DESIGN, CONSTRUCTION AND PERFORMANCE OF STICK-WOOD FIRED FURNACE FOR RESIDENTIAL AND SMALL COMMERCIAL APPLICATION

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Abstract

With funding from ERDA and DOE an experimental program was conducted at the University of Maine at Orono to develop a combustion system for residential furnaces that solves the traditional problem of wood burning: inefficiency, air pollution and fire hazzard.

The program led to the designs that are now covered by a patent application and are being manufactured by three companies:

Dumont Industries
Monmouth, Maine 04259

Madawaska Wood Furnace Company
86 Central Street
Bangor, Maine 04401

Hampton Technologies Corporation Ltd.
Box 2277
126 Richmond Street
Charlottetown, Prince Edward Island, Canada C1A 8B9

This report is an abbreviated summary of the history, the design, the performance, and the construction of pro-to-type production units.

I. A HISTORY OF THE PROJECT

First efforts leading to the present work were sponsored by the Audubon Society and Georgia Pacific Company.

Current Contract:

Fall and winter 1977-1978 - design and test various configurations for stick-wood combustion schemes.

Spring and summer 1978 - integrate designs into a heat exchanger and storage stystem.

Fall and winter 1978-1979 - refine design and construct sample units.

Spring and summer 1979 - construct production pro-to-type and testing.

II. THE PROBLEM OF BURNING WOOD

A series of very complex time-and-temperature-dependent chemical reactions accompany the burning of wood. To supply the correct amount of air is difficult; to control the output to match a particular heating load is impossible. This difficulty in carburetion and control is compounded by difficulties in ignition. The pyrolysis gases generated from heating wood have an ignition temperature between 725°F (methanol) and 1128°F (carbon monoxide). Since stove surface temperatures do not operate in this range, much of the gas distilled from wood is vented to the chimney with three unhappy consequences:

1. the loss of energy
2. the pollution of the atmosphere
3. chimney condensation with subsequent fire hazard.

As stick wood is burned, heat is transferred from the surface to the interior with a counter flow of pyrolysis material. The kinetics of the reaction depend upon:

1. surface-to-volume ratio of the stick
2. surface temperature
   a. radiant field
   b. convection field
3. wood moisture
4. specie
5. rate of air supply
6. rate of ash removed from the burning surface.

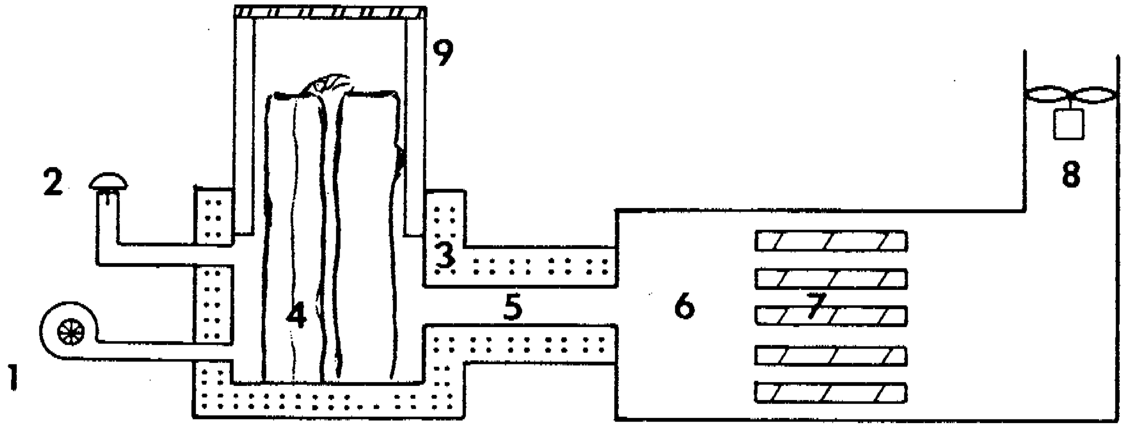
Given this complexity, the only design approach is to cut and try. The only design rule is to keep the combustion zone hot and turbulent for a sufficient time to complete the reaction.

At the start of the present work, several arrangements of all-refractory combustion chambers were tried without real success. Regardless of how the air was introduced or the wood stacked, the radiative capacity of the refractory would force carburetion problems that would sometimes result in explosions strong enough to lift a twenty-pound cast-refractory charging door.

III. A DESCRIPTION OF THE FINAL DESIGN

1. Summary

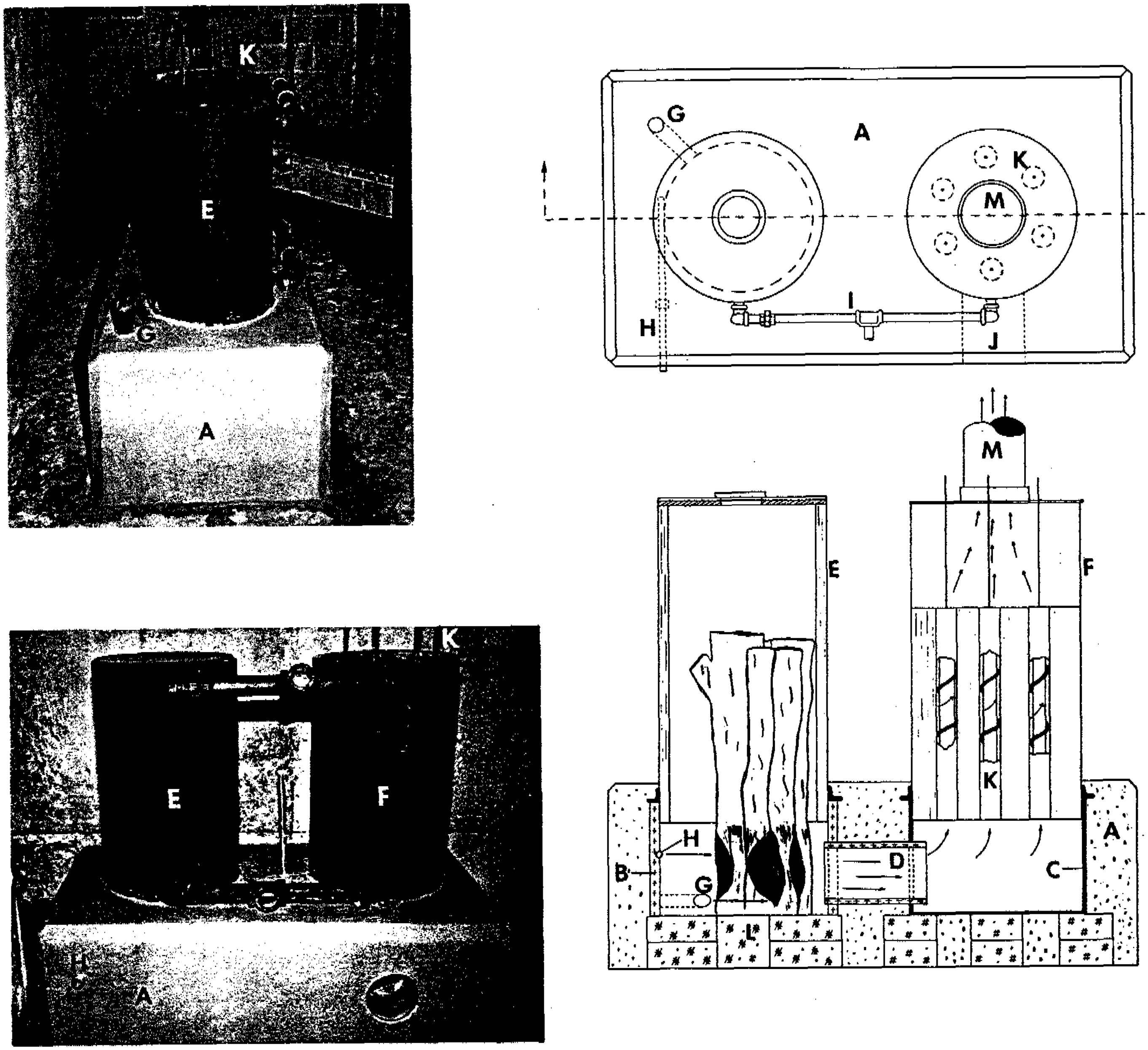
The elements of a satisfactory stick wood furnace are shown in the schematic sketch below.



1 - forced draft fan
2 - secondary air
3 - refractory base
4 - stacked wood
5 - refractory tunnel
6 - low velocity ash chamber
7 - fire tube heat exchanger
8 - induced draft fan
9 - water jacket for wood charge

Figure 1

The forced draft fan supplies combustion air at 3 inches of water static (about 100+ ft/sec). The water jacket limits the pyrolysis to the refractory base. The 1500°F+ tunnel provides mixing and ignition. The induced draft fan provides easy starting, smoke free loading and compact heat exchanger design. Figure 2 shows the configuration of the final design.



