FIREPLACE ANALYSIS FOR EFFICIENT FUEL CONVERSION AS AN AUXILIARY SYSTEM FOR SPACE HEATING

by

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CHAPTER ONE: INTRODUCTION

The story of humanity relates that the earliest generations of man used wood to cook their food and heat their homes. Wood is the oldest source of heat used by man.

With the advent of fuel shortages, man is again trying to exploit wood as a fuel source. Demand for this fuel has become so intense, particularly in Third World countries, whereas much as 90 percent of the population use wood for cooking and heating, that vast tracts of land have been literally picked clean of every tree, root, and twig...and the resulting erosion is rendering thousands of formerly fertile ground completely useless for food or timber production.[1] This demand largely stems from the fact that wood is still being burned in primitive stoves following outdated traditional practices. The result is the inefficient use of fuel wood, producing large consumption with very low output and subsequent wastage.

This wastage is further reflected in this country by the widespread usage of inefficient fireplaces for space heating. Since the hard-felt energy crunch, thousands of these devices have been brought back into use expecting to supply a large percentage of the heating demands while actually having no affect and sometimes adding to the overall heating demand.

Whether it is a question of exploiting the source of energy represented by fuel wood or of helping it retain its place in competition with other fuels or to employ it economically and at the same time to

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[1] World Watch Institute, 1976.

conserve the forests, the problem in the final analysis is the same, namely, to use the heating power of wood to the utmost.

The way to do so is clear. It calls for improving the technique of woodburning and to use the heat so released, whether to warm rooms or buildings in the best possible way. To achieve this, fireplaces must be redesigned to effectively extract the heating potential from a given amount of wood and to distribute this heat to effectively climatize a space.

The scope of this study begins with the description of wood as a fuel source, i.e., what are the ecological implications of suggesting wood as a fuel source. Secondly, the principles surrounding the effective combustion of wood are explored, as well as using this criteria to develop a fireplace unit that is capable of efficient heat extraction and distribution. Finally, ways are suggested in which wood can be used as an auxiliary fuel source to a solar system.

CHAPTER TWO: WOOD AS A FUEL SOURCE

2.0 Wood as a Natural Resource

In an environmentally conscious age facing resource scarcity, wood has many advantages as a raw material. Wood, from productive sites, is a renewable resource; it can be converted to usable products with a small amount of energy (compare, for instance, the energy required to produce a wooden beam and one made of aluminum); wood is biodegradable, if you dispose of a piece it will decay; wood can possibly be burned without putting any unnatural substances into air or water resources; it can be recycled, in fact, paper is one of the few commodities which has regularly been recycled apparently profitably, even in our throw-away economy. Wood, both new and in recycled form, can be converted into a vast variety of useful products for construction, for clothing and other fiber uses, for paper and for containers. It also has potential value as a feedstock for chemicals. Chemicals derived from wood were more common in the past than they are today, but demand for wood for this purpose is likely to rise, since fossil fuels are now the principle source for the chemicals which could be made from wood. Rayon and acetate are now derived from wood, and it is chemically feasible to make most plastics, synthetic fibers, and synthetics from wood.[1]

So it is easy to see that wood is too valuable a material to be used inefficiently and haphazardly as a fuel in any advanced economy.

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[1] Goldstein, I.S. Potential for Converting Wood into Plastics, #189, 1975, p. 847.

2.1 Wood As a Conversion Device of Solar Energy

Each year solar energy, equal to more than 25,000 times the world's present annual power demand, impinges upon the earth's surface; however, the quest for an economical method of tapping this vast supply still awaits a successful conclusion. The difficulty in finding a practical and economically feasible method can be traced to certain characteristics of solar energy, chief of which are:

a) its intermittency,

b) low concentration,

c) limited utility in its directly available form, and

d) the problem of storage.

Nature herself long ago found a method so successful that a vast array of life has been supported for many years and whose ultimate source of energy was and is the sun. This method simply consists of fixing solar energy into the cellular energy of green plants. Thus, green plants are the middleman between us and the sun, passing on to us the energy fixed by them.

2.2 The Photosynthetic Process

Photosynthesis is the process whereby plants convert part of the solar radiation falling upon the surface of the earth into storable, chemical energy. During photosynthesis plants absorb solar radiation of certain wavelengths (principally the blue and red wave lengths of the visible spectrum) and combine this with molecules of water and carbon dioxide and other elements to produce new molecules (principally carbohydrates) that store more energy than the initial ingredients were storing individually. These new molecules can then later be broken down to their original components in order to release the extra energy that was stored in them.

2.3 Conversion Efficiency - Solar Radiation to Chemical

Forest land in the temperate regions captures and converts into organic material about one percent of the incident solar radiation. It has been estimated that the ultimate theoretical efficiency of conversion by photosynthesis reaches about 5.5 percent.[2] (Table 2.0 Efficiencies of Solar Energy)

In comparison a manmade solar cell operates with an efficiency range of 15 to 20 percent. With this simple comparison it would seem that efforts would be better invested in the production of solar cells rather than seeking methods for converting plant material into useful energy.

