flow stoves. A horizontal baffle extends from the back of the stove and prevents air flow and volatile gases from leaving the combustion area directly. The S-flow provides extra turbulence and burning time for the volatiles, and the baffle also helps to increase heat transfer from the hot gases to the outside of the stove. Wood tends to burn from the front of the stove to the back. These stoves are noted for a steadiness of heat output and high efficiency. Common examples of this type of stove are the Norwegian Jøtul, Lange, and Ram woodstoves[6].

The economics of home heating are attractive if an efficient wood stove is used. Lew[6] has estimated that one cord of red oak (21 million Btu's per cord) burned in an airtight stove (50 percent efficiency) will yield heat equivalent to the use of 1.1 tons of coal, 115 gallons of number 2 fuel oil, 14,000 cubic feet of natural gas, or 3,074 kilowatt hours (Kwhr) of electricity. If a person heats with electricity and pays about 4¢ per Kwhr, the equivalent electricity cost would be $123. In the case of box stoves or Franklin fireplaces (30 percent efficiency), the heat realized would be equivalent to 1,848 Kwhr or $74. In a fireplace with 10 percent efficiency, the heat realized would be equivalent to only 616 Kwhr, or about $25 per cord. It is thus apparent that savings will depend greatly on the efficiency of the burning system.

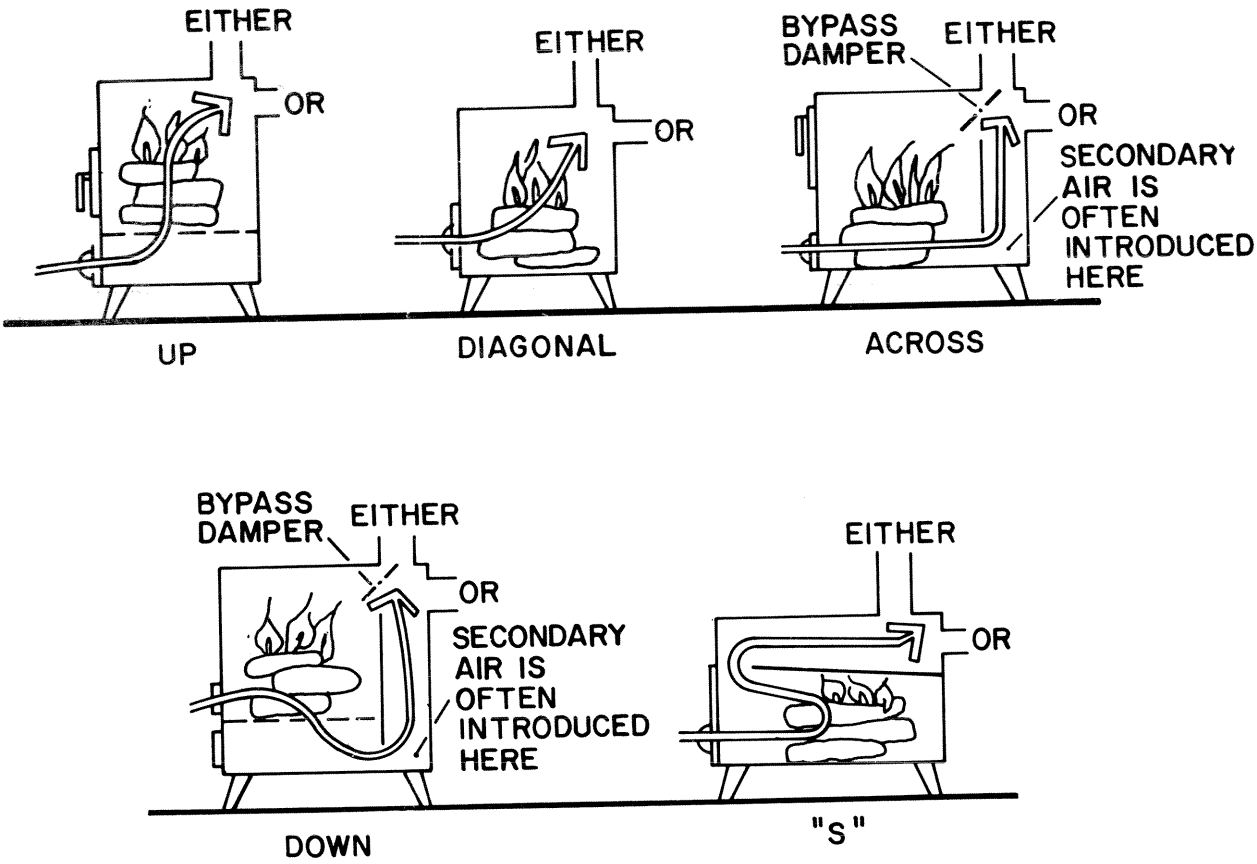


Figure 3-20.— *The five basic air flow patterns found in domestic stoves. Stoves with both the across- and down-draft flow patterns usually require a bypass damper to prevent smoke from entering the room when the stove door is opened. (Drawing after Lew[6].)*

CHAPTER 4
Gasification

Gasification is thermal decomposition of organic material in the presence of controlled and limited amounts of air or oxygen to produce a combustible mixture of gases, often referred to as producer gas. When air is used, the producer gas contains mostly hydrogen, carbon monoxide, and nitrogen. Lesser amounts of carbon dioxide, methane, and hydrocarbons are formed. The mixture is generally referred to as a *low Btu gas* (table 4-1). Heating values range from 100 to about 200 Btu/sdcf (standard dry cubic foot) (Levelton and O'Connor 1978, California State Energy Commission[7]).

When oxygen is used for gasification *medium Btu gas,* with heating values as high as 350 Btu/sdcf, is produced (Bliss and Blake 1977). Nitrogen dilution is eliminated so that the two major components of medium Btu gas are hydrogen and carbon monoxide. Lesser amounts of carbon dioxide, methane, and hydrocarbons are also produced (table 4-1).

The exact chemical composition of either low or medium Btu gas depends on variables that include gasification temperature, pressure, time, and presence of a catalyst (Love and Overend 1978). In the

Table 4-1.— *Typical composition for low and medium Btu gases produced on gasification of biomass*[1,2]

Constituent	Low Btu gas	Medium Btu gas
	Percent	
Carbon monoxide (CO)	20	40
Hydrogen (H_2)	15	30
Carbon dioxide (CO_2)	10	20
Hydrocarbons (CH_x)	5	10
Nitrogen (N_2)	60	—

[1] Data from Benemann (1978).
[2] Composition varies.

[7] California State Energy Commission, "Commercial Biomass Gasifier at State Central Heating and Cooling Plant," Feasibility Study prepared by Fuels Office, Alternatives Division, April 1978, 63 p.

crude state, both low and medium Btu gas contain high percentages of moisture which originates from the partial oxidation process and from moisture in the fuel. However, the moisture can be readily removed (Bliss and Blake 1977).

The basic processes in gasification are similar to those in combustion except that complete oxidation of carbon to carbon dioxide is avoided. Only sufficient air or oxygen is provided to the gasifier bed for (1) gasification of the carbon char by partial oxidation to carbon monoxide and (2) for generation of enough heat to support drying and pyrolysis of the fuel (Eggen and Kraatz 1976). Drying and pyrolysis of the fuel occur much as they do in combustion except the volatile gases produced are not oxidized. In pyrolysis, water vapor, carbon monoxide, and carbon dioxide are formed first. Then, more extensive decomposition gives tars which finally yield hydrogen and hydrocarbons leaving only a carbon char. The carbon char is partially oxidized to carbon monoxide by oxygen, water, or carbon dioxide. The carbon dioxide is then reduced to carbon monoxide. While the addition of air or oxygen to the fuel bed is necessary to sustain this complex oxidation-reduction scheme, no air or oxygen can be allowed to mix with the gases produced as they would readily combust.

Researchers are investigating the use of catalysts in gasification of wood (Feldman 1978, Walkup et al. 1978). A primary reason for catalyzing gasification would be to lower gasification temperature and to improve reactivity. The best catalysts found so far are calcium oxide and wood ash. Catalysis may also be used to selectively form one product. If such a catalysis system can be developed, gases that are predominantly methane, hydrogen, or carbon monoxide or optimum mixtures for a specific purpose might be produced. These products would be of much higher value than producer gas and would make gasification a more competitive conversion process.

Gasification is not new; coal was gasified in the late nineteenth century. Early gasification units operated by blowing air up through the fuel bed and allowing gases to exit the top (updraft operation). The producer gas was used to fire boilers and furnaces.

After cooling and cleaning, producer gas has been used to fuel internal combustion engines. In fact, about 600 Crossley gas plants were constructed for that purpose between 1912 and 1940 (fig. 4-1, Leveton and O'Connor 1978). Reportedly some are still in working order.

Portable gasification units were developed during the 1940's. About 700,000 vehicles were adapted to use producer gas in Europe during World War II. Coal, coke, and charcoal were commonly gasified; wood and crop residues had limited use. Although development of portable gasifiers mostly ceased after World War II, Swedish researchers produced a successful wood-fueled downdraft gasifier for use on agricultural vehicles.

While not a completely proven technology in all applications, wood gasification offers wide versatility (fig. 4-2). In North America, many types of wood gasifiers are in various stages of development (Leveton and O'Connor 1978). In general, wood gasifiers are smaller than the coal gasification units now under development and would be suitable primarily for smaller scale applications. Capacities of wood gasifiers are about 10 million Btu per hour or less.

4-1 Energy Production

On-Site Combustion of Producer Gas.—Most of the gasifiers under development are air blown and produce a low Btu gas suitable to be burned on site so that the immediate (sensible) heat of the gas can be utilized (Love and Overend 1978). Such on-site utilization is best for low Btu gas since the gas cannot be stored effectively, and its low Btu content makes transport economically unattractive. After modification of burner nozzles, low Btu gas can be burned in standard natural gas and oil furnaces.

Such gasifier systems would have advantages over solid-wood fueled furnaces. Ash and carbon residues would remain in the gasifier; the furnace would be subjected only to producer gas, a relatively clean fuel. While some tars, oils, and particulates may be carried over with the producer gas, in most cases no pollution controls will be needed on the furnace[8]

A portable gasifier developed by the University of California was successfully tested using wood as a fuel at the California State printing plant where the low Btu producer gas was burned in one of the plant's boilers (fig. 4-3, table 4-2). A feasibility analysis indicated that no major technical barrier exists to commercialization of gasifiers that produce low Btu gas for furnace boiler fuel. Emissions were within acceptable standards. The costs of using the gasifier system over 20 years would be competitive with the cost of using natural gas (in California) assuming price increases at the rate of inflation.

[8] G. D. Voss and V. A. Gauger. Gasification of wood residues. Paper presented at the For. Prod. Res. Soc. Annu. Meet. (Denver, Colo. July 1977). 13 p.