A - Vermiculite base
B - Refractory ring (Plicast 27)
C - Refractory ring (LWI 20)
D - Refractory tunnel
E - Combustion can
F - Heat exchanger
G - Secondary air inlet

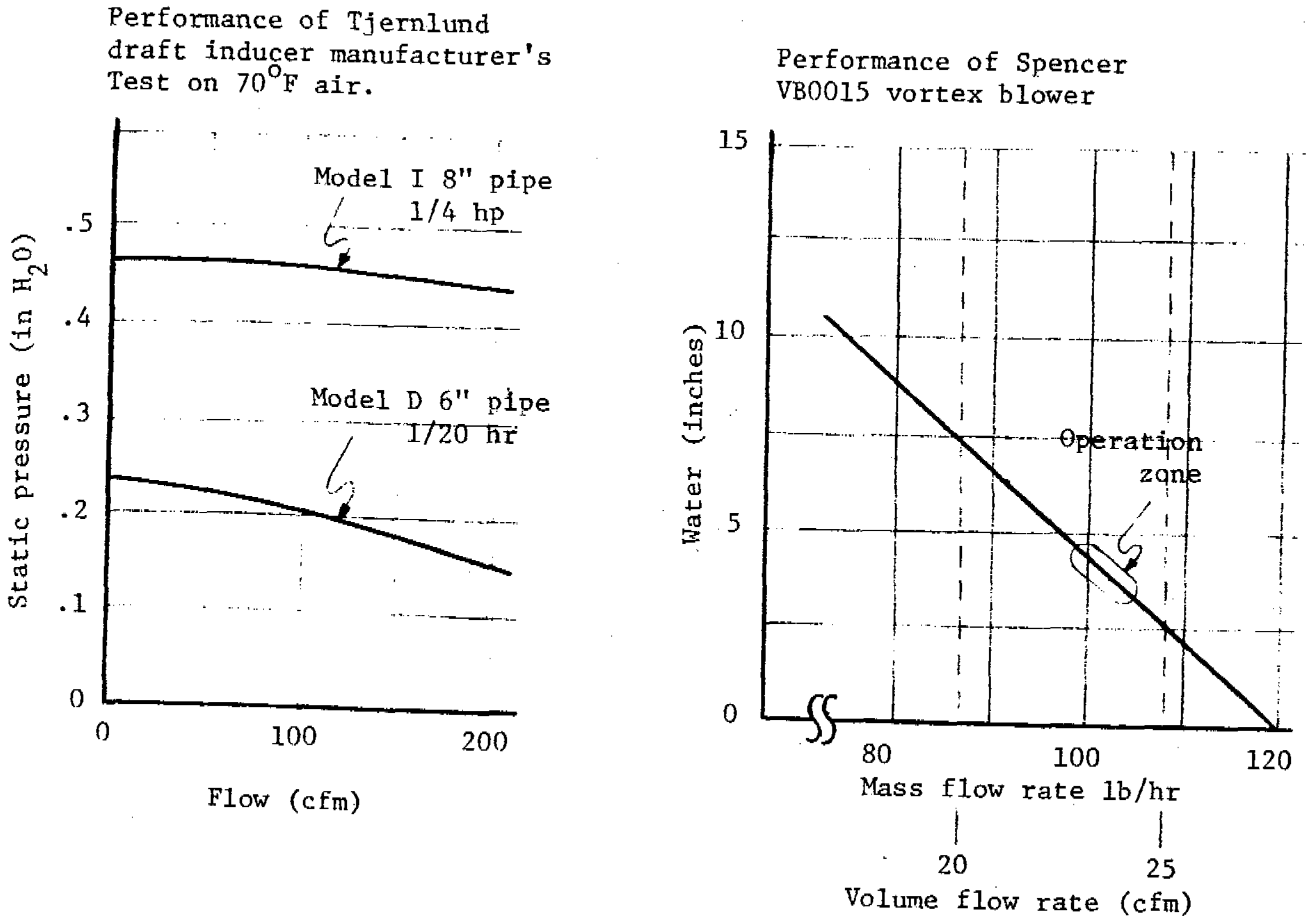
H - Primary air (stirring air)
I - Connections to storage tank
J - Ash cleanout
K - Turbulators
L - Fire brick
M - Connection to smoke pipe
(not shown on photograph)

Figure 2

2. The Forced Draft Blower and Air Supply System

Figure 3 shows the flow-pressure characteristics of the forced and induced draft fans. The combustion of 20 pounds of dry wood per hour requires about 130 lb of air per hour at zero excess air. The efficiency penalty at a 300°F stack is only three percentage points if 75% excess air is introduced. This extra air assures pollution free combustion. Hence about one half the air is introduced by the Spencer blower, the rest is pulled in by the ID fan through the secondary air port.

This secondary flow tends to be self regulating. As the combustion rate increases the volume flow rate increases. The associated pressure drop through the system forces the combustion chamber pressure close to atmospheric. The result: less secondary air and a tendency to stabilize the combustion rate.


Performance of Tjernlund draft inducer manufacturer's Test on 70°F air.

Performance of Spencer VB0015 vortex blower

Figure 3

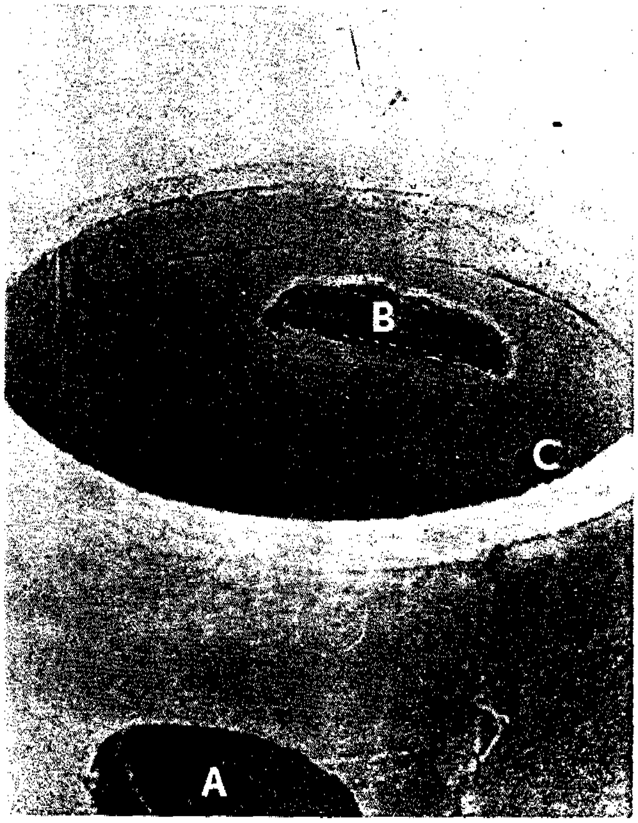
3. The Refractory System

Figure 4 shows the refractory base -- the water jacket fits inside -- the charge air pipe is about one inch below the jacket.

Ideally the refractory base should have low heat capacity and low thermal conductivity to provide rapid temperature rise for quick smokeless starts. Refractories with these properties, however, are too soft to stand the abrasion of loading wood and the erosion of high velocity particles.

The following compromise has worked well:

Combustion zone - 2" PLICAST 27
Tunnel - 1" PLICAST 27
Base of heat exchanger - 2"
PLICAST LWI 20



A - the entrance to the tunnel
B - the one inch charge air pipe with ten 1/4" holes
C - the secondary air port

Figure 4

Figure 5 shows the forms used to cast the combustion zone refractory; the heat exchanger base and the tunnel.

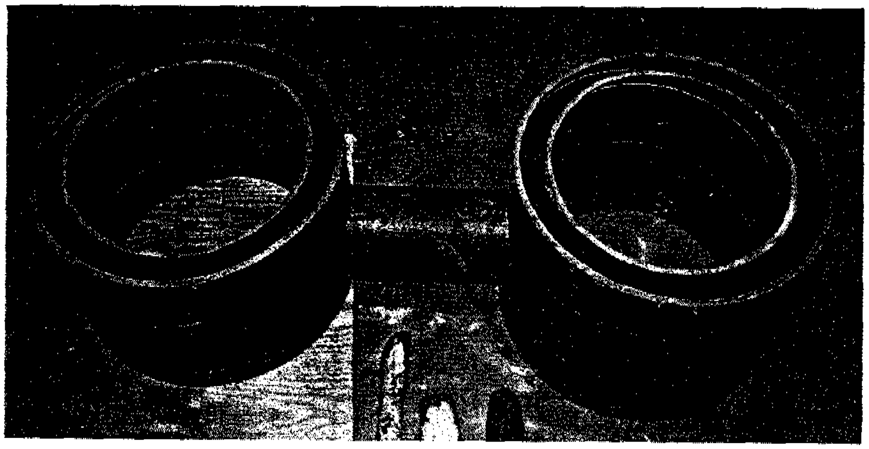


Figure 5

These materials, by themselves, would not provide the necessary thermal protection or prevent in-leakage of unwanted air. Therefore the assembly is cast in vermiculite concrete covered with BLOCKBOND to provide protection. The finished unit is shown in Figure 2. An ash cleanout port is shown under the heat exchanger; the forced air pipe is shown on the left.

The properties of the refractory and vermiculite are shown in the Appendix.

4. The Heat Exchanger and Combustion Can

A thirty-inch length of 16" diameter schedule 10 pipe was fitted with two tube sheets and seven 2 1/2" fire tubes 20" long. The unique turbulators shown in Figure 6 have extensions through the smoke collar which can be pulled while the unit is operating to remove dust. The combustion can was formed by welding a 14" diameter pipe inside a 16" diameter pipe.

Figure 7 shows the heat exchanger with smoke pipe removed. Fly ash is discernable on the top tube sheet, but no condensable conbustables are present in spite of attempts to burn 50-60 percent moisture (wet basis) wood.