Such a view reflects a narrow concept of energy conversion efficiency. Our present efficiency-based assessments of performance compares the input/output of one on a few factors and largely disregards their context. For example, the aforementioned effiency factor for the solar cell is the ratio whereby the solar cell can convert incoming solar radiation into electrical energy. The efficiency factor completely disregards the net amount of energy required to produce the cell (which is highly energy intensive) nor the amount of environmental impact from the industrialized process required to

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[2] Gates, D.M. "The Flow of Energy in the Biosphere," Scientific American, September 1971, pp. 89-100.

Table 2.0 Efficiencies of Solar Energy Conversion Systems

	% Efficiency		
	Of Process	To Heat	To Electricity
I. BASIC PHYSICAL CONVERSIONS			
A. STEAM MECHANICAL ENERGY	10-30		
B. MECHANICAL ELECTRICAL			
C. STEAM ELECTRICAL			80 A.xB.=8-25
II. SOLAR-MECHANICAL CONVERSIONS			
A. LOW TEMPERATURE SOLAR			
1. Solar energy hot water		20	
B. HIGH TEMPERATURE SOLAR			
1. Solar heaters, cookers, reflectors		50-80	
2. Solar reflector steam		40-60	
3. "I-C" above			8-25
4. Solar steam electricity			3-15
C. SOLAR ELECTRICITY (PHOTOCELLS)			
1. Cadmium sulfide			5
2. Silicon			12
D. WIND			
1. Wind mechanical	44		
2. "I-B" above			80
3. Wind mechanical electrical			35
III. SOLAR-BIOLOGICAL CONVERSIONS			
A. FOOD CHAINS			
1. Solar energy plant chem energy	0.3-3.0		
2. Plant energy herbivore energy	5-10		
3. Herbivore carnivore energy	5-15		
B. WOOD			
1. Solar energy forest wood	0.5-3.0		
2. Wood heat(steam)		60-80	
3. "I-C" above			8-25
4. Solar steam electrical			.04-.8
C. BIOGAS (DIGESTION)			
1. Solar plant	.3-3.0		
2. Biomass biogas*	40-70		
3. Biogas heat		75	
4. Biogas heat mechanical	25-40		
5. "I-B" above			80
6. Organic waste electricity (via biogas)			.02-.5
D. ALCOHOL (DISTILLATION)			
1. Fruits, grains ethanol	75		
2. Wood ethanol	65		
3. Biomass waste methanol	55		

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*Not including process heat

produce these units.

By the same factor the low efficiency given for the conversion of solar radiation into chemical energy (in the form of plant material) does not reflect the ability of plants to serve as their own energy accumulators, which as long as the plant is still alive, is protected from drastic energy loss through plant deterioration by the plant's natural protective mechanism.

Any accurate comparison between two forms of energy sources should follow the conversion process from the point of origin (be it solar thermal energy, kinetic energy of wind and water, or fossil fuels) through to the end use.

The point being made here is to express a need for a wider-based context in which plant-based technologies could be compared with other technologies.

2.4 Ecological Implications of Wood As Fuel Source (Forest Ecology)

The ideal source of firewood on rural land is a managed woodlot. The obvious useful values of a woodlot are for timber and fuel production, but even a small growth of trees can have considerable ecological benefits as well.

Besides controlling erosion and rejuvenating soil, trees can have an important influence on the micro-climate of land by helping to moderate temperatures and humidity. Winds carry moisture that is lifted by the sun from large bodies of water. This moisture-laden air will move indifinitely or until it reaches a woodland. An amazing amount of water transpires from the leaves of trees, cooling the air and multiplying the cloud cover. To give some idea as to the amount of water that transpires, a single apple tree may move more than 1,800 gallons of water into the air in a six-month growing season. This transpired water vapor rises upward until it meets moisture-laden air and then drops as precipitation. Trees located on hills and mountains offer the best obstruction to clouds and thereby increase the rainfall. Trees also improve the microclimate by filtering particulate matter out of the air. Badly eroded soil can eventually be restored by conifers (leaf-bearing) returning badly needed humus.

According to U.S. government research done by the Lake States Forest Research Station, two identical test houses, one exposed to the winds and one protected by a nominal windbreak were maintained at a constant 70 degree inside temperature. The study concluded that the one having the windbreak protection required 30 percent less fuel.

With the aforementioned assets of a properly managed woodlot, it is easy to see why an indiscriminate use of wood must be avoided. Harvesting trees for firewood as timber requires careful management on a "sustained-yield" basis. This is, removing only enough timber that can be replaced by normal growth in a year. If a woodlot is managed correctly, there should be at least one cord of new wood realized per acre per year. Since at least several acres of sustained-yield forest land are needed to supply firewood for a typical home, this emphasizes that wood is best used in combination with other lasting systems.