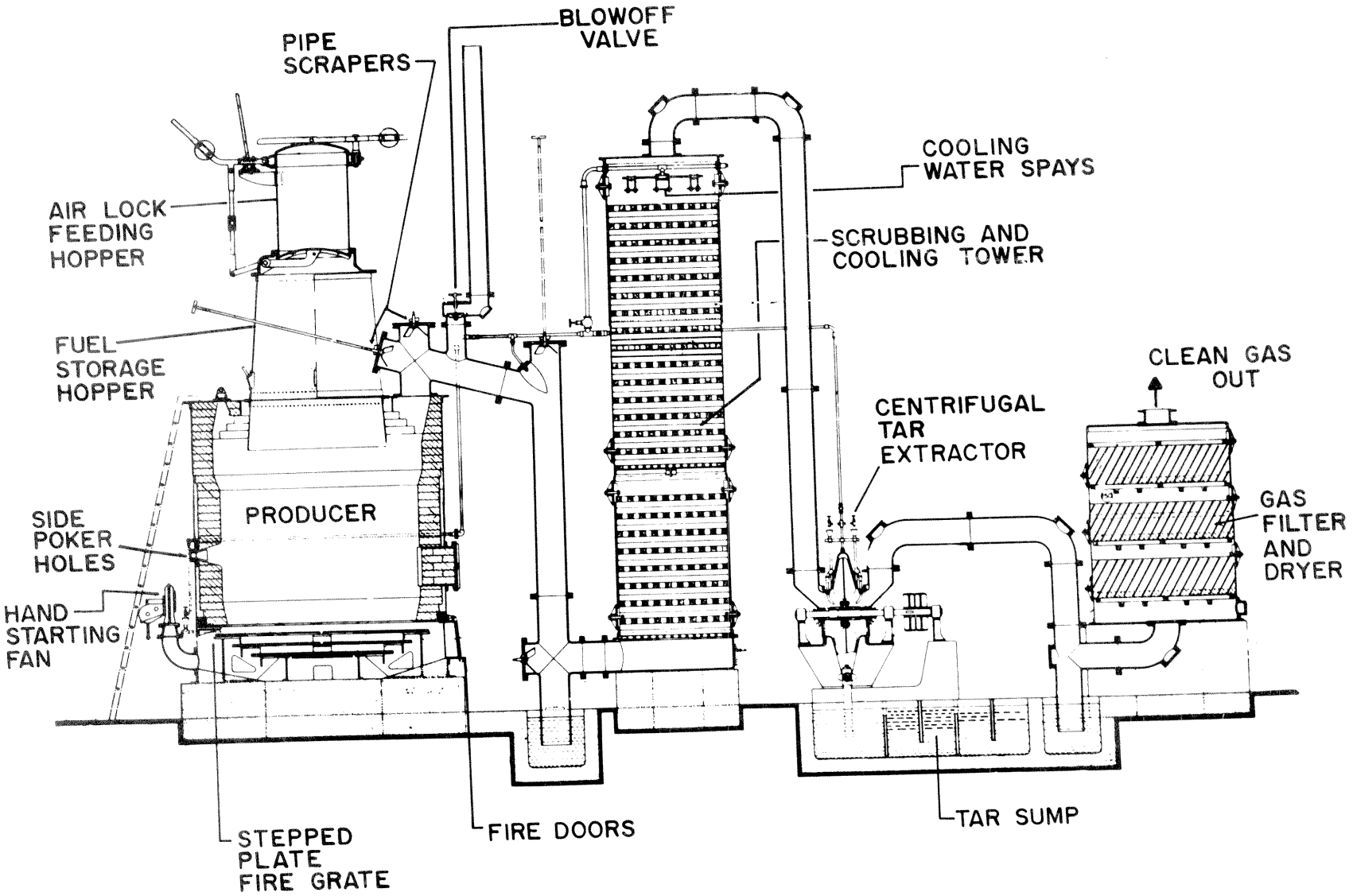


Figure 4-1.—*Original Crossley gas plant. (Drawing after Levelton and O'Connor 1978.)*

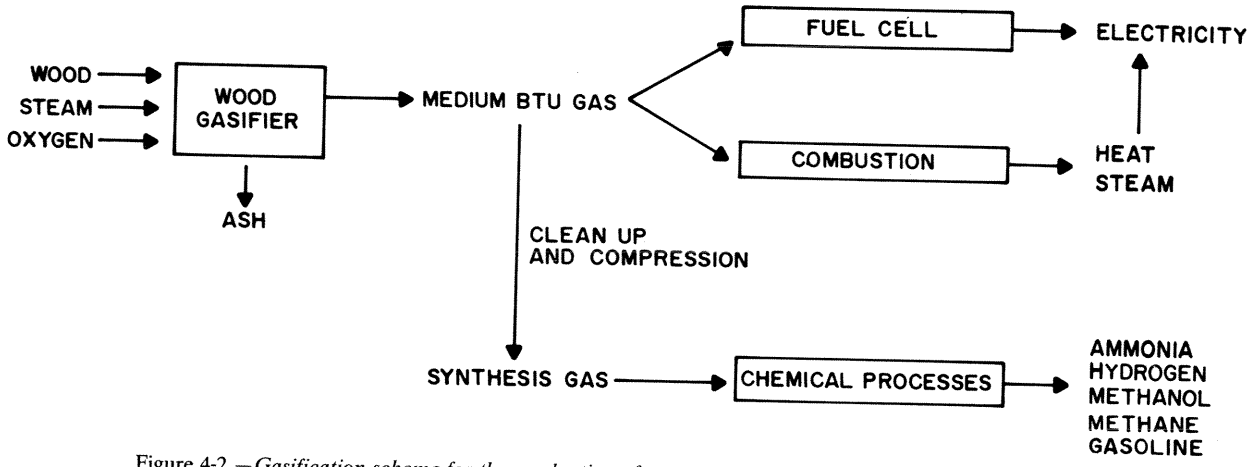


Figure 4-2.—*Gasification scheme for the production of energy, chemicals, and synthetic fuels from wood.*

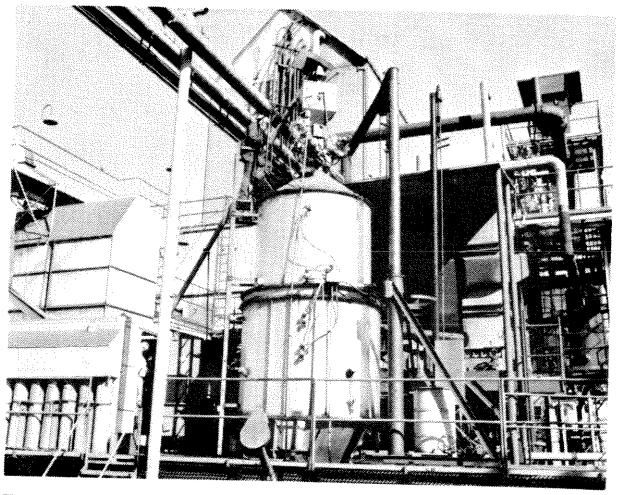


Figure 4-3.—*Downdraft gasifier developed by the University of California. (Photo courtesy of Robert Hodam, California State Energy Commission.)*

Table 4-2.—*Input and output for one hour of prototype gasifier operation*[1]

Input	Output
.75 ton of wood	10 million Btu of gas
1 gallon of gasoline	100 lb of char
5 Kw of electricity	1 quart of tar
	SO_x — negligible
	NO_x — 129 ppm
	particulates — 0.8 grams per standard cubic foot

[1] Data from California State Energy Commission (1978).

Fuel Cells.—The generation of electricity by *fuel cells* that use producer gas from wood is an unproven process but potentially a viable one (Hodam 1978, Eggen and Kraatz 1976). Fuel cells use hydrogen and oxygen (from air) to convert stored chemical energy directly to electrical energy (fig. 4-4).

$$2H_2 + O_2 \xrightarrow{\text{Fuel Cell}} 2H_2O + \text{heat} + \text{electrical power} \qquad (4\text{-}1)$$

The concept is not new. Fuel cells have provided power for moon landings and on a demonstration basis, electricity to apartments, commercial establishments, and small industrial buildings. It is expected that electrical generation from coupling wood gasifiers with fuel cells will be significantly more efficient than using turbines or diesel engines (Hodam 1978).

Fuel cells can produce electricity at 38 to 40 percent efficiency, a rate about equal to the best combustion power plant. It is expected that by 1985 fuel cell efficiency may be 50 to 55 percent. Fuel cell emissions are well within environmental limits (Energy Research and Development Administration 1976).

4-2 Chemicals and Fuels Production

Synthesis gas (hydrogen and carbon monoxide) can be used to produce several important chemicals and fuels (Wender in press). Methane, hydrogen, ammonia, methanol, ethylene glycol, and gasoline can be made directly from synthesis gas. Additionally, a high octane gasoline can be produced from methanol in a one-step process.

Medium Btu gas from wood gasification should be well suited for use as synthesis gas because of its high hydrogen and carbon monoxide content. On the other hand, low Btu gas would not be so well suited since large amounts of nitrogen would have to be removed to convert it to synthesis gas. An exception might be in ammonia production.

Hydrogen, Methane, Ammonia, and Methanol.—*Hydrogen* can be produced by the *water shift reaction* (Wender in press). Hydrogen already in the

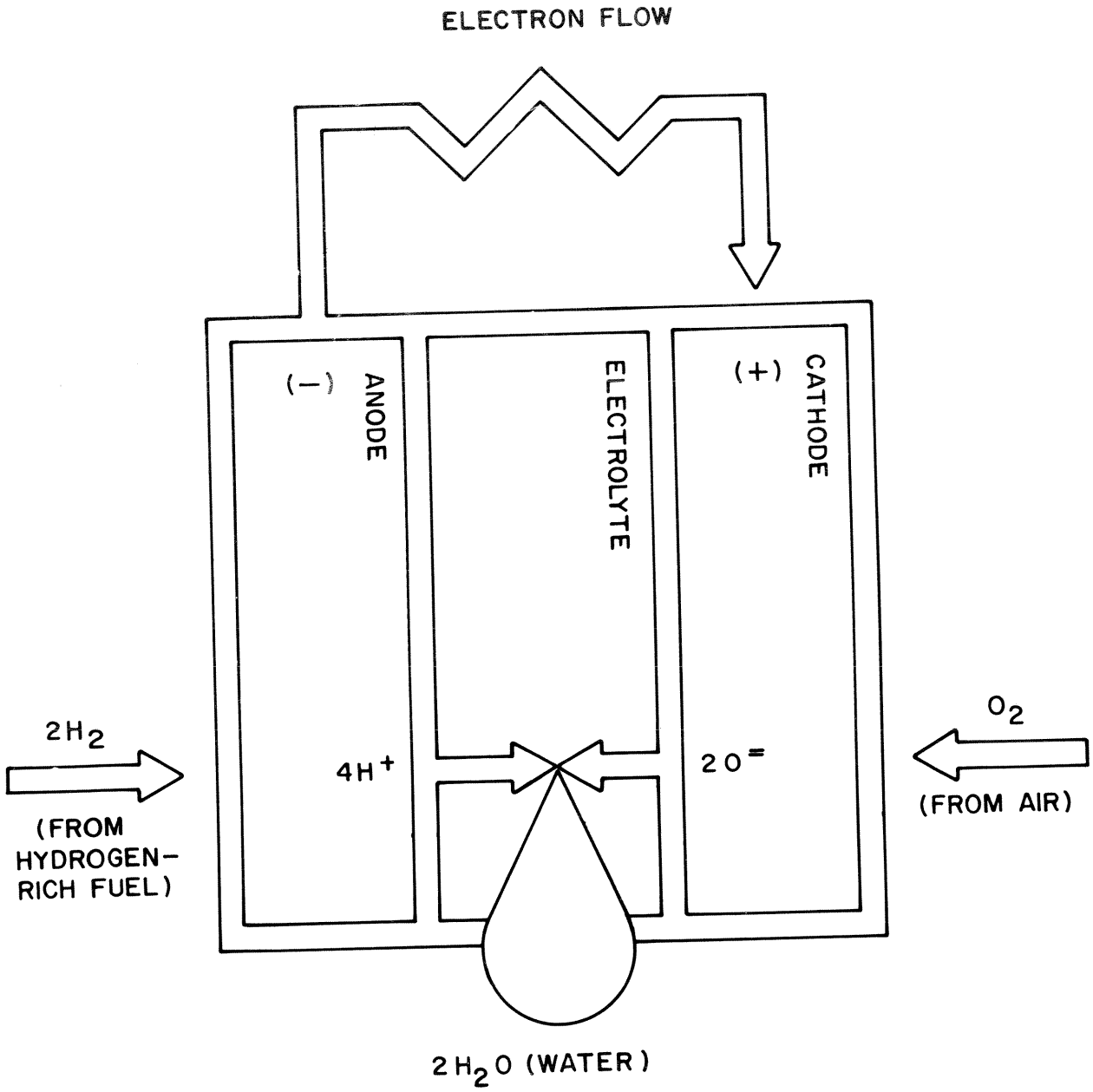


Figure 4-4.—*The basic principles of fuel cell operation (Energy Research and Development Administration 1976). The fuel cell consists of an anode, cathode, and electrolyte much as in a battery. Hydrogen rich fuel is fed down the anode side of the cell. Here the hydrogen leaves its electrons giving the anode a negative charge. Air enters the fuel cell on the cathode side. Here oxygen accepts electrons from the cell giving the cathode a positive charge. Electrical power is generated by the flow of electrons from the anode to the cathode. Hydrogen ions formed at the anode and oxygen ions formed at the cathode migrate through the electrolyte to combine and form water. Heat is also liberated in the process. The overall simplified process is shown in equation 4-1. (Drawing from Department of Energy.)*

synthesis gas remains unchanged, but added water reacts at high temperature with carbon monoxide and a catalyst to yield hydrogen.