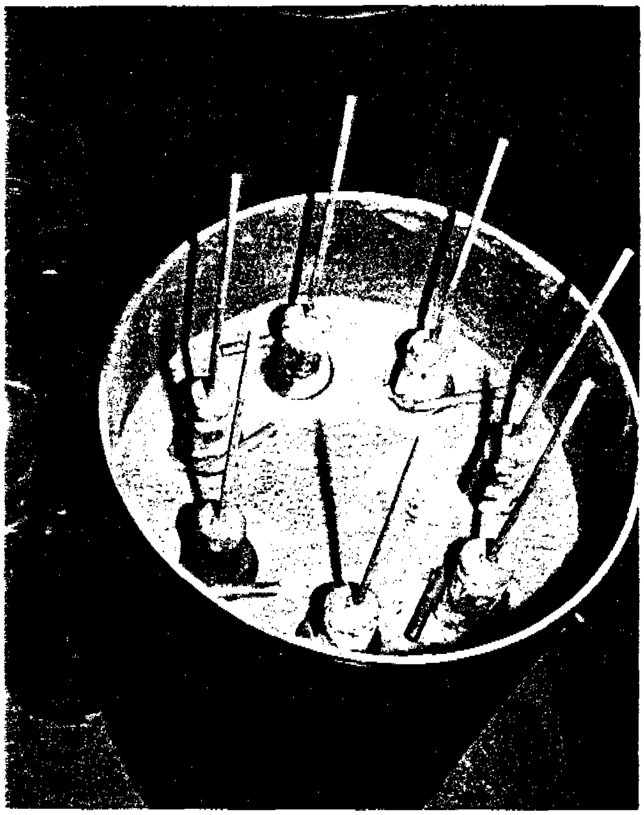


Figure 6

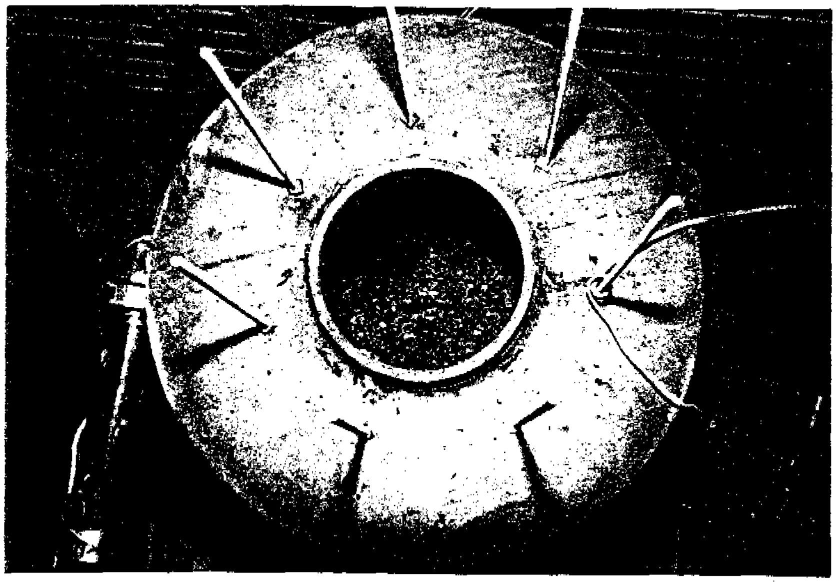


Figure 7

The heat exchanger and combustion can are connected to a storage system through pipes large enough to permit gravity circulation. An open-to-the-atmosphere expansion tank will prevent overpressure.

5. Interaction with Building Heat Load

The open tees of Figure 2 are connected to two cross-connected 275 gal oil tanks. Figure 8 shows the assembly before the tanks were placed on legs and connections made. An open expansion tank is installed above the highest radiation in the building. Standard circulator pump and thermostats respond to building load. The unit can be fired at the convenience of the operator independent of heating load at the moment. A pound of wood will increase the system temperature about one degree F.

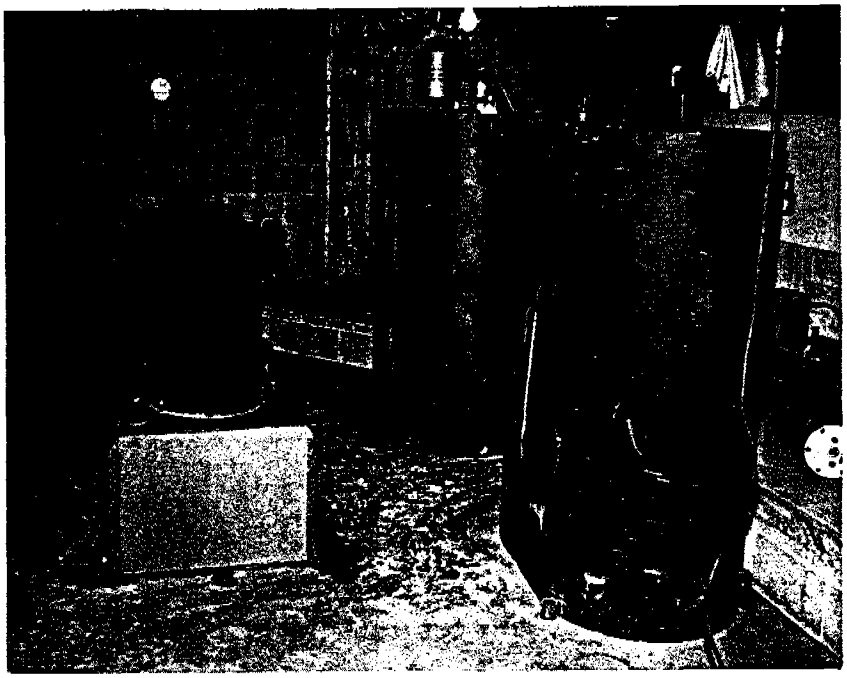


Figure 8

6. The Control of Corrosion

Ten pounds of sodium chromate or a nitrite-borate mixture added to 1,000 gal of water provides good corrosion protection for closed systems. If a domestic hot-water heat exchanger is used, provision must be made to prevent the chromate or nitrite from being syphoned into the potable supply.

IV. PERFORMANCE

1. Start-up and Shut-down

Place seven pounds of dry softwood sticks (2 x 4 ends are good) mixed with about two pounds of newspaper in the bottom of the combustion can. Start the ID fan. Drop a lighted newspaper into the can. A fire will be established at once.

Add stick wood (the amount will depend upon the weather, the temperature of the storage, and the heat loss characteristics of the building). Close the air tight cover and turn on the forced draft fan. The unit will now operate at steady state for about two hours if forty pounds of wood are added.

The secondary air damper position is "open" during start-up when the large surface area of kindling demands much air. After ignition the damper can be changed to a "run" position. The setting will depend upon the surface area of the wood, wood moisture, chimney height and ID fan characteristics. If the wood is very dry and finely divided (small scrap from a wood working shop for example) the pyrolysis process may proceed faster than air can be supplied. The fuel-rich, air-lean condition will reduce the combustion rate and slow the pyrolysis process. The constant forced air supply will soon return the combustion zone to the stoichiometric state. The result: a small "bump" will occur forcing combustion products back through the secondary air port. A pad of coarse steel wood should be placed in this pipe to act as a flame suppressor.

An open-on-temperature-drop thermostat in the stack can shut off both fans when the stack temperature falls below 250°F.

Figure 9 and 10 show a stick after about forty minutes in the combustion chamber. The length is about half the original length. Note that pyrolysis is confined to the refractory zone.

Figure 9

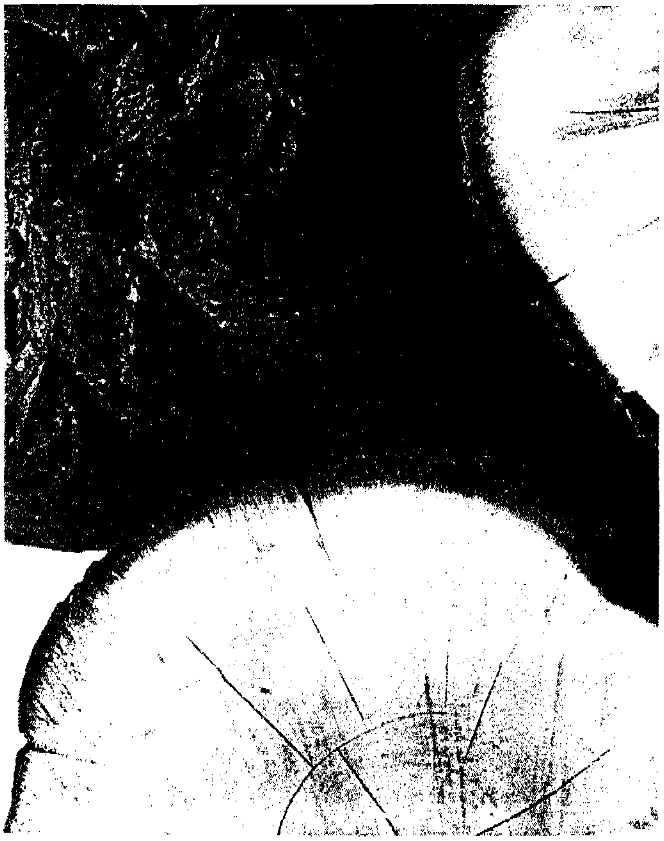


Figure 10

2. Efficiency

The energy content of each pound of bone dry wood is close to 8,600 Btu. If the energy of the stack gas can be determined, then the difference is the energy release rate:

1. "input" for each lb of dry fiber 8,600
2. stack energy for each lb of dry fiber including the steam associated with the initial wood moisture XXXXX
3. difference is gross output . . . . YYYYY

If combustion is complete, stack gas consists of oxygen (from the excess air), water vapor, carbon dioxide and nitrogen. The energy of these gases is a function of temperature alone; hence item (2) above can be calculated. Chapter VII explains these calculations in detail.

Chapter VI describes the tests that lead to the assumption of complete combustion. Figure 11 is an efficiency map of seven tests (thirty percent moisture wood - wet basis). All eighty data points fall within the shaded zone. Start-up (A) tends to have low stack temperature because the refractories and heat exchanger are cold; and low excess air because the kindling has much surface area and combustion tends to be close to stoichiometric. The bulk of the running time is in zone (B). Zone (C) is the shut down condition. The surface area of the wood tends to be low and excess air tends to be high. Prompt shut down is necessary to avoid losses associated with pulling much excess air through the refractories and heat exchanger.