There are several alternatives that can be considered other than obtaining wood from sustained-yield woodlots:

a) utilizing wood waste from manufacturing processes,

b) "Energy Plantation Concept" (growing fast-producing plant material as a fuel crop), and

c) utilizing wood in combination with a solar heating system.

Wood is one of the chief raw materials in many industries, and often large quantities of waste are unavoidably produced in the various manufacturing processes. In the sawmill, bark-covered slabs, cut-off defective timber, cross-cuts and sawdust result from the cutting of logs into boards. Factory waste is produced mainly from seasoned timber and consists of sawdust, wood chips, short lengths cut from boards and square stock. Yet another source for wood waste would be from the tremendous volume of solid waste headed for the dump. According to the U.S. Forest Service as much as 30 percent of the debris discarded by a city is reusable wood material. The only problem with the utilization of this wood waste is that it requires specially designed burners.

Throughout the United States there are a large number of waste wood boilers operating successfully. Largely, these installations are at lumber mills where tremendous amounts of energy are required. These plants are burning wood residues which average 9000 BTU/lb and generate enough energy to operate without any supplementary fuel.[3]

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[3] Clark, Peter. "The Energy Plantation: Nature's Own Solar Collector and Storage Cell," Air Conditioning and Refrigeration Business, June 1976, pp. 11-14.

There has been a rising interest in growing high-yielding plants in "energy plantations" and burning the biomass in conventional power plants to generate electricity. In a study conducted by the Intertechnology Corporation, growing energy or "BTU Bushes" was fully explored and the conclusion optimistic.[4,5] Plant matter (biomass) grown in energy plantations can be consumed directly as solid fuels by, for instance, central electric-generating plants. A 64-acre plantation will support between one and two megawatts of generating capacity. Or, the solid fuel can be converted by anaerobic digestion into pipeline-quality synthetic natural gas for distribution within an existing pipeline system. Under this concept fifty million cubic feet of SNG can be produced from a 640-acre plantation. That would be enough gas to heat 500 households every year in an area where average winter temperatures center around 30°F.[6]

There is, however, one major problem with the energy plantation concept; it means that large land areas will be converted into single crop stands (monocultures) which are nortoriously susceptible to disease and pest outbreaks.

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[4] Szego, G.C. and C.C. Kemp. "Energy Forests and Fuel Plantations," Chem Tech, May 1973.

[5] Szego, G.C. and C.C. Kemp. The Energy Plantation, Intertechnology Corporation, P.O. Box 340, Warrenton, Virginia.

[6] Clark, Peter. "The Energy Plantation: Nature's Own Solar Collector and Storage Cell," Air Conditioning and Refrigeration Business, June 1976, pp. 11-14.

Wood could possibly be best utilized as an auxiliary source to a solar heating system. (See Section 4.2) A woodburning device would be coupled to the already existing solar thermal storage system. In this combined relationship, wood would only be used to take over the space heating demands when the temperatures in the storage tank dropped below a usable level. This situation would likely occur during long periods of cloudy or overcast days. Once the immediate space heating needs were met, any excess heat produced by the woodburning device could be transferred to the storage tank for later use.

A woodburning device as an auxiliary source is attractive for several reasons:

a) easily combined with a solar system's heat distribution network;

b) low cost - low maintenance (neither system has to be sized to meet the total heating load);

c) ecologically advantageous;

  1) reduces the amount of wood needed to a minimum,
  2) draws from a renewable resource base,
  3) much lower in pollutants than conventional fuels.

Wood and other proposed biomass fuels offer some outstanding advantages compared to other sources of energy. First and foremost are their renewability. As long as the sun shines and the biosphere remains in balance, wood can be available forever if it is harvested on a sustained-yield basis. Secondly, nature has provided trees and plants with collectors (the leaves with their chlorophyl) and their own energy accumulators (plant material) which, as long as the plant is still alive, is protected from drastic energy loss through plant deterioration by the plant's natural protective mechanisms. Thirdly, the air pollution aspects of wood combustion is virtually superior to all fossil fuels. Wood contains very little sulfur dioxide (SO_2), generally, less than 0.1 percent to .05 percent. Fossil fuels, such as oil and coal, contain 1 to 3 percent sulfur. Sulfur dioxide is a compound which has been linked to various lung diseases and has been found to inhibit the growth rate of plants. Emissions of fossil fuels containing high percentages of this compound necessitates its removal. Fourthly, the use of wood as a fuel will not interfere with the carbon dioxide balance of the earth. Unlike fossil fuels the forest consumes as much carbon dioxide as it will ultimately release when it is burned. The carbon dioxide released when woody material is burned will have been collected during the relatively recent past whereas the combustion of fossil fuels will release CO_2 that was withdrawn from circulation millions of years ago resulting in a CO_2 increase. Carbon dioxide was not normally considered a pollutant at all. It has been recently theorized that if the concentration of carbon dioxide in the atmosphere changes significantly, the climates of the earth may change. Carbon dioxide is a relatively good absorber of infrared radiation coming from the earth's surface. As a result, increasing the amount of carbon dioxide in the atmosphere tends to inhibit infrared radiation from leaving the earth. This natural effect ("greenhouse effect") is worsened by the addition of CO_2 from fuel combustion because the extra CO_2 absorbs more solar rays than would be absorbed in the absence of combustion.