$$CO + H_2O \xrightarrow{\text{catalyst}} CO_2 + H_2 \qquad (4\text{-}2)$$
$$\Delta H = -9.84 \text{ kcal}$$

Carbon dioxide formed can be removed from the gas stream to give pure hydrogen gas. The reaction is also used to obtain hydrogen to carbon monoxide ratios appropriate for certain syntheses. Methanol production requires $2H_2$:1CO, while methane requires $3H_2$:1CO.

Hydrogen can also be used as a fuel, although its general use as such may be in the more distant future. However, hydrogen holds much promise as it is an environmentally clean fuel; combustion yields only water and heat energy. Therefore, one might expect to see increased use of hydrogen as a transportation fuel, especially for mass transit in areas with air pollution problems. A promising new technology is in the development of metal hydrides for the safe storage, shipping, and use of hydrogen as a fuel.

Methane (CH_4) can be produced by the *methanation reaction* shown below:

$$3H_2 + CO \xrightarrow{\text{catalyst}} CH_4 + H_2O \qquad (4\text{-}3)$$
$$\Delta H = -49.3 \text{ kcal}$$

Since this reaction requires 3 moles of hydrogen to one mole of carbon monoxide, the water shift reaction can be used to adjust this ratio in the medium Btu gas and maximize the yield of methane. Methane is a suitable substitute for natural gas inasmuch as natural gas is composed primarily of methane (85 percent) with lesser amounts of other hydrocarbons and nitrogen. While the relatively low Btu values of low and medium Btu gas from wood gasification preclude storage or transport over any distance, conversion to methane provides a route for the production of a pipeline-quality substitute (950 Btu/sdcf) for natural gas (Bliss and Blake 1977).

Ammonia is manufactured from synthesis gas produced from natural gas by steam reforming, $CH_4 + H_2O \rightarrow 3H_2 + CO$, the reverse of equation 4-3 (Wiseman 1972). The synthesis gas is enriched in hydrogen by the water shift reaction (equation 4-2). Carbon dioxide and small amounts of unconverted carbon monoxide have to be removed as they poison the ammonia synthesis catalyst. Most of the carbon dioxide is removed by scrubbing with a solution of potassium carbonate. After scrubbing, the gas still contains small amounts of carbon dioxide and carbon monoxide; final removal is accomplished by the methanation reaction (equation 4-3). Both carbon monoxide and carbon dioxide are converted into methane, which is left in the hydrogen gas as it does not interfere with ammonia synthesis. In the final step (equation 4-4), ammonia synthesis is carried out by reacting the hydrogen gas with nitrogen gas at high temperature and pressure over an iron catalyst.

$$3H_2 + N_2 \xrightarrow{\text{catalyst}} 2NH_3 \qquad (4\text{-}4)$$
$$\Delta H = -26 \text{ kcal}$$

Ammonia is used to manufacture fertilizers, explosives, nitric acid, and synthethic fibers.

High yields of *methanol* are also obtainable from synthesis gas (Wender in press). The water shift reaction alters the hydrogen to carbon monoxide ratio in the medium Btu gas to that required in equation 4-5.

$$2H_2 + CO \xrightarrow{\text{catalyst}} CH_3OH \qquad (4\text{-}5)$$
$$\Delta H = -26 \text{ kcal}$$

Methanol is a major industrial organic chemical. It is widely used both as a solvent and intermediate for the synthesis of other materials. Its largest use is for conversion into formaldehyde which is important to the forest products industry. Formaldehyde is used to make synthetic resins such as urea-formaldehyde and phenol-formaldehyde. The resins are used in the manufacture of plywood, particleboard, and plastics.

Both ammonia and methanol will have economic competition from coal gasification. Coal to methanol conversion efficiency (59 percent) is higher than that for wood to methanol (38 percent). Furthermore, coal conversion facilities will be larger, making them even more efficient. Ammonia from wood appears more promising than methanol. Wood has a lower carbon to hydrogen ratio than coal which favors the wood feedstock. There is also a possibility that natural gas currently being flared in the Middle East will be converted to methanol or other synthesis gas derivatives and exported (Love and Overend 1978).

Liquid Fuels for Automobiles.—Methanol and ethanol (see chapter 6 for ethanol process) can both be used to fuel modified automobile engines. Such modification includes the use of fuel injection systems as well as some type of induction heating system to improve vaporization of the alcohols (Park et al. 1978ab). Methanol and ethanol can also be blended with gasoline to fuel unmodified automobile engines. Such mixtures are popularly termed gasahol.

Addition of methanol and ethanol increases the octane rating of gasoline, much in the way that tetraethyl lead and other additives do. Potential problems include loss of performance (especially in blends higher than 15 percent alcohol), possible phase separation of the alcohol from the gasoline caused by excessive moisture, and corrosion of fuel system parts. Although these problems will not be difficult to overcome, correction will cost the consumer.

A national gasahol plan for the United States has become a major controversy (Anderson 1978). Proponents contend that by blending 5 to 10 percent ethanol or methanol with gasoline, oil imports could be reduced as much as 20 percent. Opponents indi-

cate the economics are not justified as long as gasoline remains cheaper than the alcohols. The current price of ethanol is $1.25 per gallon while gasoline is $.38 per gallon at the refinery gate (late 1978).

In Brazil, a $400 million program is now underway to produce ethanol from sugar cane and cassava to replace 20 percent of the country's gasoline requirements by the early 1980's (Hall 1978, Hammond 1977). But in Brazil, which imports over 80 percent of its oil, ethanol costs the consumer $1 per gallon compared with $1.50 per gallon for gasoline.

Park et al. (1978ab) indicate in a preliminary report to the Department of Energy that a national gasahol program appears premature. After 1990, the potential for such a program should be more promising. By then, however, methanol and ethanol might be economically converted to gasoline.

A new process to convert methanol into gasoline has been developed by Mobil Research and Development Corporation (Meisel et al. 1976, Chang and Silvestri 1977). The *Mobil process* uses a newly discovered zeolite catalyst to quantitatively convert methanol to hydrocarbons and water.

$$XCH_3OH \xrightarrow{\text{catalyst}} (CH_2)_x + XH_2O \qquad (4\text{-}6)$$
$$99+\%$$

Most of the hydrocarbon molecules produced are in the gasoline boiling range (C_4 to C_{10}); total gasoline yield is about 80 percent of the hydrocarbon product. This synthetic gasoline has unleaded Research Octane Numbers (RON) of from 90 to 100. Some of the remaining lower-boiling hydrocarbons can be converted into gasoline by an additional alkylation reaction. When this is done, total gasoline yield approaches 90 percent. The remaining 10 percent is valuable liquified petroleum gas (LPG) (Meisel et al. 1976).

The primary source of methanol for the Mobil process is expected to be coal in the United States and perhaps natural gas in some other countries. However, in some areas it may be economically feasible to use wood as a source of methanol (fig. 4-5).

The *Fischer-Tropsch reaction* also makes hydrocarbons from synthesis gas (Wiseman 1972). The process was used by Germany during World War II to produce both liquid fuels and hydrocarbons for chemical syntheses. The reaction uses a cobalt catalyst at high temperatures to give a complex mixture of hydrocarbons. While gasoline can be made from the process, extensive facilities are needed to separate and upgrade the primary reaction products. Today the process is uneconomical in most countries, but is used in South Africa.

Catalysis.—All of the reactions described above are carried out with *heterogeneous catalysis.* That is the reactants are gases and liquids which come in contact with a solid catalyst. The reactions occur on the surface and in crevices of the catalyst. Heterogeneous catalysis is advantageous because the catalyst can be separated readily from the product stream resulting from the reaction.

Heterogeneous catalysis has been the backbone of the petrochemical industry. Recently, *homogeneous catalysis* (both reactants and catalyst are in solution) by use of metal cluster compounds has been demonstrated for several reactions. Of interest to the utilization of synthesis gas is the reduction of carbon monoxide. *Ethylene glycol,* an important industrial chemical, can be produced in high yield from the reaction of synthesis gas with a rhodium complex.

$$H_2 + CO \xrightarrow[\text{complex}]{\text{Rhodium}} HOCH_2CH_2OH + \text{other alcohols} \qquad (4\text{-}7)$$
$$78\% \qquad 22\%$$
ethylene glycol other alcohols

Under certain conditions methanol can also be produced by this approach. While these homogeneously catalyzed reactions will undoubtedly be employed in the future, they are not yet commercially feasible (Wender in press, Anderson in press).

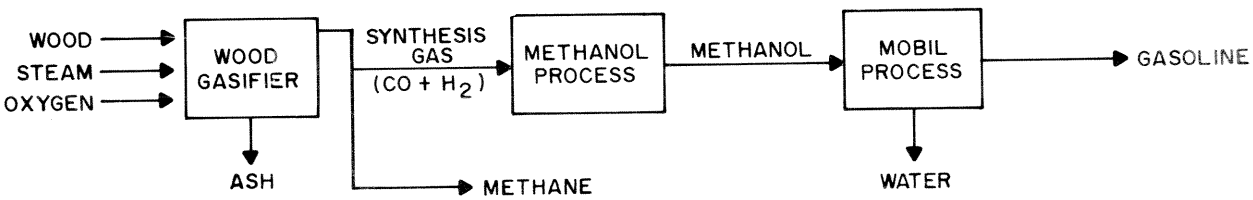


Figure 4-5.—*Overall scheme for the production of gasoline from wood. Selling the methane produced in the gasification step instead of reconverting it into synthesis gas would lower the cost of methanol production. (Drawing after Meisel et al. 1976.)*

CHAPTER 5
Pyrolysis

Pyrolysis is the thermal decomposition of organic matter in the absence of air. The heat to initiate the process can be applied externally, or as is common in charcoal manufacture, part of the wood may be burned by air combustion to generate the heat necessary to start the pyrolysis process (U.S. Forest Prod. Lab. 1961). Pyrolysis is generally carried out at lower temperatures than gasification and is primarily for producing solid or liquid fuels.