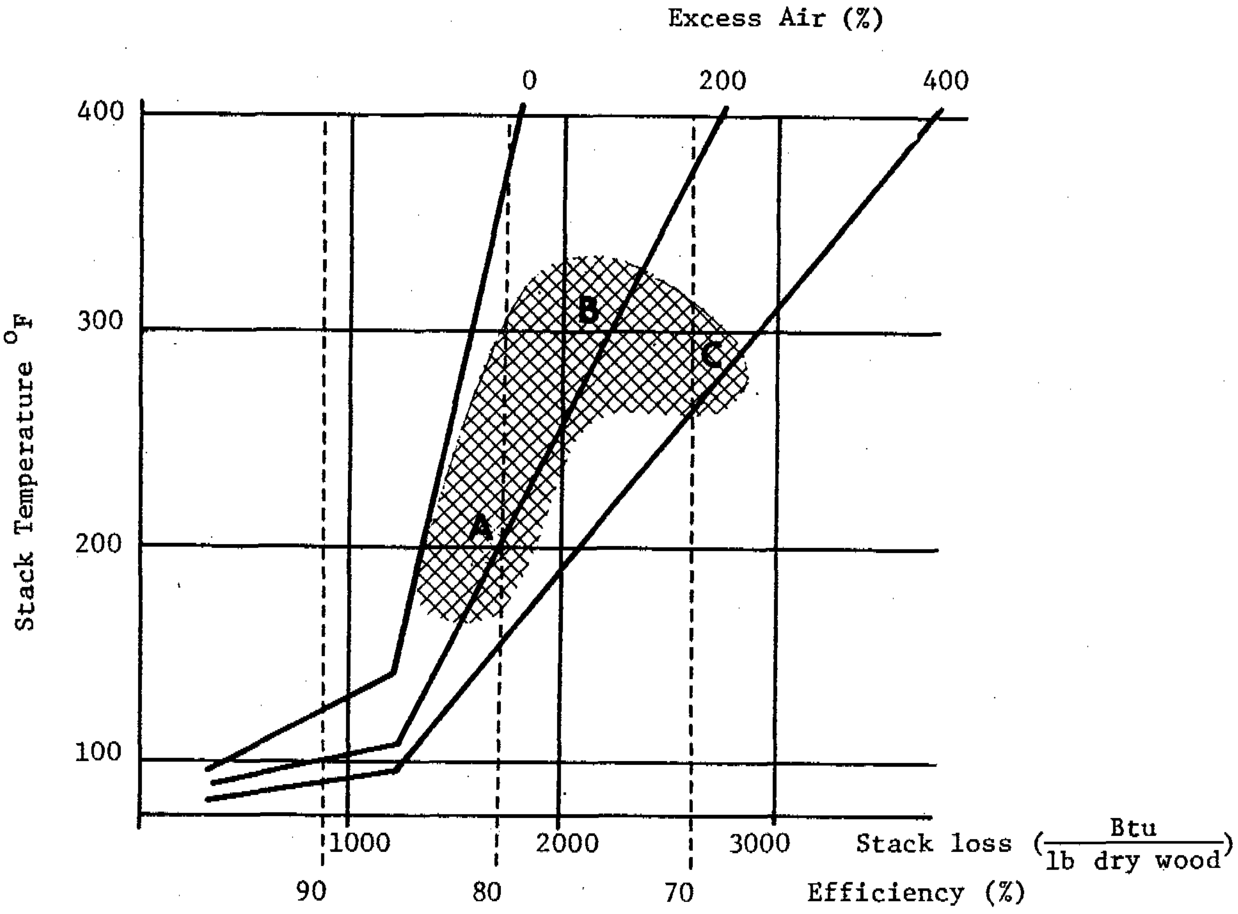
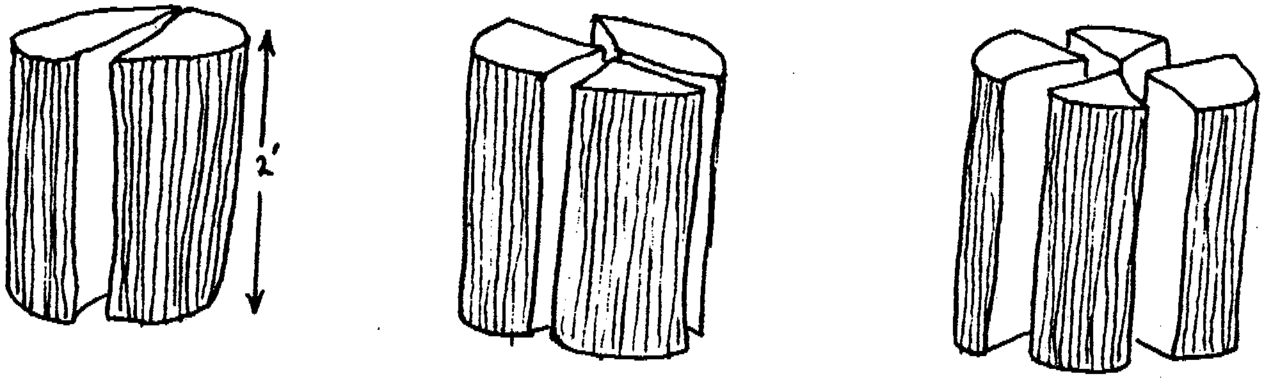


Figure 11

With an induced draft fan very low stack temperatures are possible. The 300$^+$ stack temperature reported here is a practical lower limit. At 300°F there is sufficient stack bouyancy to purge smoke from the system in the event of a power failure. The "knee" of the excess air lines at stack temperatures between 95°F and 135°F reflect the dew point of the combustion gas.

3. Wood Arrangement

Figure 12 indicates satisfactory wood arrangements; Figure 13 unsatisfactory arrangements. The single unsplit log will burn if introduced into already hot refractory, but with the efficiency penalty of high excess air. The pine slab wood exposes too much surface and fuel-rich, air-lean "bumping" will result.



2, 3, 4 or 5 sticks

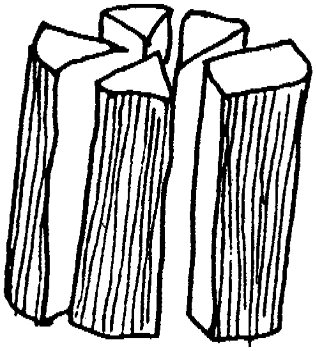
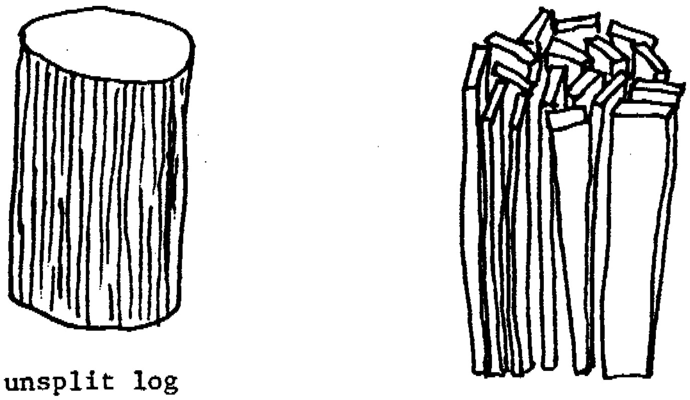


Figure 12

Optimum Wood Configurations



unsplit log

pine slabwood

Figure 13

The key to constant-output combustion is the mode of stirring air entry.

If the wood burns to a point as shown in Figure 14, the surface area exposed decreases and output will fall. If the air can be introduced to force an "hourglass" combustion pattern (Figure 15) the stick will break off and drop fresh wood into the combustion zone. This will hold the output constant from first ignition to final burnout. A one-inch pipe with ten 1/4" holes as shown in the photographs (see Figure 4) worked well.