Some of the consequences of temperature rise of the earth might include:[7]

1) a shift in global circulation patterns altering temperatures of land masses,
2) altering precipitation patterns, and
3) flooding of land masses due to rising sea levels from the melting of polar regions.

No one should draw the conclusion that by-products of wood combustion are completely harmless. Studies and research are now being done to determine the full environmental impact of burning wood.[8] There is yet a great deal of chemical analysis to be done to determine the wide varieties of products resulting in incomplete combustion. There is one advantage in that there is a great similarity between these intermediate products of combustion and those liberated in the forest by decay. Since the combustion process is so closely related to the natural decaying process, there are natural provisions for dealing with these by-products. Many of the intermediate products are volatile, and, when they are formed in decaying wood, escape into the forest air where they undergo chemical reactions with one another under the influence of sunlight, giving rise to the haze characteristics of forests on hot, still summer days.

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[7] Bryson, R.A. "A Perspective on Climatic Change," Science, no. 184, p. 753 (1974).

[8] Hall, J.A. Forest Fuels, Prescribed Fire, and Air Quality, Pacific Northwest Forest and Range Experiment Station, U.S.D.A., Portland, Oregon, 1972.

We have yet to completely understand the delicate relationships that exist in ecological processes. It is for this reason that the full environmental impact of wood as a fuel source is yet to be determined. Before widespread implementation is to be considered, detailed analysis will have to be done to determine the interrelationships that do exist and to determine the load limits that exist for the natural processors that eliminate pollutants from wood combustion.

With the potential increase in the use of wood as a fuel source, woodburning devices must be so designed as to attain as complete a combustion as possible. If combustion is complete, the end products are carbon dioxide and water vapor, eliminating harmful pollutants that would normally be released under incomplete combustions.

2.5 Availability

There is presently an abundance of wood available in the United States, despite many stories in our press to the contrary. It is a fact, however, that there are serious shortages of certain species, particularly the big trees of high quality. The amount of standing wood in this country, however, is enormous and on the increase in spite of soaring paper and plywood consumption.[9]

There are three major reasons for the increase in wood productivity:

1) the reversion of millions of acres of former cropland in the east to forest,

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[9] Gay, Larry. The Complete Book of Heating with Wood, Garden Way Publishing, 1975, p. 14.

2) a reduction in the per capita consumption of wood. This is largely due to the fact that wood is no longer used as a fuel source and synthetic materials have largely replaced products that were once made of wood.

3) the burning of fossil fuels having released a large percentage of carbon dioxide into the atmosphere. This increased level of carbon dioxide will enhance the growth of organic material provided light and water are abundant. (See Section 2.2, Photosynthetic Process) On the other hand, increased carbon dioxide levels may have a detrimental effect by increasing the temperature of the earth by hindering the escape of radiant energy to outer space.

Table 2.1 shows the results of research done by the U.S. Forest Service in estimating the potential amount of firewood available in the United States.[10] The table shows a tremendous amount of growth occurring in eastern forests every year. Even after cut timber and natural mortality have been taken into account there is still a net annual growth of 4884 million cubic feet (61 million cords) of hardwoods and 2891 million cubic feet (36 million cords) of softwoods in the east. To give some idea as to the fossil fuel equivalency the following is given: (See Table 2.1)

- 61 million cords of hardwood is comparable to 1.22×10^{10} gallons of oil which at .35 cents/gallon is equivalent to 4.27×10^{9} dollars. (Assumed conversion efficiencies for

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[10] U.S.D.A. Forest Service, "Forest Statistics for the United States by State and Region," 1972.

Table 2.1 Potential Fuelwood Available per Year by Region

Source: <u>Heating with Wood</u>, Garden Way Publishing.

(millions of cubic feet)

	Manufacturing Residues		*Logging Residues*		*Mortality*		*Net Growth*	
	Hard	*Soft*	*Hard*	*Soft*	*Hard*	*Soft*	*Hard*	*Soft*
Northeast	71	24	125	52	357	208	1153	477
North Central	70	7	97	9	540	152	2978	1019
Southeast	78	89	238	98	323	293	503	667
South Central	90	86	179	163	390	164	250	728
Total East	309	206	639	322	1610	817	4884	2891
Pacific Northwest	2	177	16	365	76	874	10	—1063
Alaska Coast*		8		39	1	166		—127
Cal.-Hawaii		152	14	92	11	338	353	—1475
N. Rocky Mountains		93		84	5	387	13	272
S. Rocky Mountains		46		103	44	177	69	82
Total West	2	476	30	683	137	1942	445	—2311
Total United States	311	682	669	1005	1747	2759	5329	580

Total Hardwoods = 8056
Total Softwoods = 5026
Grand Total = 13,082

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* Interior Alaska excluded because of remoteness.

this calculation is 50 percent for wood stoves and 65 percent for oil furnaces.)