In the past, pyrolysis was referred to as destructive distillation. Principal marketable products from a hardwood distillation industry 30 years ago were acetic acid, methanol, and charcoal (Beglinger 1948). Distillation was carried out in externally heated ovens and retorts. Today, methanol and acetic acid are produced much more cheaply by the petrochemical industry. However, wood charcoal remains an economically viable product.

Most charcoal produced in the United States today is processed into briquets for cooking. Some is used as an industrial fuel and some for metallurgical processing and some to make activated carbon (Baker 1977, Walker in press). In the near future, wood charcoal may be slurried with high-sulfur oil or mixed with high-sulfur coal before pulverization to make a fuel which would have lower sulfur dioxide emissions and thus possibly comply with air pollution regulations (Bliss and Blake 1977). Additionally, the charcoal-oil slurry could help reduce reliance on imported oil. Technically, both processes are expected to be feasible, but a problem may come about in securing a reliable charcoal supply for the large, conventional oil- and coal-fired central stations where this is proposed.

Wood is also suitable for making activated carbon. This can be done by steam activation of wood charcoal; yield is generally around 12-15 percent based on the weight of the dry wood (Baker 1977). Little activated carbon is made from wood today because that made from coal and coconut hulls is sufficient to supply the market. However, the EPA is considering requiring the use of activated carbon by all water treatment plants. The EPA has found suspected carcinogens such as chloroform and carbon tetrachloride in municipal water systems, and activated carbon can remove these agents. Today, the main markets for activated carbon are for water and waste water treatment, air pollution control systems, catalyst supports, sugar decolorization, and auto evaporation control systems. About one-third of the market is for water and waste water treatment (Walker in press).

In the United States, most wood charcoal is now produced either in a batch process using Missouri-type kilns or in a continuous process using a Herreshoff multiple-hearth furnace. Other continuous processes recently have been developed which can be used to produce liquid and gaseous fuels as well as charcoal (Bliss and Blake 1977, Baker 1977).

5-1 Charcoal Formation in Kilns

Ignition, coaling, and cooling are the three stages in the formation of charcoal from wood (Hallett 1971). These stages are readily distinguished when describing the production of charcoal by batch processes.

Ignition is endothermic (requires heat) and requires considerable air (U.S. Forest Prod. Lab. 1961). The wood is first ignited with kindling and kerosene and allowed to burn. Temperatures in the kiln rapidly rise to about 1,000°F and then drop when most of the starter fuel has been consumed. Coaling begins around 540°F, and at that temperature the process becomes exothermic (gives off heat). When the coaling stage is reached, the amount of air is restricted to control kiln temperature and to ensure that the wood will form charcoal and not burn to ash. For the production of good quality charcoal, kiln temperatures of 850° to 950°F are maintained during coaling.

After coaling, the kiln is completely sealed to exclude all air and allowed to cool. When temperatures are 150°F or less, it is generally safe to open the kiln.

A complete cycle, from ignition through cooling, may require 6 to 7 days. Typical charcoal produced from wood will have a higher heating value of about 12,000 Btu/lb. Proximate analysis will be about 20 to 25 percent volatile matter and 75 to 80 percent fixed carbon on a moisture free and ash free basis. Ash content is generally about four times that of wood (Peter 1957, Baker 1977, U.S. Forest Prod. Lab 1961).

The transformation of wood into charcoal has been studied recently by simulating commercial charring conditions in the laboratory (Slocum et al. 1978). Most work has been done on oak and hickory. Study of mass loss, shrinkage, and physical properties of charcoal produced under various coaling conditions will lead to a better understanding of this very complex and incompletely understood process (McGinnes et al. 1971, Anon 1975). Analytical techniques that have been found especially useful for these studies include the use of scanning electron

microscopy to follow shrinkage and small angle X-ray analysis to evaluate micropore formation in the charcoal (von Bastian et al. 1972, Blankenhorn et al. 1972, Beall et al. 1974, McGinnes et al. 1974, McGinnes et al. 1976).

In the past, small-scale charcoal production was accomplished with a variety of kilns. As any relatively air-tight structure with properly placed smoke and draft vents can be used to produce charcoal, small kilns with capacities of 1/2 cord to 10 cords or more were popular through the late 1950's (fig. 5-1) Such kilns varied considerably in construction and size; building materials commonly were cinder blocks, bricks, stone, metal, and reinforced concrete. Yields of charcoal varied greatly in the kilns, even under optimal operating conditions. In cinder block kilns typical yields for seasoned hardwoods averaged around 900 lb of charcoal per cord and slightly less for unseasoned hardwoods (Witherow 1956, Witherow and Smith 1957, Peter 1957, Page and Wyman 1969, U.S. Forest Prod. Lab 1961).

Today, over half of the Nation's wood charcoal is produced in Missouri-type kilns (Baker 1977). Missouri-type (fig. 5-2) kilns use roundwood or sawmill slabs. Typically the kilns are made of poured concrete and have an average capacity of 50 cords. Some, however, hold up to 100 cords. White oak and hickory are the two major species of wood used.

5-2 Herreshoff Multiple-Hearth Furnace

The Herreshoff multiple-hearth furnace uses hogged wood or bark to produce charcoal in a continuous process (fig. 5-3). Production rates range from 1 to 4 tons per hour. As these units operate continuously, they must be fed a steady supply of wood. The smallest of these furnaces requires about 100 tons of wood per day on a dry basis. With wood that has moisture content of 40 percent, the production rate of charcoal is about 1 ton per hour.

The Herreshoff furnace consists of several hearths stacked one on top of the other and enclosed in a cylindrical, refractory-lined steel shell (Nichols Engi-

Figure 5-1.—*One-half-cord sheet metal beehive kiln. Fully portable, these kilns were developed in the 1930's and were still in wide use through the 1960's. The kiln shown here is in the coaling phase. (Photo from Page and Wyman 1969.)*

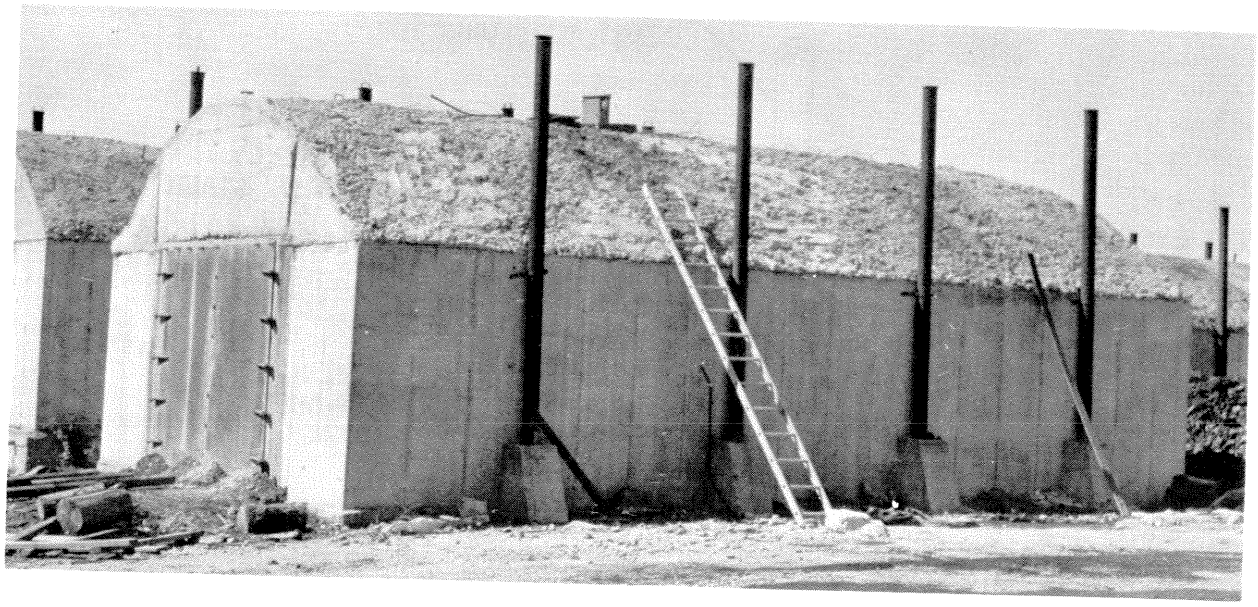


Figure 5-2.—*Missouri-type batch kiln. (Photo courtesy of Bob Massengale, Missouri Department of Conservation.)*

neering and Research Corp. 1975, Bliss and Blake 1977). Passing up through the center of the furnace is a shaft which carries arms with rabble teeth. As the shaft turns, the teeth constantly plow through and turn the fuel over while moving it in a spiral path across the hearth floors toward drop holes that connect each hearth. The drop holes alternate on each hearth floor between the inner periphery (around the shaft) and the outer periphery of the hearth. The rabble teeth are alternately angled so that the material moves in the direction of the next set of drop holes. In this way material fed at the top of the furnace is spread over and across each hearth floor in a radial flow that alternates inwardly and outwardly until the charcoal is finally discharged from the bottom of the furnace. Material is dried, heated, and carbonized as it passes downward through the furnace while hot combustible gas produced passes upward in a current counter to the flow of the material (fig. 5-4).

Heat for startup is provided by gas- or oil-fired burners mounted in the sides of the hearths. When the proper furnace temperature has been attained, the auxiliary fuel is turned off. To sustain pyrolysis, sufficient combustion air is allowed into the furnace to burn some of the volatile gases produced. Air entry is regulated to maintain furnace temperatures at 900 to 1200°F. The evolving combustible gases are more than that needed for drying and carbonizing the wood and can also be burned in a boiler after they exit the furnace. With a heating value of about 200 Btu per sdcf plus the sensible heat of the exhaust temperature, the pyrolysis gases from the production of 2 tons of charcoal per hour can generate about 50,000 lb per hour of high pressure steam (Bliss and Blake 1977). Yield of charcoal will vary with moisture content of the feed; about 8 tons of wet wood (50 percent MC) are required to produce 1 ton of charcoal.

5-3 Tech-Air System

Knight and Bowen[9] describe a steady-flow pyrolysis system that produces a pyrolytic oil, charcoal, and off gases. The oil, which has a heating value of 10,000 to 13,000 Btu/lb, is obtained by passing the pyrolysis vapors through a condenser. Remaining non-condensable gases which contain about 200 Btu/sdcf, are used to pre-dry incoming wood fuel (fig. 5-5). Incoming fuel is pre-dried to about 4 percent moisture content before entering the converter or pyrolysis unit. The non-condensable gases are sufficient to pre-dry fuel of up to 50 percent moisture content. About 35 percent of the energy content of the wood fuel is in the charcoal and about 35 percent in the pyrolytic oil. On a weight basis, charcoal yield is 23 percent while pyrolytic oil yield is 25

[9] J. A. Knight and M. D. Bowen. Pyrolysis—a method for conversion of forestry wastes to useful fuels. 13 p. Paper presented at the Southeast. Tech. Div. of Am. Pulpwood Assoc. fall meeting. (Atlanta, Ga., Nov. 5-6, 1975).