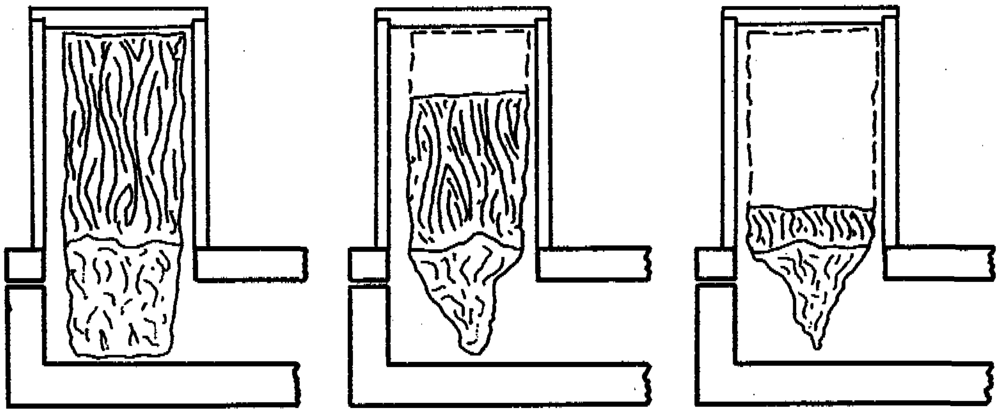


Figure 14

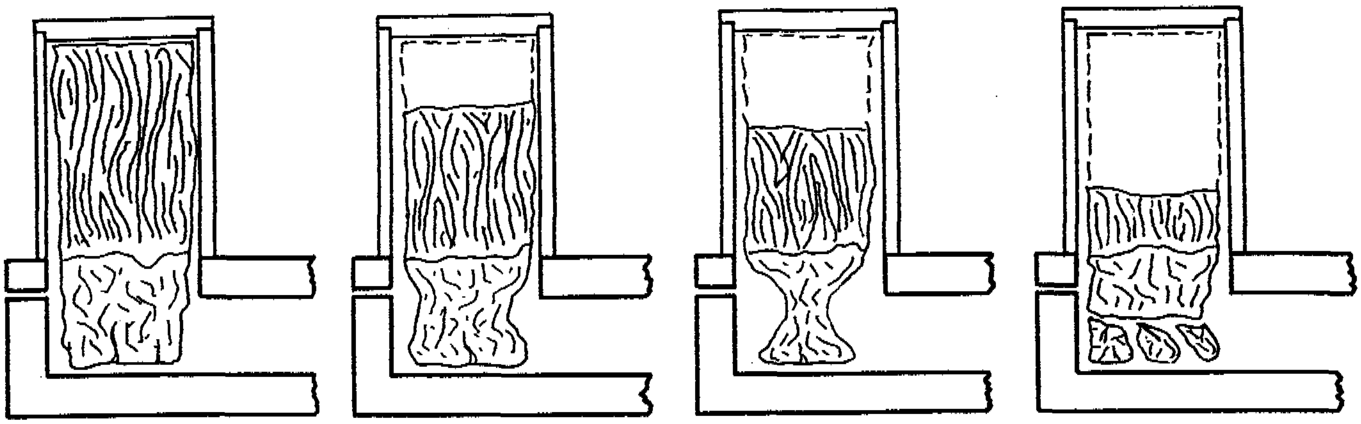


Figure 15

4. The Thirteen Hour Test

Figure 16 shows performance data for a 13 hour test. The wood was 27% moisture (wet basis) and the "wood charged" includes this moisture. The "temperature outside the refractory" is in the vermiculite base that surrounds the refractory. The "tunnel temperature" was measured by an unshielded thermocouple in the tunnel. City water was passed through the storage tank. The output (about 100,000 Btu/hr) was measured from the flow rate of this water and its temperature rise. No insulation was used. Between the 3rd hour and the 10th hour 180 lb of wood were added. The energy gained by the circulating water was 700,000 Btu. The "as fired" wood energy is about 6,000 Btu/lb. The efficiency based on this data is about 65%. The difference between this efficiency and the 70-80% reported earlier is the heat loss from the uninsulated tank, combustion can, heat exchanger, etc.

As a new batch of wood is added the CO_2 will rise - new wood has a greater surface and with a fixed air supply the combustion tends to approach stoichiometric. This increase in combustion rate does not tend to be reflected in an increase in stack temperature. The moisture in the "green charge" will absorb the added energy release. The eratic tunnel temperature reflects the irregular way the wood drops due to the "hourglass" geometry of a burning log and its subsequent fall into the refractory zone. Figure 17 shows the experimental facility.

5. Green Wood

Several attempts were made to burn green fir (60% moisture wet basis) without success -- the fire simply went out. When mixed with some dry (30% moisture) hard wood, however, it burned satisfactorily (Maine has several hundred thousand acres of bud worm damaged fir -- an immediate use for this material would be helpful).

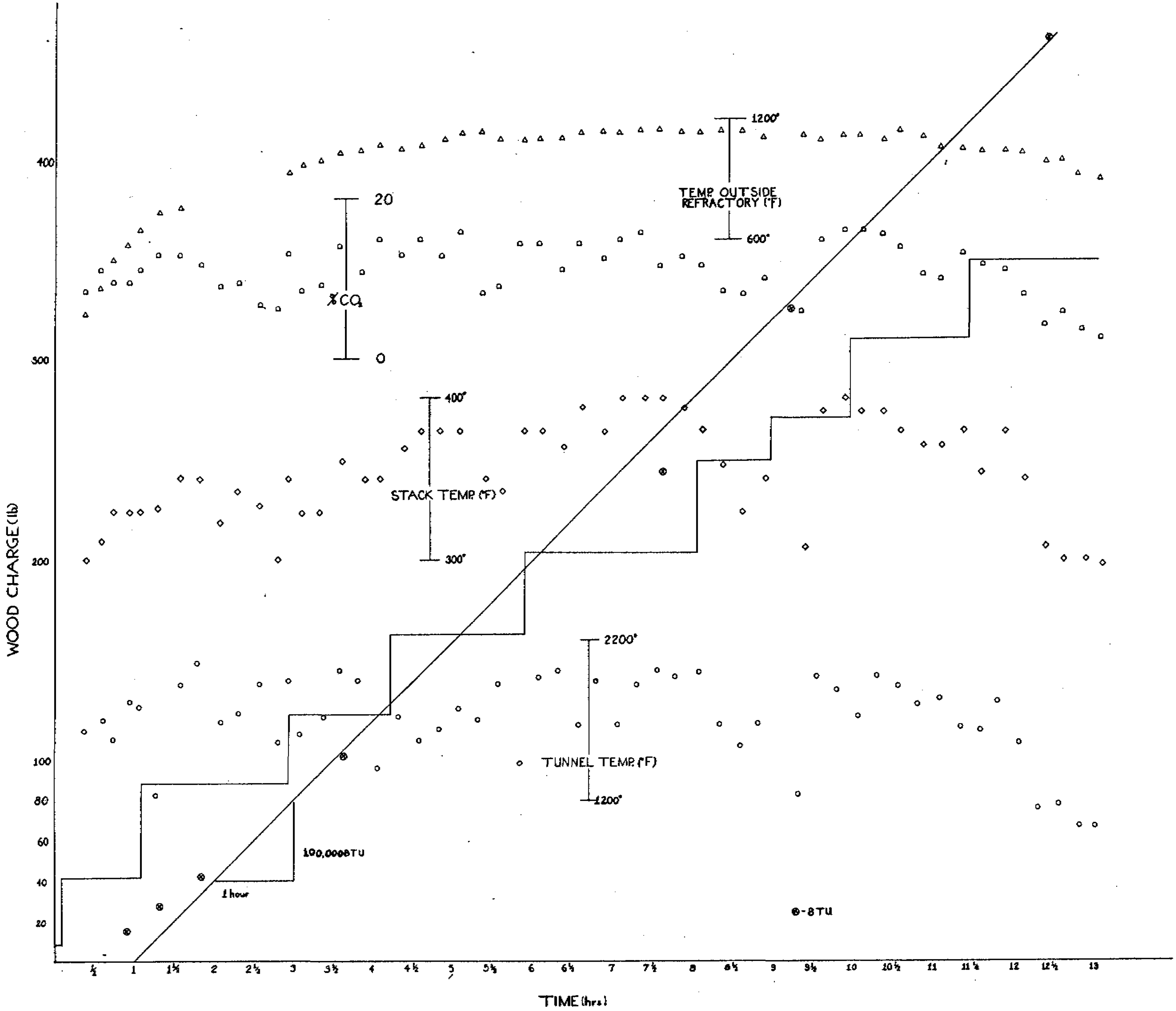
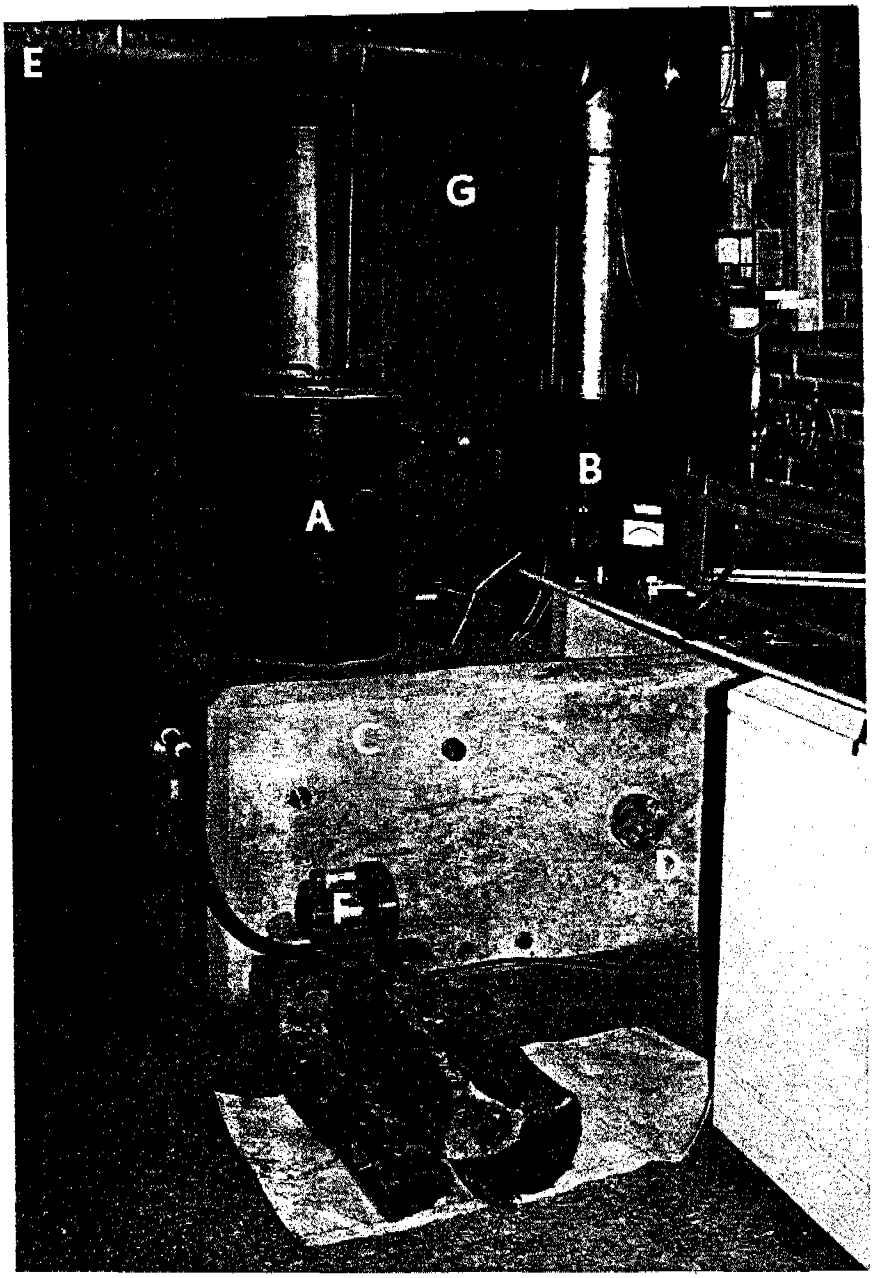

WOOD CHARGE (lb)
400
300
200
100
80
60
40
20
TIME (hrs)
½
1
1½
2
2½
3
3½
4
4½
5
5½
6
6½
7
7½
8
8½
9
9½
10
10½
11
11½
12
12½
13
TEMP. OUTSIDE REFRACTORY (°F)
1200°
600°
% CO₂
20
0
STACK TEMP. (°F)
400°
300°
TUNNEL TEMP. (°F)
2200°
1200°
100,000 BTU
1 hour
⊗-BTU

Figure 16



A - combustion can
B - heat exchanger can
C - vermiculite case
covered with BLOCKBOND
D - ash cleanout
E - to ID fan
F - FD fan
G - storage tank

Figure 17

V. SCHEMES AND DEVICES ATTEMPTED AND REJECTED

1. Several all-refractory combustion chambers were tried. The hope: if the chamber could be air-tight the wood storage zone could be kept fuel-rich and air-lean so that combustion could take place only in the bottom zone where the air is supplied. But the temperature rise in the storage area became so high that pyrolysis proceeded uncontrolled. Steady state burns could not be achieved.