- 36 million cords of softwood is comparable to 4.8×10^9 gallons of oil which at .35 cents/gallon is equivalent to 1.68×10^9 dollars.

The aforementioned calculations are meant to do no more than suggest the tremendous resource of wood that is presently available for fuel in this country. There is, in fact, far more wood available than indicated by the U.S. Forest Service, since they do not include cull trees, smaller trees, branches and deadwood.

Current growth rates in most natural forests range from ¼ to 3/4 cord per acre per year. This sustained yield could probably be doubled by forest management-- including thinning, cutting of less productive individual trees, selecting for (or planting of) more productive species, and harvesting trees at the optimum time.

With the potential of increased usage of forest areas comes the problem of environmental effects. Soil erosion and nutrient loss are both potential problems, especially if whole trees are harvested since then the nutrient-rich small branches, twigs and leaves would not be left in the forest. The question then becomes one of not how much potential wood is available from a forest, but rather what fraction of the volume that we can take without upsetting the forest ecosystem. "Only in the knowledge of the forest's productivity and its complex ecological relationships lies the key to its use and avoidance of its over-exploitation.[11]

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[11] Gay, Larry, op.cit., p. 27.

2.6 Energy Content and Economics

Determining the effective heating value and, in turn, determining a cost comparison of heating with wood is not an easy task. Whereas the energy content of a homogeneous fuel (gas, oil) is relatively constant, the energy content of wood is dependent on the following variables. The most important factor in determining energy content is the oven-dry density of the particular wood under consideration since a pound of dry wood of any kind has approximately the same energy content (*i.e.*, 8,600 BTU/lb). Therefore, the denser the wood, the more energy per cord. (See Average Density and Fuel Value Equivalents, Table 2.2) The other variable in determining the energy content is the moisture content of the wood. Moisture in wood decreases its available energy. Green wood (with 50 percent moisture) has 14 percent less available energy per cord than typical 20 percent moisture wood (air-dried). The third variable involved is the variability in the unit measure of wood. Oil can be measured quite precisely but the measure of wood varies considerably with its straightness and length of pieces. A standard cord is defined to be 128 cubic feet pile of wood in 4-foot long pieces. The actual wood content due to spaces in stacking reduces this figure to around 80 to 90 cubic feet of actual wood. This difference is responsible for the large variability in the amount of energy per cord even for a given kind of wood.

Table 2.2 computes the energy content per cord from the assumption of uniform energy content per unit weight of wood and using solely the difference in weight per cord to estimate the differences in energy.

Table 2.2 Fuel Values of Some Common Woods

	Average Density (lb/cord;	Fuel Value/Cord	Price/Cord Equivalent to Oil at:			Price/Cord Equivalent to Electric Heat (100% Conversion Efficiency) at:	
Type	20% moisture)	(BTU's)	35¢/gal	40¢/gal	45¢/gal	2.5¢/kwhr	4.0¢/kwhr
Shagbark Hickory	4400	30.8 million	$59	$67	$76	$113	$180
White Oak	4400	30.8 million	59	67	76	113	180
Sugar Maple	4100	29.7 million	57	65	73	109	174
American Beech	4000	28.0 million	54	62	69	103	164
Red Oak	3900	27.3 million	52	59	67	100	160
Yellow Birch	3800	26.6 million	51	58	66	97	156
White Ash	3700	25.9 million	50	57	64	95	152
American Elm	3400	23.8 million	46	53	59	87	139
Red Maple	3400	23.8 million	46	53	59	87	139
Paper Birch	3400	23.8 million	46	53	59	87	139
Black Cherry	3300	23.1 million	44	50	57	84	135
Douglas Fir	2900	21.4 million	41	47	53	78	125
Eastern White Pine	2200	15.8 million	30	34	39	58	93

Assumed Efficiencies: wood stove, 50%; oil furnace, 65%; electric resistance heating, 100%

Column 2 in Table 2.2 indicates the average density of air-dried wood. Air-dried defines the condition when there is no longer a net moisture loss from the wood to the surrounding air which averages 20 percent water by weight.

The amount of BTU's liberated from burning bone dry wood approximates 8,600 BTU/pound. But air-dried wood has a moisture content reducing the amount of possible heat to 7,000 BTU. Thus, the third column is obtained from the second by multiplying the average density by 7,000 for the hardwoods and 7,360 for Douglass Fir and 7,200 for white pine. The escalated BTU figures for the pine and fir represent the large volume of flammable resins.