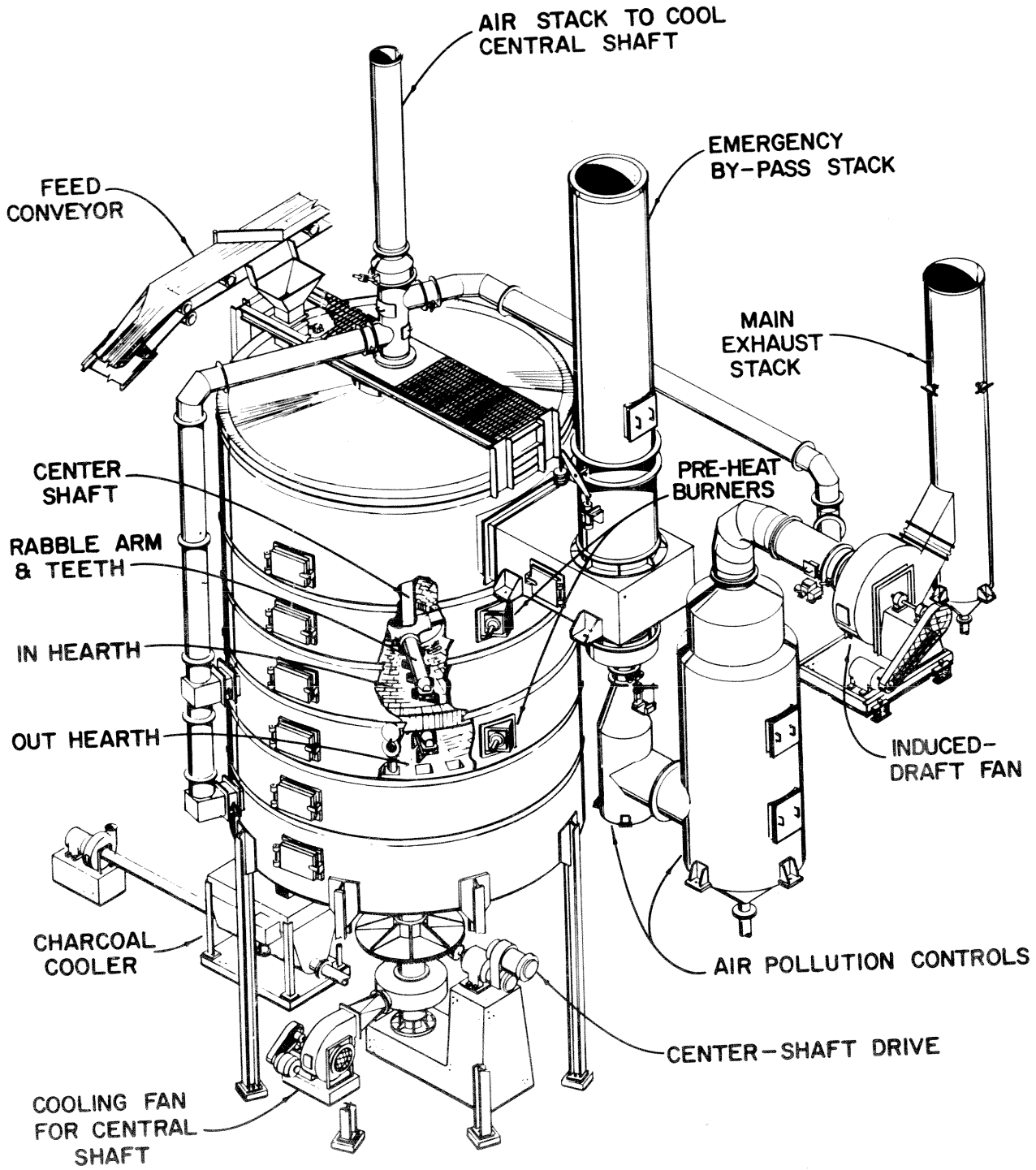


Figure 5-3.—*Nichols-Herreshoff multiple hearth furnace for the production of wood charcoal. (Drawing from Nichols Engineering and Research Corporation.)*

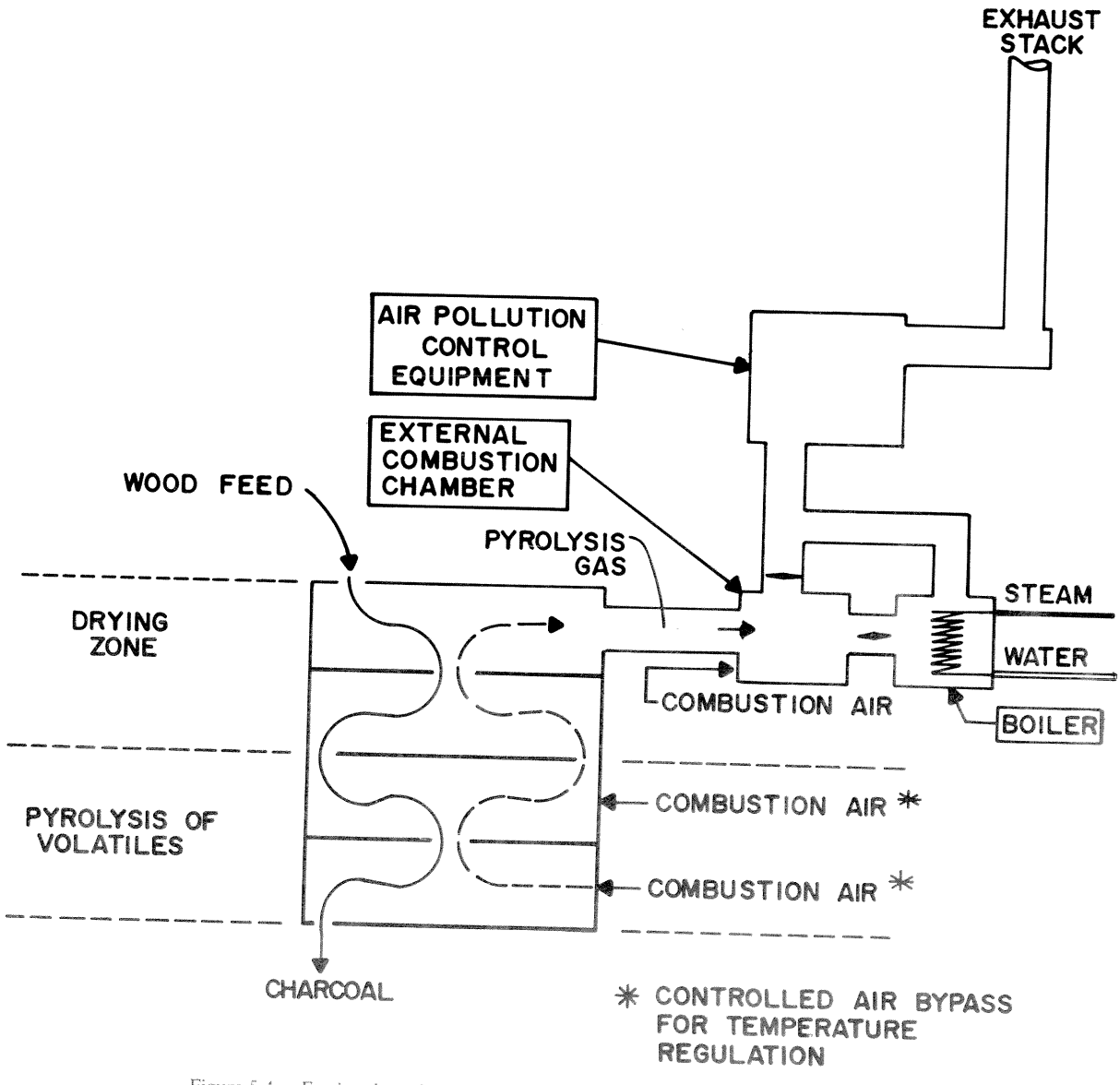


Figure 5-4.—*Feed and gas flow diagram for the Nichols-Herreshoff multiple hearth furnace.*

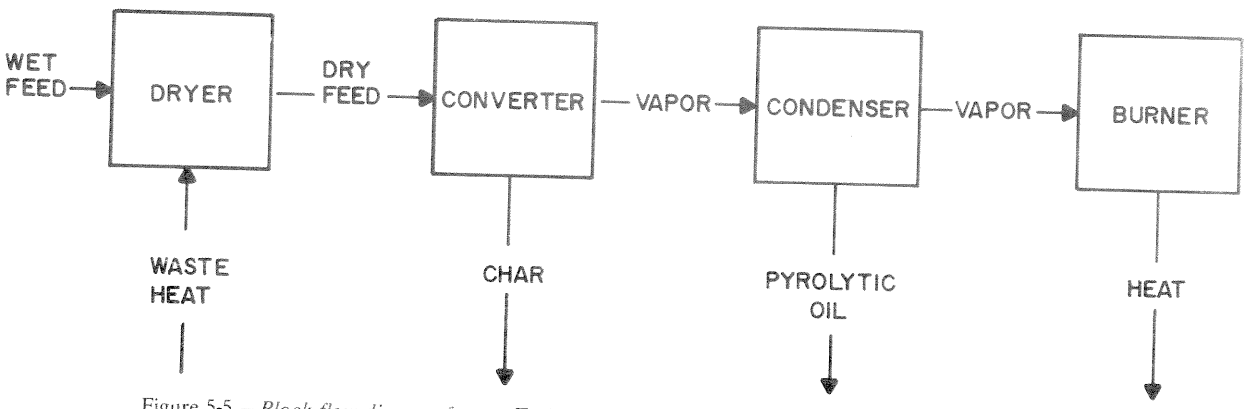


Figure 5-5.—*Block flow diagram for the Tech-Air pyrolysis system. (Drawing after Knight and Bowen[9].)*

percent. Charcoal heating values ranges from 11,000 to 13,500 Btu/lb. The process has been operated on a scale of 50 dry tons of fuel per day, and processing up to 200 tons per day appears feasible (Bliss and Blake 1977).

5-4 Occidental Flash Pyrolysis

Preston (1975) describes a pyrolysis system that internally recycles the charcoal produced in order to supply heat energy for the pyrolysis process. The primary products are pyrolytic oil, off-gases, and water. The process was developed primarily for pyrolyzing municipal refuse while recovering valuable metals and glass (fig. 5-6). It is presented here because the process will work as well, maybe better, with wood feed. Of course, the glass and metal recovery systems will not be needed.

This pyrolysis is aimed at producing a maximum yield of combustible liquid or oil. Pyrolysis is carried out on finely shredded organic material which is carried into the reactor by recycled off-gases. Pyrolysis takes place at 950°F at about 1 atmosphere and with short residence time. The charcoal is separated from the product stream by cyclone separators and then combusted in the charcoal burner. The remaining pyrolytic vapors are rapidly quenched to prevent further cracking of the oils. At this point, the products are separated into pyrolytic oil, gas and water. The pyrolytic oil (10,600 Btu/lb) produced is intended to be sold as a substitute for No. 6 residual (Bunker C) fuel oil. The pyrolysis gases have a heating value of about 380 Btu/sdcf, are recycled for use as a transport medium, and eventually are burned to provide heat to the rotary-kiln dryer.

CHAPTER 6
Other Processes

6-1 Liquefaction

Wood can be converted to an oil by reaction with synthesis gas and an alkaline catalyst under high temperature and pressure (Lindemuth 1978) (fig. 6-1). Part of the wood can be used to produce the synthesis gas by gasification. Preparation includes drying and grinding the wood before blending with recycled oil to produce a wood oil slurry of about 30 percent solids. The slurry, synthesis gas, and the alkaline catalyst (sodium carbonate solution) are then reacted at 600° to 700°F and 2,000 to 4,000 psi for various lengths of time. The oil is separated from unreacted wood and ash and part is recycled to blend with incoming wood. The waste stream contains catalyst and unreacted wood.