2. The obvious advantage of using one fan was tried. The forced draft was omitted and all charge air was pulled into the combustion zone by the ID fan. The fire burned in a traditional wood stove mode: yellow smokey fire, heat exchanger deposits, etc. The high velocity stirring of the FD fan seems essential.

3. Again a single fan was tried. A Quick Draft (P.O. Box 1353, Canton, Ohio) model 05CA-1/2 blower-venturi combination was installed. The venturi aspirated the stack gas; a bleed from the fan became the charge air. The fan required about 1,000 cfm to provide the necessary venturi action. The penalty in noise, power consumption, and added building infiltration load was deemed too great.

4. Using a hot water system restricts the theoretical lower limit of stack temperature to the temperature of the water. A stack-gas-to-charge-air heat exchanger was tried, but the small increase in efficiency did not justify the complexity and pressure drop.

5. The desire for simplicity would suggest that the base be made of appropriate fire brick with the heat exchanger and combustion can placed on top. The units constructed this way could not be maintained sufficiently air tight to prevent uncontrolled dilution of the burning gas. The vermiculite case provides an expansion cushion and a cool envelope that can be sealed against air leakage.

6. The use of outside air for combustion was abandoned. The unit uses about 2,000 ft^3/hr for 100,000 Btu/hr. A home may have 10,000 ft^3; the furnace charge air is only a small fraction of the necessary building ventilating air; therefore nothing is gained by pulling this air in from outdoors.

7. Round wire brushes were used in the fire tubes as turbulators. The performance was satisfactory, but cost and projected life were unsatisfactory.

VI. EVIDENCE OF COMPLETE COMBUSTION

1. Smoke Spot Testing and Visual Observation

Tar, pitch, creosote, and soot give wood smoke its characteristic blue-gray color. The furnace produces blue-gray smoke only during the first 10 to 20 minutes after start-up. Once the refractory becomes hot, visible emissions cease.

A Bacharach True-spot smoke tester was used and results compared to an oil burner smoke scale. The smoke scale meets ASTM D 2156-63T. Number 0 is whitest and number 9 is blackest. During cold start-up, 10 to 20 minutes after lighting the fire, the smoke spots ranged between 4 and 8. For comparison, traditional wood stoves will produce smoke ranging from 4 to 9.

2. Chimney Condensate Carbon Analysis

Samples of stack gas were cooled to $70^{\circ}F$ and condensibles collected. The liquid was analyzed for carbon content.

The total carbon content of the condensate was 3200 ppm or 0.3%. Of this, 5 ppm was inorganic carbon[5].

Acetic acid (CH_3COOH) and formaldehyde (HCHO) are two pyrolysis products expected in the condensate. If all of the carbon in the condensate were in acetic acid, the sample would contain 0.7% acetic acid. If all of the carbon in the condensate were in formaldehyde, the sample would contain 0.8% formaldehyde.

Of course, the carbon is not all contained in acetic acid or formaldehyde, but the above supositions lead to the conclusion that the condensate contains only about 1% carbon containing compounds. The rest is presumed to be water.

3. Gas Chromatography and Infrared Photospectroscopy Analysis[6]

A stack gas sample was examined by gas chromatography and infrared photospectroscopy. The results:

CO	0.21% by volume
CH_4	0.00% by volume

4. Distillation of Stack Condensate

The samples were distilled according to ASTM E 133-71. Ninety seven percent was collected at $100^{\circ}C$ and presumed to be water.

5. Orsat

Several determinations with the Orsat apparatus indicated less than 1% CO.

VII. THE CHEMISTRY OF COMBUSTION

Two traditional methods are used to determine the efficiency of radiant and convection wood burning stoves and furnaces:

1. calorimeter room; and
2. stack loss.

In the case reported here, the large water storage makes the use of the calorimeter room impossible. A more convenient method is to simply pass city water through the unit and down the sewer -- the flow and temperature rise is a measure of the output. The results of this test are reported on page 13. The material that follows describes the stack-loss method and assumes wood to consist of:

50.9%	carbon
6.6%	hydrogen
42.5%	oxygen

This assumption is based on Table I, which shows the elemental content of various woods found in Maine. Table II shows some typical heating values for oven dry wood. The average heating value was taken to be 8600 Btu/lb dry wood.

The error attributed to using these average values is very slight. Suppose white cedar, having 20% moisture content on a wet basis, is burned at 100% excess air with a stack temperature of 320°F. The computed values based on the actual composition and energy content of white cedar do not vary significantly from the computed values based on the average chemical composition and energy content assumed previously. The error in computing the efficiency is only .35%.

	Correct values for white cedar	Average values based on this paper
MW (wet	28.81	28.79
MW (dry)	30.03	30.05
Molar percentage stack CO_2	9.018%	8.872%
Molar percentage stack O_2	9.484%	9.450%
Stack loss	1675	1741
Efficiency	80.05%	79.74%

TABLE I

TYPICAL ANALYSIS OF DRY WOOD

	Percent by Weight					
	Carbon, C	Hydrogen, H_2	Sulfur, S	Oxygen, O_2	N_2	Ash
HARDWOODS						
Ash, white	49.73	6.93	- -	43.03	- -	0.30
Beech	51.64	6.26	- -	41.45	- -	0.65
Birch, white	49.77	6.49	- -	43.45	- -	0.29
Elm	50.35	6.57	- -	42.34	- -	0.74
Hickory	49.67	6.49	- -	43.11	- -	0.73
Maple	50.64	6.02	- -	41.74	0.25	1.35
Oak, black	48.76	6.09	- -	44.98	- -	0.15
red	49.49	6.62	- -	43.74	- -	0.15
white	50.44	6.59	- -	42.73	- -	0.24
Poplar	51.64	6.26	- -	41.45	- -	0.65
SOFTWOODS						
Cedar, white	48.80	6.37	- -	44.46	- -	0.37
Cypress	54.98	6.54	- -	38.08	- -	0.40
Fir, Douglas	52.30	6.30	- -	40.50	- -	0.80
Hemlock, western	50.40	5.80	0.1	41.40	0.1	2.20
Pine pitch	59.00	7.19	- -	32.68	- -	1.13
white	52.55	6.08	- -	41.25	- -	0.12
yellow	52.60	7.02	- -	40.07	- -	0.31
Redwood	53.50	5.90	- -	40.03	0.1	0.20

Source: Wood Energy Systems, State-of-the-Art and Developing Technologies. Presented at the Future of Wood as an Energy Source, Gorham, ME, June 20-23, 1976, Dr. J. H. Fernandex, Coordinator, Environmental Control Systems, Combustion Engineering, Inc.

TABLE II

TYPICAL HEATING VALUES OF OVEN DRY WOOD[1]

SPECIES	WT/CORD[2]	BTU/LB	BTU/TON	BTU/CORD[2]
White Ash	4034	8920	17,840,000	35,983,280
Fir Balsam Bark		9100	18,200,000	36,400,000
Yellow Birch	4121	8650	17,300,000	35,655,300
Yellow Birch Bark		9870	19,740,000	
White Cedar	2236	8400	16,800.000	18,782,400
Elm Bark		7600	15,200,000	
Eastern Hemlock	2722	8620	17,240,000	23,463,640
Eastern Hemlock Bark		8890	17,780,000	
Red Maple	3460	8580	17,160,000	29,686,800
Red Maple Bark		8190	16,380,000	
Oak (white)	4433	8810	17,620,000	39,063,540
Pine (yellow)	3917	9610	19,220,000	37,642,370
Pine (white)	2352	9000	18,000,000	21,168,000
Pine (white) Bark		8930	17,860,000	
Poplar	2187	8920	17,840,000	19,516,960
Poplar Bark		8810	17,620,000	

1) Source: Bulletin 1176 Forest Fuels, Inc.

2) A cord is a 4' x 4' x 8' pile of wood and is estimated to contain about 85 cubic feet of wood, the remaining volume being air space.

The stoichiometric equation for burning 100 lb of wood in air is:

$$\left[4.24C + 3.3H_2 + 1.33O_2\right] + nH_2O + Y\left[O_2 + 3.76N_2\right] \rightarrow \left[3.3 + n\right] H_2O + 4.24CO_2 + 3.76Y\ N_2 + \left[Y - 4.56\right] O_2$$

where n is the number of moles of free water associated with 100 lb of dry wood, and Y is the number of moles of air supplied for each 100 lb of dry wood. Air contains 3.76 moles of N_2 for each mole of O_2.