The figures in the third column represent the maximum heat that can be liberated from a cord of wood, and must be adjusted by an efficiency factor to estimate the actual amount of heat transferred to the living space. All the figures in column 3 should be adjusted to reflect the energy conversion efficiency of the particular wood-burning device. (See Table 2.3)

Oil furnaces are in the heating efficiency range of 30 to 75 percent with particular studies indicating averages of 55 to 65 percent.[12] Since the fuel value of one gallon of heating oil is 140,000 BTU's, the heating effect from one gallon is 91,000 BTU's (assuming 65 percent conversion efficiency), at .40 cents per gallon that amounts to 0.440 cents per thousand useful BTU's.

If we were to determine what the oil utilization equivalency would

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[12] Summers, C. M. "The Conversion of Energy," Scientific American, September 1971, p. 151.

Table 2.3

CONVERSION EFFICIENCIES FOR VARIOUS WOODBURNING DEVICES[13,14]

		% Heating Effect
A.	Ordinary fireplace (steady-state operating conditions)	10 - 12
B.	Ventilating fireplaces	33 - 35
C.	Common stoves without circulation of air	83 - 90
D.	Metal stoves with circulation of air	68 - 93
E.	Heaters with pipes for circulation of hot air	63 - 80
F.	Apparatus for circulation of hot water	65 - 90

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[13] Putnam, J.P. The Open Fireplace, 1880.

[14] Smithsonian Reports, "Heating Efficiency of Various Fireplace Designs," 1873.

be for a cord of white oak, we would first adjust its fuel value per cord by 50 percent (wood conversion efficiency) which amounts to 15.4 million BTU's per cord. At .440 cents per thousand BTU's of oil, that would amount to $67.00 per cord. Therefore, white oak at anything less than $67.00 per cord is less expensive than oil.

Column 5 provides the price per cord equivalent to electric resistance heat (assuming 100 percent conversion efficiency). It is here where we can see the greatest cost benefit of using wood. Our same cord of white oak would be worth $180.00 compared to electricity at 4.0¢/kwhr (1Kw-hr = 3413 BTU's).

The price for a cord of wood, depending on its type and availability, ranges between $25.00 and $120.00. To determine whether wood is more economically viable depends on local price per cord and the cost structure of comparison fuels.

CHAPTER THREE: WOOD AND THE COMBUSTION PROCESS

3.0 Introduction

The focal point of this chapter is the efficient combustion of wood fuel. To further qualify "efficient" is to say complete combustion has occurred only when the end products are carbon dioxide and water vapor. If incomplete combustion has occurred, compounds which are combustible and highly toxic may be released to the atmosphere. The presence of these volatile compounds are also witness to the fact that the heating potential of the wood fuel has been greatly reduced. Granted, complete combustion is seldom attained except in laboratory conditions but it should be a standard to work towards in the design of woodburning devices.

Wood has special properties as a fuel, quite different from those of others. Therefore, especially for wood, its chemical and technical properties have to be taken into account in order to utilize it effectively. Sections 3.1 - 3.3 deal with the properties of the fuel and its combustion. The remaining section, 3.4 deals with woodburning devices designed around the components of complete combustion.

3.1 Composition of Wood

Wood is a complex vegetable tissue composed principally of cellulose and lignin of which carbon makes up about 50 percent. Water, amounting to 15 percent or more by weight (depending on seasoning) is also present. There are also other extraneous materials as nitrogen and oxygen, small amounts of sugars, starches and nitrogenous substances as stored food, extracts and coloring matter. There are, in addition, salts of sodium, magnesium, calcium and iron, all of which become ash when the wood is burned. It is this chemical complexity that results in the quite complicated process of wood combustion.

When a quantity of wood is burned, the original components, cellulose and lignin, are broken down and volatile gases and vapors, not present in the raw wood, are formed. It is these combustible vapors that are responsible for roughly 20 to 50 percent of the chemical energy in the wood. This value varies with wood type, its moisture content, and how quickly it heats in the fire.

3.2 Factors Influencing Energy Content of Wood

The energy content of wood is basically due to three factors, those being:

1) density of wood,
2) resin content, and
3) moisture content.

The energy content of one pound of oven-dry wood of almost any kind is approximately the same. The major differences between the energy level in wood is its density. A cubic foot of white oak weighs approximately 55 pounds (20 percent moisture); a cubic foot of white pine weighs approximately 28 pounds (also at 20 percent moisture). The energy content of the oak is twice that of the pine. The energy content of wood is in direct proportion to its air-dried weight. (See Table 2.2, Chapter 2.) The reason all wood has approximately the same energy content on a similar weight and moisture basis is that they are all fairly similar in chemical composition.

There are slight chemical differences among woods which are responsible for the differences in their energy content. The chemical differences stem from the fairly large range of resin in the different woods. For instance, if 8,600 BTU per pound is taken to be the energy content of wood except the resins, then wood which is 5 percent resin (at 17,400 BTU per pound) has an overall energy content of .95 X 8,600 + .05 X 17,400 or 9,040 BTU per pound. Softwoods tend to have more resins and their higher lignin content may also contribute to their slightly higher energy values.