In the original process, which was developed by the U.S. Bureau of Mines, carbon monoxide plus steam and/or hydrogen was used as a reducing mixture in the presence of alkaline catalysts (Na_2CO_3 or HCO_2Na) at temperatures up to 750°F and pressures as high as 5,000 psi (Appel et al. 1975). Under these conditions it was found that cellulosic materials such as urban refuse, sawdust, bovine manure, and

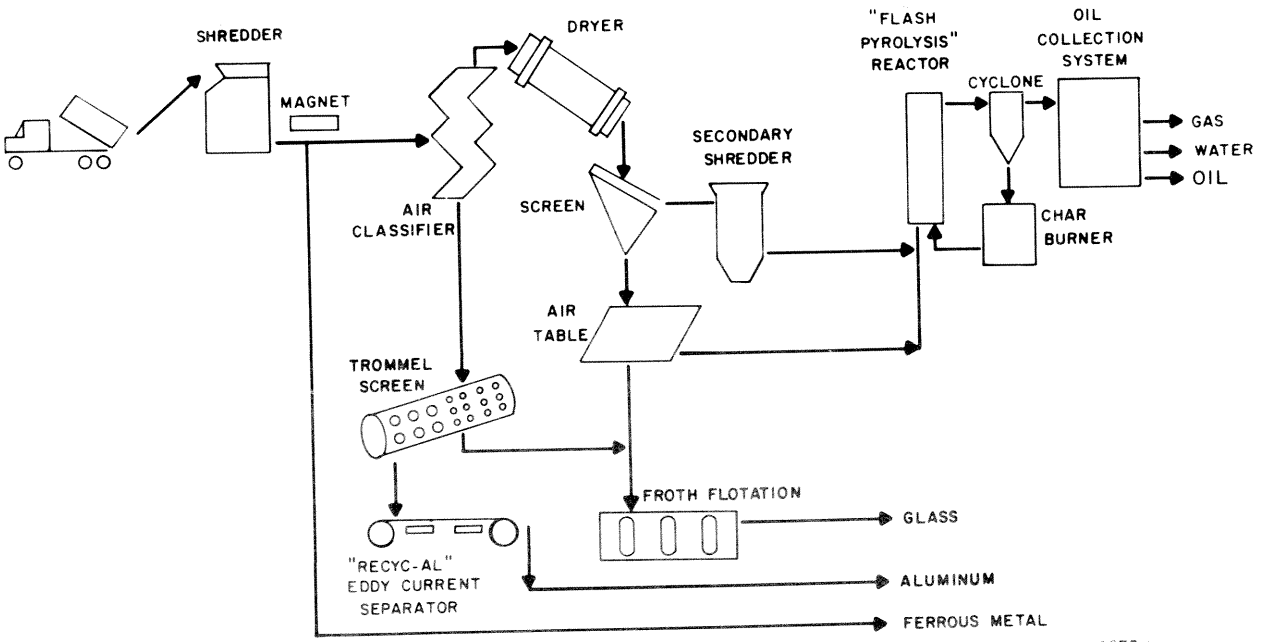


Figure 5-6.—*Simplified flow diagram for the Occidental resource recovery system. (Drawing after Preston 1975.)*

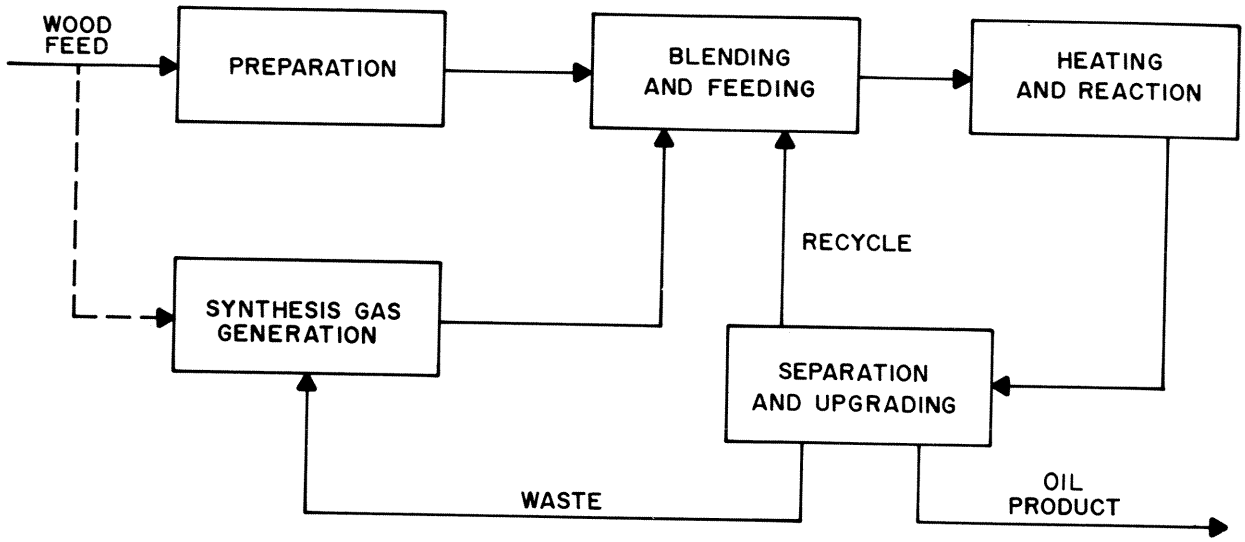


Figure 6-1.—*Wood liquefaction scheme. (Drawing after Lindemuth 1978.)*

sewage sludge could be converted to heavy oils. However, it was noted that materials containing larger quantities of lignin or other non-carbohydrates may require more severe reaction conditions. Bark, which has a high phenolic content that would consume considerable quantities of the alkaline catalyst, may not be suitable for this process as originally designed.

A unit in Albany, Oregon is testing the feasibility of using the U.S. Bureau of Mines process to liquefy wood and other biomass on a large scale. Incoming wood chips, which normally have a moisture content of about 50 percent, are dried to about 1 to 5 percent moisture content in a gas-fired rotary drier. The dried wood is then hammermilled to about 50 mesh before being slurried with recycled product oil. A catalyst solution of sodium carbonate is added and carbon monoxide gas is sparged through the mixture. Results to date have indicated reaction times of 25 to 30 minutes should be adequate for a commercial plant. Product yield ranges from 40 to 50 percent. On a volume basis, the heating value of the wood-produced oil is about four times higher than that of wood. The viscosity of the oil is high and has presented some problems in mobility (table 6-1). Current research at the Albany plant is aimed at solving problems of viscosity buildup and purification of the oil (Lindemuth 1978).

Table 6-1.—*Average properties of wood produced oil (Lindemuth 1978)*

	Reactor residence time	
	20 min	60 min
Viscosity @ 100° L.Cp	10,000-20,000	3,000-12,000
Heating value Btu/lb	15,700	16,000
Elemental analysis		
% C	86.0	88.3
% H	6.4	6.7
% O	6.4	4.0
% N	0.4	0.1

6-2 Hydrolysis and Fermentation

Cellulose and hemicelluloses, the principal polymeric carbohydrates (polysaccharides) of wood, can be converted into simple hexose (six carbon) and pentose (five carbon) sugars by hydrolysis. Cellulose, which is a linear polymer of β (1 $\rightarrow$ 4) linked anhydroglucose units, yields the hexose sugar glucose. Hemicelluloses are composed of several different polysaccharides. In the pine-site hardwoods the major hemicellulose is an acetylglucuronoxylan.[10] Hydrolysis of the pine-site hardwood hemicelluloses predominantly yields the pentose sugar xylose. Lesser amount of other constituents will also be released from the hemicelluloses, as follows: arabinose (a pentose sugar); glucose, galactose, and mannose (hexose sugars); and glucuronic acid.

An insoluble lignin residue can also be recovered from wood hydrolysis processes by centrifugation or filtration (Hoyt and Goheen 1971). Called hydrolysis lignin, this material is condensed and contains some unhydrolyzed cellulose residues. Hydrolysis lignin should not be confused with kraft lignin or sulfite lignin, residues from pulping processes (Sarkanen and Ludwig 1971).

[10] Unpublished data from H. L. Hergert, ITT, Rayonier, New York, N.Y.

The three major products of pine-site hardwood hydrolysis, glucose, xylose, and lignin, potentially can be used in a number of ways. At present, using them to produce ethanol, furfural, and phenol is of much interest (fig. 6-2).

Ethanol is used as a solvent to manufacture pharmaceuticals and perfume and as an intermediate in organic syntheses. It could be used as a clean burning fuel and can be mixed with gasoline to make gasohol. In the United States, most ethanol is produced by the petrochemical industry from ethylene.

Fermentation to produce ethanol is an old, well established process. In one approach that might be taken with a pine-site hardwood hydrolysis mixture, glucose and the other hexose sugars can be selectively fermented to ethanol by *saccharomyces* yeast. Xylose and arabinose are left unchanged, and the xylose can be recovered by crystallization (Herrick and Hergert 1977).

The dehydration of pentose sugars such as xylose to *furfural* is a well known acid-catalyzed reaction that is favored by high temperature and pressure. Current production of furfural in the United States is from pentose-rich agricultural residues such as corn cobs, grain hulls, and sugar cane bagasse. Furfural is used as a solvent and as an intermediate for the production of furan derivatives.

The largest use of *phenol* is in producing plywood adhesives. Thus, the phenol market fluctuates with demand for new housing. Phenol is also used in molded products and adhesives that are used in automobile and appliance manufacture.

Today, nearly all phenol is made from cummene, a petrochemical, but various hydrogenolysis techniques also can produce phenols from lignin. Reportedly, yields in the neighborhood of 40% of monomeric phenol derivatives have been obtained in pilot-plant experiments (National Research Council 1976). However, hydrodealkylation of the mixture of phenol derivatives to a high yield of phenol is not a proven process.

Other potential uses for the hydrolysis products of pine site hardwoods include the production of *Torula* yeast, a protein supplement (Herrick and Hergert 1977). Unlike fermentation to ethanol, which utilizes only the hexose sugars, both hexose and pentose sugars, certain sugar acids, and carbohydrate fragments can be used to grow the yeast. A reagent such as Raney Nikle or a hydrogenation catalyst can reduce xylose and glucose to xylitol and sorbitol, their corresponding sugar alcohols. Hydrolysis lignin can be used as a soil conditioner, filler for resins and rubber, depressant in ore floatation, decay-retardant in fabrics, a binding agent for particle and hardboard, and a grinding aid for Portland cement (Hoyt and Goheen 1971). In the Soviet Union, much of the hydrolysis lignin is burned as fuel. However, the high moisture content must be removed first. In one process, the lignin is dried to 12-18 percent moisture content with hot flue gases and then pressed into briquettes. It has also been suggested that hydrolysis lignin be used as a source of activated carbon (National Research Council 1976).

Hemicelluloses are readily hydrolyzable under mild acidic conditions; cellulose, on the other hand, is much more difficult to hydrolyze because of its crystalline organization and stable structure. Efficient production of sugars from whole-wood hydrolysis must take into account this difference or a competing reaction in which sugars are destroyed can occur (Harris 1975).