An oxygen balance reveals that 4.56 moles of O_2 are required for complete combustion of 100 lb of dry wood -- all carbon to carbon dioxide and all hydrogen to water.

Excess Air (EA) is defined as the percent ratio of extra air to stoichiometric air. Since oxygen is in direct proportion to total air, the number of moles of oxygen (X) supplied will fix the amount of excess air:

$$EA = \frac{X-4.56}{4.56} \times 100\% \text{ or } X = 4.56\left[\frac{EA}{100}\right] + 1$$

The moisture content of wood on a wet basis is defined as the weight of the water in a piece of wood divided by the total weight of the wood and the water.

If the water in the products of combustion is condensed and extracted, the remaining gas is called dry flue gas. The mole fraction of each constituent of the dry flue gas is independent of the moisture content of the wood.

Putting the derived expression for X into the formula for dry flue gas yields:

$$4.24\ CO_2 + 17.1\left[\frac{EA}{100} + 1\right] N_2 + 4.56\ \frac{EA}{100}\ O_2$$

This equation represents the number of moles of product for each 100 lb of dry wood burned. The molar percentage of a constituent gas is the ratio of the number of moles of that constituent gas divided by the total number of moles present in the mixture. The products are at sufficiently high temperature and low pressure to be treated as ideal gasses. The molar percentage of each constituent is therefore equal to its volume percentage.

$$yCO_2 = \frac{4.24}{4.24 + 17.1\left[\frac{EA}{100} + 1\right] + 4.56\ \frac{EA}{100}} \times 100\%.$$

Similarly, the molar percentage of oxygen in dry flue gas is:

$$yO_2 = \frac{4.56\ \frac{EA}{100}}{4.24 + 17.1\left[\frac{EA}{100} + 1\right] + 4.56\ \frac{EA}{100}} \times 100\%$$

From these two equations, the relationship between CO_2, O_2 and excess air can be shown (see Fig. I-1).

To determine the efficiency of the wood furnace, the volume percentage of CO_2 in the stack was measured using a Bacharach Firite instrument. The amount of excess air was then determined using the above graph.

The stack-loss-efficiency curves were developed by adding up the energy above 77°F:

1. Excess air (oxygen and nitrogen)
2. Moisture content of the wood
3. Water vapor formed by burning hydrogen
4. Carbon dioxide.

This energy is the loss to be subtracted from 8600 Btu/lb of bone-dry wood. Minor factors which were neglected are:

1. Moisture in the air
2. Ash content of the wood.

Specific heats were taken from gas tables at 300°F. The stack loss above 77°F for each pound of wood burned is:

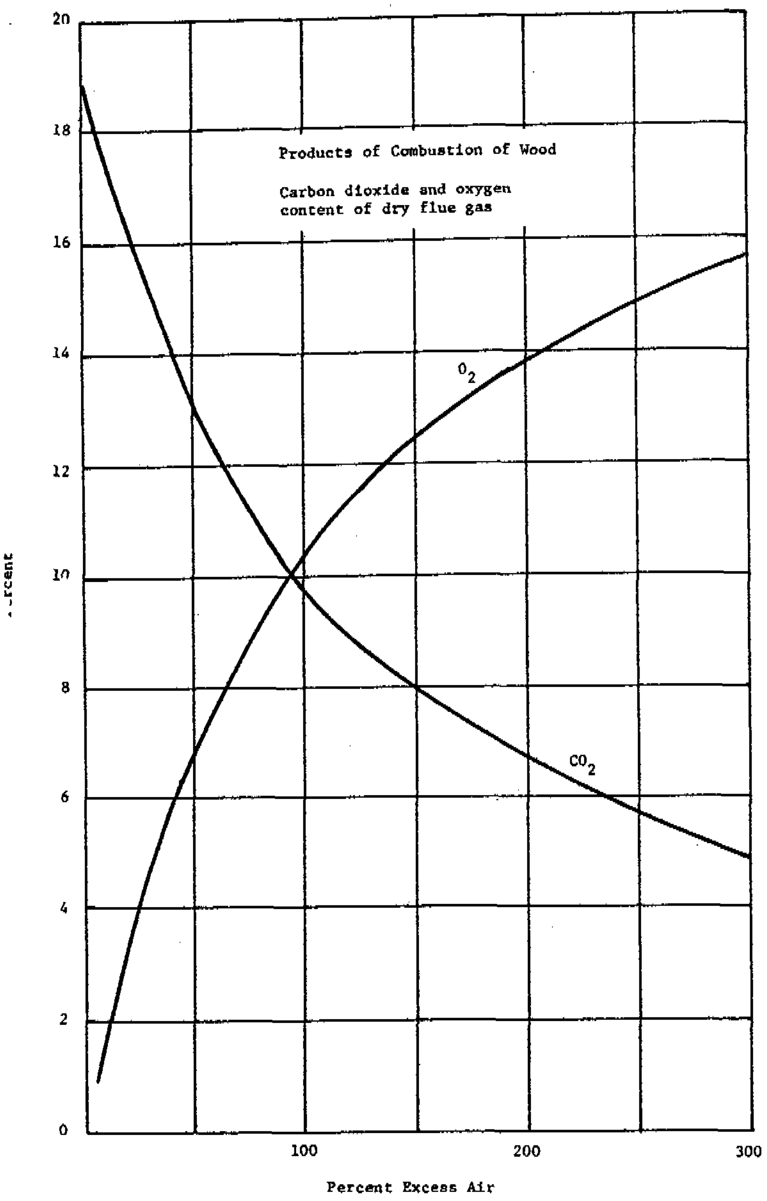
$$\text{loss} = \Delta H_{CO_2} + \Delta H_{N_2} + \Delta H_{O_2} + \Delta H_{H_2O}$$

$$\Delta H_{gas} = \bar{n}_{gas} \bar{C}_{P_{gas}} \quad (\text{stack temperature} - 77)$$

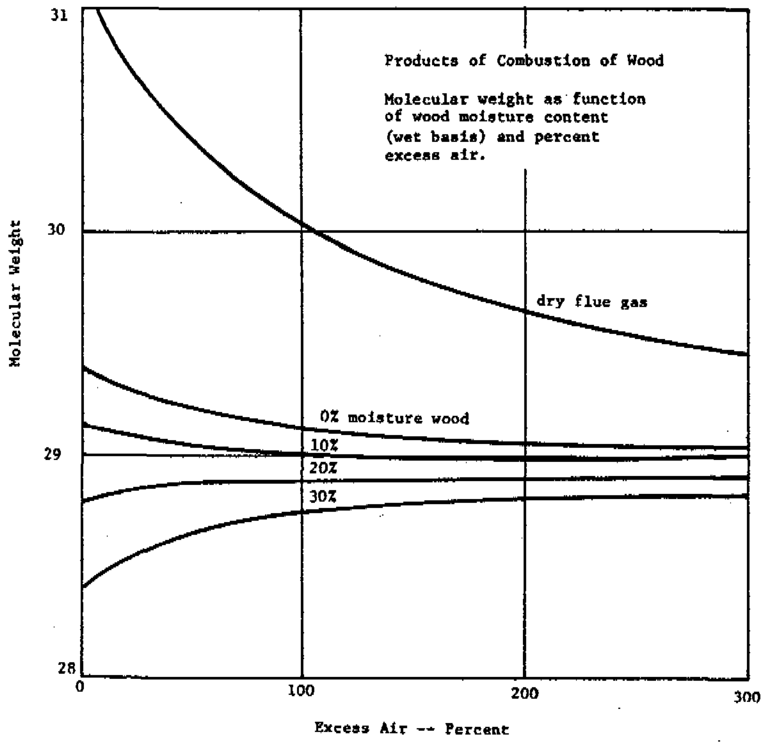
$$\Delta H_{H_2O} = \bar{n}_{H_2O} \quad (h_{stack} - h_{77^\circ F})$$

$$\text{Efficiency} = \frac{8600\ \frac{Btu}{lb} - \text{loss}\ \frac{Btu}{lb}}{8600\ Btu/lb}$$

I-1

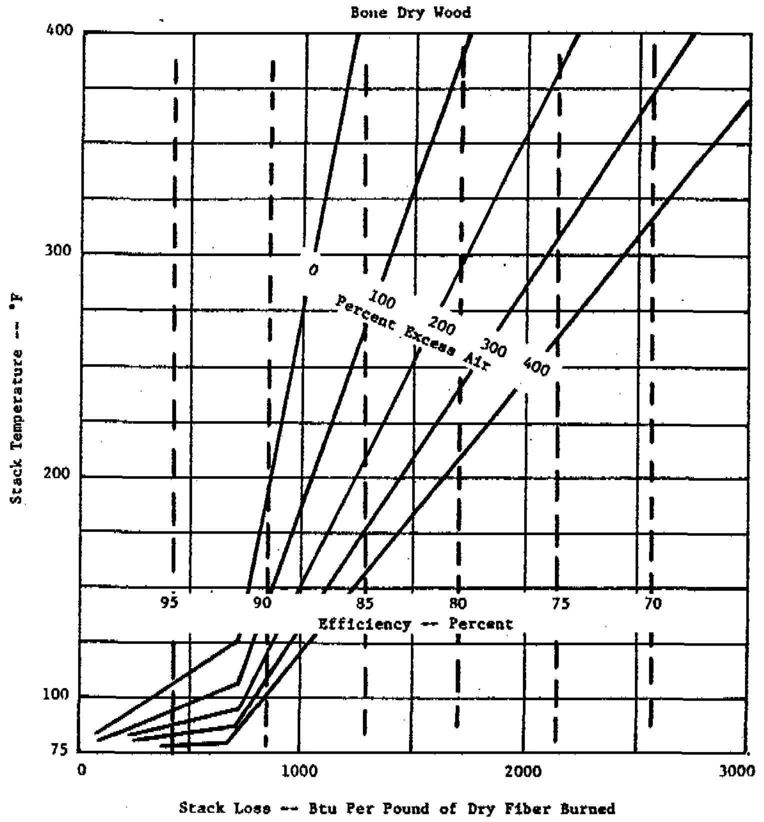

Products of Combustion of Wood
Carbon dioxide and oxygen content of dry flue gas
O_2
CO_2
..rcent
0
2
4
6
8
10
12
14
16
18
20
100
200
300
Percent Excess Air