Moisture in a piece of wood does not change the amount of chemical energy contained within it, but less of that chemical energy is likely to be turned into useful heat. The presence of moisture results in less complete combustion. Water evaporating from wood with a high moisture content, i.e., freshly felled wood at 50 percent moisture, forms a sheath of water vapor that surrounds the fuel and blocks the entry of oxygen, thereby lowering ignition and combustion rates. The point of combustion of wet wood can be lowered to a reasonable level only by increasing the air intake. This, in turn, creates an excess draft through the fire with consequent heat loss via the flue.

In summary when determining the energy content of a given wood, the most important parameter is the oven-dry density of that particular wood, since a pound of dry wood of any kind has nearly the same energy. The densest woods have the most energy per cord (at equal moisture contents). The presence of moisture in wood decreases its combustability. Green wood with 50 percent moisture has 14 percent less available energy per cord than typical 20 percent moisture wood.

3.3 Combustion of Wood and Factors Influencing Complete Combustion

Combustion involves energy conversion-- chemical energy in the fuel is converted into heat, light, infrared radiation and other forms of energy. Oxygen is required and is consumed (incorporated into other molecules) in the process. Common fuels, including wood, are made almost entirely of carbon, oxygen and hydrogen. When complete combustion occurs the only end products are carbon dioxide and water vapor.

Wood combustion takes place in four successive phases. The first stage occurs around 212°F in which moisture that was present in the wood is driven out. The ignition source is responsible for this endothermic reaction. As temperatures increase to 540°F additional water is driven off and compounds start to evolve out of the wood, such as carbon dioxide, carbon monoxide, formic acid, acetic acid, glyoxal and probably many other compounds.

All of the aforementioned compounds except water vapor and carbon dioxide are combustible. The processes involved here are still endothermic with the heat energy largely converted into chemical energy. It is when temperatures reach approximately 540°F that we reach our second phase or ignition point. The reaction changes from an endothermic to a heat producing or exothermic reaction. With the increase of temperature large amounts of the aforementioned gases are produced. The most abundant ones, carbon monoxide, methane, carbon dioxide, methanol, formaldehyde and hydrogen, are highly combustible.

These gases serve as the main fuel source for the wood flames. As the temperature increases and decomposition accelerates, we enter into the third phase or combustion (proper). The surface of the wood gets hotter and hotter and the heat gradually penetrates into the inner layers. The gases generated inside by decomposition escape through the pores and cracks of the wood or wood charcoal already formed and ignite on coming into contact with the oxygen.

In general, the pyrolysis, ignition and combustion proper phases, cannot be sharply separated; they partially overlap. After a certain time, however, a slowing down of the combustion process can be observed. This is due to the layer of charcoal which forms on the surface of the wood and which forms an envelope, constantly growing thicker around the inner, still intact core. The charcoal, a good insulator, prevents the heat from penetrating inward.

The fourth and final phase is the incandescence of the wood charcoal. This phase begins when the combustible decomposition gases end and the flame diminishes and dies down on the surface. The wood charcoal once more comes into contact with the oxygen in the air and becomes incandescent and then falls as ash.

If complete combustion has occurred during the four phases, the only gases that escaped would be carbon dioxide, water vapor, oxygen from the excess air and nitrogen, an inert compound of the air. Smoke and soot eminating from a chimney are a clear indicator of incomplete combustion. What is escaping from the chimney are small quantities of hydrocarbons and free carbon (soot) that are not burned. Thus, much of the heating cpapcity of the wood fuel is lost.

For combustion to be complete there must be:

1) adequate air intake,
2) intimate mixture of combustible gases and air,
3) ignition of the gas-air mixture, and
4) adequate space for the gases to burn completely.

It is with the supply and control of these components that we will look at the design of woodburning devices in the following section.

3.4 Woodburning Devices

Wood, since it is very flammable, can be burned without any special apparatus; however, the combustion will be incomplete. Doubtless, the most primitive and oldest system of burning wood was the open hearth fire. (See Figure 3.0) In the middle of the dwelling space a heap of wood was burned on the floor of beaten earth or on a hearth of earth covered with flat stones. Providing light and heat, the open fire was also used to cook food. The smoke escaped through the opening which served as a doorway or through a hole in the roof.

In time man set about to enclose the dangerous flame. The next step was probably called the fireplace, an open fire no longer located in the middle of the room but against a wall. Above the hearth was placed a roof-like hood ending in a flue through which the smoke escaped outside. A more intense heat was obtained by the concentration of the fire and the radiation from the walls enclosing the hearth. Later, the fireplace was to reappear located in the middle of the room where the benefits of stored heat in the masonry could best be utilized.