There are a number of potential wood hydrolysis processes (Oshima 1965, Wenzl 1970, Titchener 1976, Bliss and Blake 1977, Karlivan in press). The processes use hydrochloric acid, sulfuric acid, or enzymes (table 6-2). The acid-catalyzed processes can be further divided into those using dilute or concentrated acids. Hydrolysis with dilute acids is carried out in a single stage at elevated temperature and pressure. Concentrated-acid processes are generally conducted in two stages, a prehydrolysis and

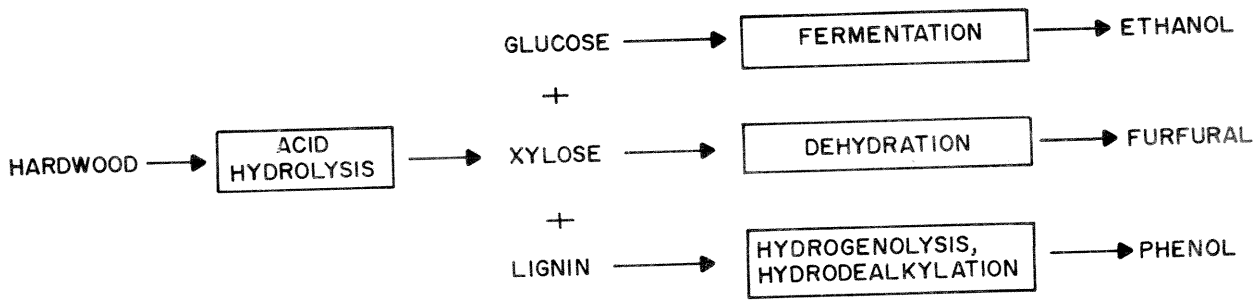


Figure 6-2.—*Production of ethanol, furfural, and phenol from pine-site hardwoods by hydrolysis.*

Table 6-2.—*Some processes for wood hydrolysis* (Bliss and Blake (1977).

Name	Main hydrolysis conditions			Yield of Fermentable Sugar (kg/t wood)	Sugar Concn (wt %)	Recovery method for medium	Status
	Medium	Temp. (°C)	Time (h)				
Scholler	1/2-1% H_2SO_4	180	12	352	4	As $CaSO_4$	Several plants operated in Europe before and during World War II
Madison	1/2-% H_2SO_4	180	3	>352	5.5	As $CaSO_4$	Demonstration plant built 1946 and 1952
Hokkaido	80% H_2SO_4	40	>1	—	20	Ion exchange to recover 25-35% acid	100 T/D plant at Asahikawa in 1963
Rheinau-Udic	41% HCl	20	About	—	10	Vacuum distillation	Semi-commercial plant (2000 ODT/yr operated 1959)
Noguchi-Chisso	HCl gas	50	>1	—	30	Vaporization using hot air	1 t/d plant operated (1956)
U.S. Army Natick Development Center	Enzymes	50	48	90-220	1.6-4.6	—	Experimental bench-scale

a main hydrolysis stage that is kept near ambient temperature.

Dilute acid processes are typified by the *Scholler-Torensch process* which uses 0.5 percent sulfuric acid to complete hydrolysis in one stage at elevated temperature and pressure. Dilute acid is percolated through wood chips or sawdust followed by a charge of steam. The short hydrolysis time does not completely hydrolyze the cellulose, so the acid-steam percolation is repeated up to 12 times. The dilute sulfuric acid in the hydrolyzate is neutralized by calcium carbonate to form calcium sulfate ($CaSO_4$) which is removed by filtration. The yield of sugar on a weight basis is around 40-50 percent for softwoods (Titchener 1976, Bliss and Blake 1977).

The *Madison process* is a continuous-flow variation of the Scholler-Torensch process. A continuous flow of reagent removes the hydrolyzate to a cool zone to reduce sugar degradation. Total saccharification time is about one-fourth of that required in the Scholler-Torensch process, thus lowering the production cost. Hardwoods yield about 35 percent fermentable sugars and 20 percent pentoses on a weight basis (Titchener 1976, Herrick and Hergert 1977).

A typical example of a concentrated-acid process is the *Rheinau-Bergius process* which was used by Germany in World War II to produce yeast from hydrolyzed sugars. In stage one, fuming hydrochloric acid (up to 41 percent) is used to degrade cellulose mostly to lower oligomers at ambient temperatures. In the second stage, the acid is diluted with water and heated to yield monomeric sugars. In the *Rheinau-Udic process,* a modification of the earlier procedure, prehydrolysis, is carried out with a 32 percent acid solution and the main hydrolysis uses 41 percent hydrochloric acid. The hydrochloric acid is recovered by vacuum distillation. The hydrolyzate is post-hydrolyzed, filtered, decolorized, and passed through an ion-exchange column, before crystallization of the glucose. Reportedly, 22 kg of crystalline glucose can be obtained per 100 kg of wood (Wenzl 1970).

The use of hydrogen chloride gas, rather than concentrated hydrochloric acid, is the basis of several proposed processes (Titchener 1976). In the Japanese *Noguchi-Chisso process,* wood is first prehydrolyzed to remove hemicelluloses. The residue is heated with a 5 percent hydrochloric acid solution and cooled. Gaseous hydrogen chloride is then administered; the temperature is kept below 10°C. Next, the temperature is raised to 40°C to effect hydrolysis to lower oligomers. The hydrogen chloride is recovered by blowing hot air through the hydrolyzate. Post-hydrolysis at 100°C with 3 percent hydrochloric acid yields glucose. In this step, acid is recovered by vacuum distillation.

The advantages of this system are the simplicity of acid recovery, fewer corrosion problems, and the sugar solutions are more highly concentrated.

In the *Hokkaido process,* first prehydrolysis is carried out with steam or dilute sulfuric acid at temperatures up to 185°C. A furfural yield of 65 to 75 kg per tonne of dry wood is obtained from dehydration of the pentoses in the reactor. The prehydrolysis residue is then dried, powdered, and treated with 80 percent sulfuric acid for about 30 seconds. The

reaction mixture is immediately washed with water and filtered. Acid is recovered by use of ion-exchange resins. The hydrolyzate, which still contain dilute sulfuric acid, is post-hydrolyzed by heating at 100°C. Yield of crystalline glucose is about 280-290 kg/ton of dry wood (Bliss and Blake 1977).

Interest in enzymatic hydrolysis of cellulose to glucose has been spurred by the United States Army Natick Development Center's development of strains of *Tricoderma* fungi. These fungi produce cellulase enzymes that have been tested on several cellulosic substrates (Mandels et al. 1978, Bliss and Blake 1977).

The *enzymatic hydrolysis process* requires two stages. In the first, the enzyme is produced by growing the fungus in a culture medium of cellulose pulp. After a period of growth, the broth is filtered to give the enzyme-containing solution used in hydrolysis. Hydrolysis generally is carried out at pH 4.8 and 50°C on ball-milled cellulosic substrates. Pulverization by ball milling is necessary to break down cellulose crystallinity. Yields depend on the substrate and range from 16-77 percent. Pure cellulose pulp and shredded paper give respectable yields of up to 77 percent. Wood waste, on the other hand, yielded only 16 percent reducing sugars. On pulped wood chips the yield was 57 percent (Mandels et al. 1978, Bliss and Blake 1977).

While these enzymes may lead to a non-corrosive process (as opposed to acid hydrolysis), they require pretreatment of the wood cellulose because they are greatly inhibited by the cellulose crystallinity and the ligno-cellulosic complex. In fact, lignocellulosics present a formidable barrier for most enzyme systems. Thus, utilization of wood to produce methane gas by anaerobic digestion using bacteria or use of wood as food for ruminants is not yet fully practical. However, wood is used as a roughage for ruminant rations (Baker et al. 1975). The best possibility for overcoming the low reactivity of wood is to develop a cost-effective pretreatment that makes lignocellulosics react to enzymatic hydrolysis (Millett et al. 1975).

6-3 Prehydrolysis

An alternative to whole-wood hydrolysis is to remove the hemicelluloses for chemical or other use in a mild prehydrolysis step, and then to use the remaining fibrous cellulose residue in a pulping process or for particleboard or fiberboard manufacture or for fuel (fig. 6-3, Herrick and Hergert 1977).

Prehydrolysis can be carried out by hot water extractions. Acids in the wood and those released by hydrolysis cause extensive depolymerization of hemicelluloses. The resulting water soluble carbohydrates are mostly low molecular weight polysaccharides with smaller amounts of monomeric sugars. Yield and composition depend on temperature and time of extraction. Typically, water temperatures of 100° to 170°C and extraction time of 30 minutes are sufficient. The polysaccharides containing xylose units (xylans) are more easily hydrolyzed than the corresponding glucans; thus, prehydrolysis of hardwoods for recovery of xylose can be accomplished at lower temperatures than for hemicellulose removal from softwoods. Typically the hot water prehydrolyzate of hardwood will contain polymers of xylose (30 percent) and glucose (25 percent) (Herrick and Hergert 1977).

Hemicellulose extracts have been marketed since 1965 as Masonex, an ingredient of livestock feed (Galloway 1975). The fibrous residue or pulp is used to manufacture hardboard. Only steam and pressure are used to pulp the wood chips and so the hemicellulose fractions removed are not contaminated by added chemicals. The hot water extract is separated from the pulp by vacuum filtration and concentrated by evaporation to 65-percent solids. The resulting product resembles molasses and can be added in cattle feed to 10 percent by weight. Reportedly, the product contains 890 kilocalories of metabolizable energy per gallon (10.4 lb).

Funk (1975) describes a prehydrolysis process that enables recovery of up to 80 percent of the hemicelluloses, mainly as the monomeric sugar xylose. The process does not seriously affect the fiber residue. The degree of polymerization of the residual cellulose is on the order of 900 DP with viscosity between 30 and 40 centipoise.

In the process, organic acids (acetic and formic) are vaporized and injected with steam into the digester where the wood chips are. Reaction time ranges from 15 minutes to 1 hour and the temperature is kept below 135°C. Above 135°C, xylose degradation and fiber deterioration occur. More acids are generated in this process than are injected, so acid recovery by vacuum distillation is feasible. Xylose can be separated from glucose and other sugars by selective crystallization or microbial conversion. An alternative is to reduce the product mixture and separate the sugar alcohols.

When furfural is desired as the product from a hardwood prehydrolysis process, it may be advantageous to add some dilute sulfuric acid. The dilute mineral acid helps to produce furfural by removing and hydrolyzing the hemicelluloses and dehydrating xylose. Thus, it is possible to produce furfural in a one-stage process in which both hydrolysis and dehy-

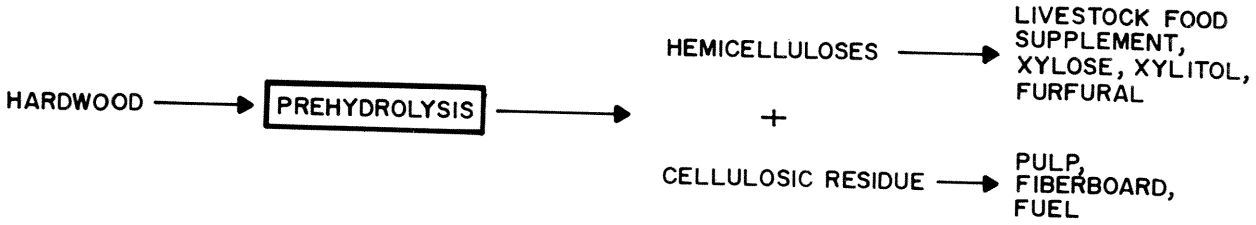


Figure 6-3.—*Prehydrolysis of pine-site hardwoods for chemical, animal food supplement, and fiber or fuel use.*

dration occur in the reaction vessel. Harris (1978) indicates that the residue from such a process can supply more fuel for heat energy than the process requires.