I-2



I-5

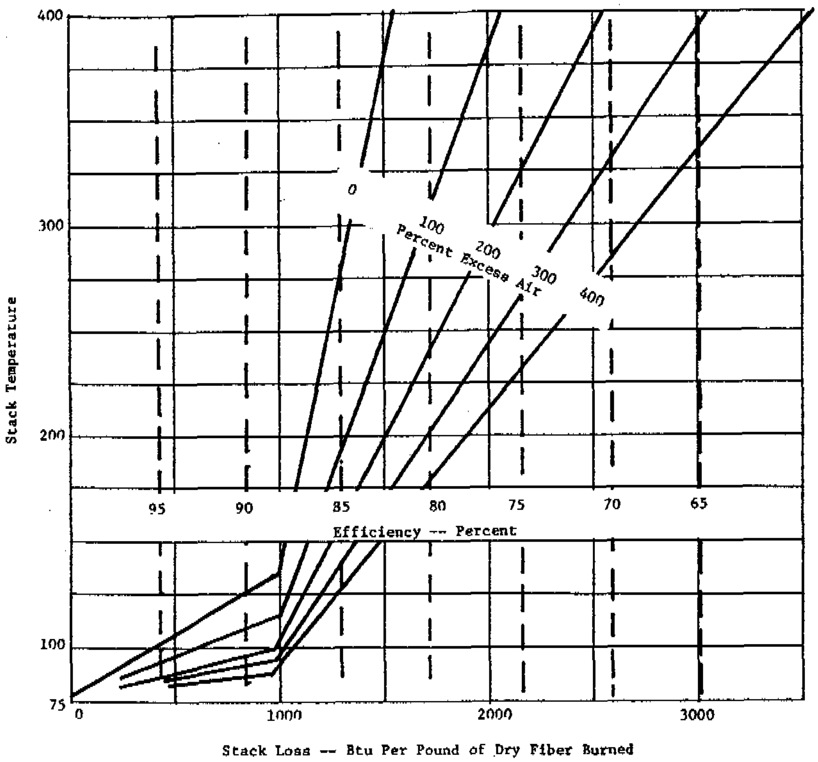
The Efficiency and Stack Loss from the Complete Combustion of wood as a Function of Stack Temperature and Percent Excess Air.



I-6
(Corrected)

The Efficiency and Stack Loss from the Complete Combustion of Wood as a Function of Stack Temperature and Percent Excess Air.

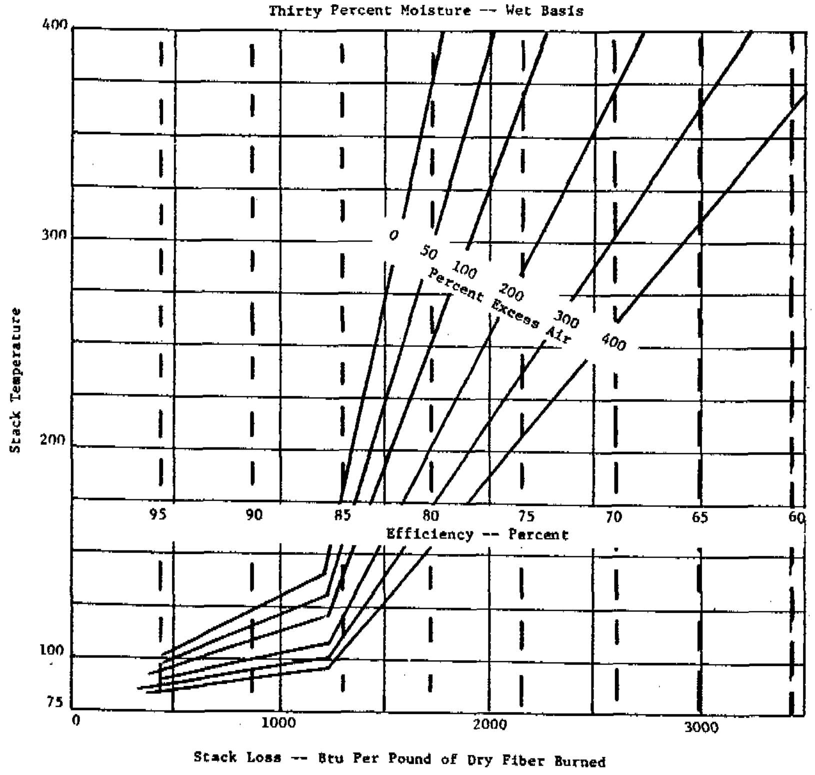
Twenty Percent Moisture -- Wet Basis



I-7

The Efficiency and Stack Loss from the Complete Combustion of Wood as a Function of Stack Temperature and Percent Excess Air.

Thirty Percent Moisture -- Wet Basis



APPENDIX

VERMICULITE CONCRETE AND REFRACTORY

1. Introduction

The case of the UMO furnace is cast of vermiculite concrete. Vermiculite is a mineral containing mica, which, as mined, has a laminated structure with combined water. During manufacture the material is heated; the combined water turns to steam, providing an expanded light-weight aggregate.

Vermiculite aggregate can be used along with conventional aggregate to make concrete having a density ranging from 15 to 90 lb/ft^3.[1] The "R" value* of vermiculite concrete increases with decreasing density and can range from 0.3 to 2.0 as compared to normal weight concrete which has a density of around 120 lb/ft^3 and an "R" value of about 0.1. The compressive strength of the concrete is directly proportional to the density.[2]

2. How to Mix Vermiculite Concrete

The vermiculite aggregate was mixed to meet ASTM C332-66 standard specification for light-weight (no conventional aggregate -- all vermiculite) insulating concrete. Vermiculite is available through masonry suppliers or through W. R. Grace and Co., 62 Whitemore Ave., Cambridge, MA 02140 and is available in five grades. Expanded #1 is the coarsest and expanded #5 is the finest.

Expanded #3 aggregate may be used or, if #3 is unavailable, expanded #1 and #5 may be mixed. If #1 and #5 are to be used, the #1 aggregate must first be passed through a #4 (1/4" opening) U.S. standard sieve to break up the largest pieces. The large pieces are easily pushed through the mesh by hand or with a block of wood.

The proportions are: 8 parts vermiculite; 1 1/2 parts Portland cement; and 3 1/2 parts water. Following is the procedure for mixing a batch:[3]

1. Mix equal volumes of sifted #1 and #5 aggregate or, if available, use #3 aggreate.
2. Place half the water into the mixer.
3. Add all the cement and mix to a thin, soup-like consistency.
4. Add the vermiculite. The mix will become dry as the vermiculite absorbs water.
5. Add additional water and 2 oz of air entraining agent (available at any ready-mix concrete plant) until the mix becomes workable (the consistency of shaving cream is about right). This must be done slowly and carefully -- the material can become too soupy if care is not taken.

Above 1000°F Portland Cement bonded concretes rapidly lose strength.[4] The free lime released on firing can cause crumbling when the concrete is submitted to thermal cycling with intervening periods of moist air. The best combination of refractory material and vermiculite concrete will not be known until tens of thousands of hours are accumulated on production units. At this time the recommendation is:

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* $\frac{hr\text{-}ft^2\text{-}^{\circ}F}{Btu\text{-}in}$

1. Two-inches Plicast 27 around the combustion chamber.
2. One-inch Plicast around the tunnel.
3. Two-inches LWI-20 under the heat exchanger.
4. All the rest, vermiculite concrete.

3. Refractory Characteristics

(Plibrico Company, 1800 Kingsbury St., Chicago, Ill. 60614)

Property	Plicast 27	LWI 20
Recommended service range	200-2500°F	200-2000°F
Weight	120 lb/ft^3	52 lb/ft^3
Thermal conductivity (1500°F) $\frac{\text{Btu-in}}{\text{hr-ft}^2\text{-}^o\text{F}}$	5.7	1.7

NOTES

1. ASTM C332-66 Standard Specifications for Lightweight Insulating Concrete.
2. Design and Control of Concrete Mixtures, 11th ed., Portland Cement Association, 5420 Old Orchard Rd., Skokie, Illinois, 60076. Pp 90, 101.
3. Zonolite Brand Vermiculites, Properties and Uses. W. R. Grace and Co., Construction Products Division, 62 Whittemore Avenue, Cambridge, MA, 02140.
4. Refractory Concrete, Publication SP-57 Am. Concrete Institute. Detroit
5. Loundsbury, A.K., Department of Civil Engineering, University of Maine, in correspondence with Richard C. Hill, March 14, 1979.
6. Wolfhagen, J.L., Professor of Chemistry, University of Maine, in correspondence with Richard C. Hill, July 30, 1979.
7. Shelton, J.W., Black, T., Chaffee, M. and Schwartz, M. Wood Stove Testing Methods and Some Preliminary Experimental Results, ASHRAE Transactions, Vol. 48, Part 1, 1978. At-78-1, No. 2.
8. Shelton, J.W., The Woodburners Encyclopedia, Vermont Crossroads Press, Waitsfield, Vt., p. 58 and Appendix 4.
9. Cassiday, M. An Analysis of the Stack Energies from the Complete Combustion of Wood, Dept. of Mechanical Engineering, University of Maine, Orono, ME, 04469, Dec. 6, 1978. Dist. by Dept. of Industrial Cooperation, University of Maine.