CHAPTER 7

Industrial Use of Wood Energy

The forest products industry is the fourth largest user of purchased energy in the Nation (U.S. Forest Service 1976). (The petroleum, chemical, and primary metals industries are the three largest users.) In 1974 the forest products industry purchased about 1.8 quads, or slightly more than 2 percent of the Nation's total energy use (Salo et al. 1978). About 1.3 quads were fuel oil and natural gas, energy sources particularly vulnerable to curtailment and interruption.

The industry also generates much of its own energy from mill wastes and residues. Pulp and paper mills generate the most by burning spent pulping liquors, wood, and bark. Nationally, pulp and paper mills are about 40 percent energy self-sufficient, sawmills about 20 to 40 percent, and plywood and veneer mills, about 50 percent (U.S. Forest Service 1976). At 50 percent, southern pulp and paper mills are more energy self-sufficient than the national average (table 7-1). However, they also purchase more energy than anyone else in the forest products industry (table 7-2).

Most fuel, purchased and residue, is burned to generate steam which satisfies most of the process requirements for the industry. However, some electricity is also generated in the industry by co-generation. Pulp and paper mills in general produce only about one-half of their electrical needs, but sawmills could sell excess electricity if the economics were favorable (Pingrey and Waggoner 1978).

Table 7-1.—*Energy use pattern for southern pulp and paper mills*[1]

Energy source	Percent total energy used
Electricity	3
Natural gas	20
Oil	20
Coal	7
Pulping liquors	43
Wood and bark	7

[1] Data from U.S. Forest Service (1976).

Table 7-2.—*Energy purchased by the pulp and paper sector by geographical area*[1]

Geographic area	Energy purchased	
	10^{12} Btu's	*Percent*
South	806	62
North	286	22
Rocky Mountain	26	2
Pacific Coast	182	14
Total	1300	100

[1] Data from U.S. Forest Service (1976).

The forest products industry is in a good position to achieve greater energy self-sufficiency by burning more wood and bark residues to replace or supplement purchased fossil fuels (Grantham 1978, Salo et al. 1978, Pingrey and Waggoner 1978, Benemann 1978, Hodam 1978). Such action would also free oil and natural gas for use elsewhere as a fuel or petrochemical feedstock. Because of its proximity to vast amounts of virtually unused pine-site hardwoods, the forest products industry in the South has a better opportunity than anyone else in the country to convert to wood fuel.

The industry already has experience in handling such bulky wood materials. However, certain problems will have to be addressed, mainly storing and handling the large volume of wood fuel that will be required to replace fossil fuels. Wood-fueled furnaces are less convenient and have more emissions than those operating on oil and natural gas. Finally, the use of pine-site hardwood chips as a fuel may have to compete with their use for making higher-value products.

CHAPTER 8

Economics

As a replacement for natural gas (at $2 per million Btu) to generate steam, pine-site hardwoods have a fuel value of about $15/green ton and when used to

Table 8-1.—*Fossil fuel cost for steam production and fuel replacement value for pine-site hardwoods*[1]

Fuel	Fuel cost[2]	Furnace efficiency	Steam cost	Fuel replacement value for pine-site hardwoods[3]
	$/MM Btu	*Percent*	*$/MM Btu*	*$/green ton*
Oil	2.20	80	2.75	15.73
Natural gas	2.00	76	2.63	15.04

[1] Does not include handling, storage, maintenance, amortization, or other costs.
[2] Representative values for natural gas and oil.
[3] Following assumed: 42 percent moisture content, higher heating value 7,827 Btu/lb, 63 percent furnace efficiency.

replace oil, the value is slightly higher (table 8-1). In other words, 1 green ton of pine-site hardwoods can be used to generate the same amount of steam as $15 worth of natural gas. If the wood costs less than $15, there is then a savings in fuel cost. The replacement fuel value for the pine-site hardwoods will, of course, continue to rise with the cost of oil and natural gas.

Fuel costs, however, are only one consideration in the total economic picture. Wood-fired boilers cost more and are more expensive to maintain than oil or gas-fired units. Koch and Mullen (1971) indicated that a steam boiler for burning bark and oil would cost about twice as much as a boiler using oil only. Similar cost comparisons have been noted by Corder (1973). Salo et al. (1978) estimated capital costs for installing new wood-fired steam boilers at about $13 million and $25 million for 155,000 and 387,000 lb/hr units. Annual operating and maintenance costs were projected at 1.4 and 2.8 million dollars. To retrofit an oil-fired boiler (1400 Bbl/day) to an 850 ovendry ton/day wood-fired unit would result in an additional capital investment of $21.5 million and an increase in annual operating and maintenance costs of $2.3 million, but would decrease fuel costs $4.2 million annually.

For the near future, the economics of changing to wood fuel will be site-specific. Pingrey and Waggoner (1978) and Salo et al. (1978) indicate there is general lack of economic incentive to change based on fuel savings alone. Salo et al. suggest an early retirement tax credit or an investment tax credit to encourage the use of wood as a fuel.

The economics of converting the pine-site hardwoods to other energy-related products is subject to considerable uncertainty because most of the conversion processes are not yet widely used. Additionally, costs of harvesting such hardwoods with conventionai equipment are sometimes excessive. Several studies have been made to estimate the cost of converting wood into various energy forms, and the projected costs vary considerably. For example, the projected price of methanol from wood ranges from 40¢/gallon to 98¢/gallon. Such differences occur because different variables are used in the models to make the projections. The most obvious variables include feedstock cost, production plant size, and the amount of return on investment.

In a Mitre Corp. study, Salo et al. (1978) estimate the plant gate selling prices for various wood-derived energy products in order to assess the near-term potential (table 8-2). These values should be considered optimistic as feedstock costs are very low and a 10 percent rate of return was used on all products for comparison purposes. For the methanol, ammonia, and ethanol, this rate would probably be too low to be attractive to a private enterprise. The conclusion was that direct combustion of wood fuel is probably the best option for the forest products industry. The study indicated that a thorough gasification of wood to low Btu gas should be assessed to determine its potential for large-scale industrial applications such as pulp mills.

Table 8-2.—*Estimated "plant-gate" selling prices*[1] *for energy products derived from wood*[2] *($/10⁶ Btu heating value)*

	Plant size	
	850 dry tons/day	1700 dry tons/day
Process steam	2.70	
Low-Btu fuel gas	2.70	
Medium-Btu fuel gas	3.10	2.60
Charcoal without credits	4.90	4.60
Charcoal with steam credit	2.10	1.90
Subtitute natural gas	4.60	3.80
Ammonia	5.50 ($107/ton)	4.43 ($88/ton)
Methanol	7.60 ($0.50/gal)	6.20 ($0.40/gal)
Ethanol	20.40 (1.65/gal)	17.50 (1.40/gal)
Electricity	11.80 (40 mills/kWh)	8.80 (30 mills/kWh)

[1] Data from Salo et al (1978). Assumptions include a 10-percent return on investment after taxes.
[2] Wood cost is $1.00/10⁶ Btu.

Stanford Research Institute is preparing an economic report on wood energy processes likely to achieve commercialization by 1985 (table 8-3). (Schooley et al. 1978). The base case assumes feedstock cost of $30/dry ton while the optimistic case assumes $20/dry ton. The model assumes no subsidies or tax incentives and 15 percent return on investment.

In 1975 Katzen Associates reported on the separate or combined production of chemicals from wood (U.S. Forest Service 1976, Seaman[11] Grantham 1978, Hokanson and Rowell 1977). Table 8-4 summarizes data on the selling prices for a hardwood plant. Assumptions included a delivered price of $34/dry ton and that its availability is limited to 1,500 dry tons per day. Conclusions drawn from the Katzen report are that chemicals production from wood is not economically attractive.

CHAPTER 9
The Future

Wood fuel will play a major role in supplying increasing amounts of energy for the forest products through the turn of the century. However, the industry will probably depend on oil and natural gas for as long as these resources are available. Natural gas use is likely to continue for at least a decade. Coal is not a popular fuel alternative due to environmental considerations and the cost of shipping and handling, but its use will grow to perhaps 25 percent of the industry needs by 1985 (Junge 1975b). Wood residues will remain the best energy bargain, but economic use of wood sources such as pine-site hardwoods will depend on the development of adequate harvesting technology.

Oil and natural gas will continue to be the primary feedstocks for organic chemicals through the turn of the century and for as long thereafter as they remain the least expensive alternative (Krieger and Worthy 1978, Grantham 1978, Maisel 1978, Herrick and Hergert 1977). A popular view is to reduce the use of oil and natural gas for fuel and to reserve this source for petrochemical production. Before the 1940's, coal was the major source of organic chemicals and is considered the first alternative for both fuel and petrochemicals. At current energy consumption rates, there is enough coal to last several hundred years.

Wood will become more important as an industrial raw material because it is renewable. Demand for fibers for paper and textile products will more than double by the turn of the century (Jahn in press). While wood is not competitive with petroleum and coal for petrochemicals, it should be looked at for other specialized chemical products that take advantage of the unique molecular structure of wood and

[11] J. F. Saeman. Energy and materials from the forest biomass. 20 p. Paper presented at Institute of Gas Technology Symp. on Clean Fuels from Biomass and Wastes. (Orlando, Fla., Jan. 25-28, 1977).

Table 8-3.—*Sales prices required on 8 products to yield a satisfactory profit in large conversion facilities*[1]

Route	Conversion process[2]	Base case[3] (including feedstock at $30/dry ton)	Base case, (no feedstock cost[3]	Optimistic case[3] (including feedstock[4] at $20/dry ton)
		Dollars per million Btu		
Wood to:				
Heavy fuel oil	CL	5.37	3.47	4.76
Methanol	GOB	7.77 (0.50/gal)	6.01 (0.39/gal)	6.72 (0.44/gal)
Ammonia ($/short ton)	GOB	164.00	126.00	141.00
Substitute natural gas	GOB	6.41	4.80	5.56
Steam	DC	3.00	1.68	2.73
Electricity	DC	16.38	11.62	14.40
Steam and electricity	DC	3.42	2.09	3.06
Oil and char	P	4.50	1.40	4.00

[1] Data from Schooley et al. (1978).
[2] Key: CL = catalytic liquefaction
GOB = gasification—oxygen blown
DC = direct combustion
P = pyrolysis
[3] 1977 dollars in year 1985. Sales values tabulated will return yield calculated to yield a 15-percent discounted cash flow rate of return on equity and a 9-percent rate of return on debt.
[4] Capital cost = 80 percent of base case.

Table 8-4.—*Estimated selling prices for chemicals from single-product and multiproduct hardwood plant*[1]

Type of plant	Product output	Plant size	Selling price[2]	1975 market price
		Dry tons/day		
Single-product plant				
Methanol	50 x 10^6 gal/yr	1,500	$0.98/gal	$0.38/gal
Ethanol	25 x 10^6 gal/yr	1,480	$1.90/gal	$1.04/gal
Furfural	40 x 10^6lb/yr	760	$0.61/lb	$0.37/lb
Multiproduct plant[3]				
Ethanol	25 x 10^6 gal/yr	1,500	$1.28/gal	$1.04/gal

[1] Data from J. F. Saeman. Energy and materials from the forest biomass. 20 p. Paper presented at Institute of Gas Technology Symp. on Clean Fuels from Biomass and Wastes. (Orlando, Fla., Jan. 25-28, 1977).

[2] Selling price based on an annual depreciation of investment of 8 percent and profit of 15 percent (after Federal taxes).

[3] Selling price assumes a credit for furfural and phenol at 65 percent of market selling price.

bark. For better chemical utilization of wood, research should focus on making the ligno-cellulosic complex accessible to chemical and biological action, increased use of cellulose and lignin as polymers, producing specialized chemicals, and catalyst research and development.

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