The fireplace finally evolved to the point where the flame was completely enclosed, the result being the wood stove or furnace. This

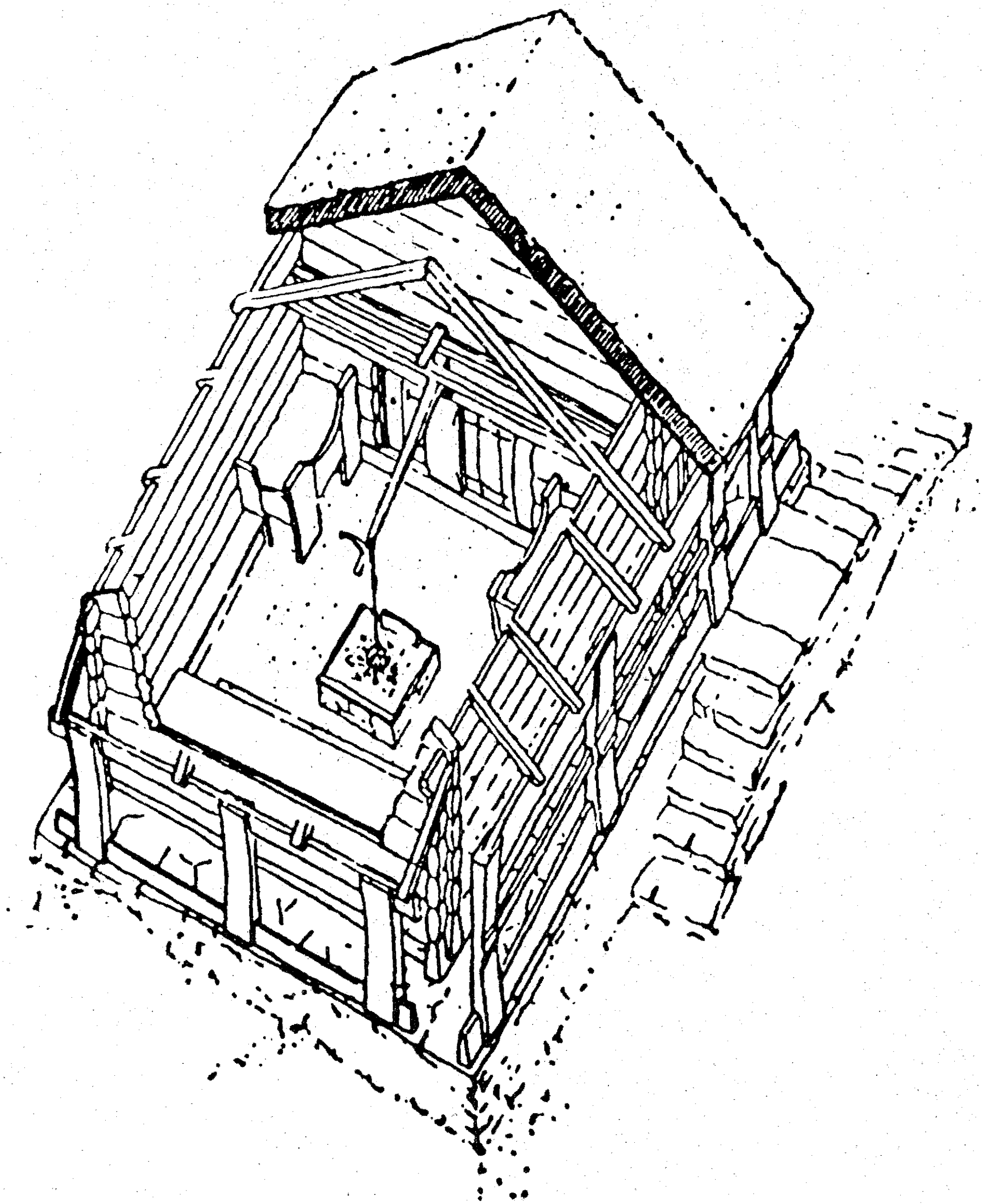


Figure 3.0 Open Hearth Fire

was originally a thick-walled structure made of clay and stones with an opening through which the smoke reached the exit of the room. Later, stoves were made with plates of stone or earthenware tiles set on supports and fitted with a closing door. Next, there was added an enclosed flue which penetrated through the roof. Completely enclosing the fire also had the benefit of providing control over the air reaching the flames, thereby increasing the rate and temperature of combustion, and also providing regulation of the heat output.

3.4-1 The Fireplace

The open fireplace was once the only source of heat in all American homes, but now it is a mute reminder as to its original task of providing warmth by taking its place as an instrument of interior decoration.

Net efficiency or actual heating effect of most modern fireplaces ranges from -5 to 10 percent. This low and sometimes negative heating efficiency is due to the following factors:

1) The required air-volume flow toward a fire for the average fireplace opening is about 3000 cubic feet per hour. This air volume is much more than what is normally infiltrated into a house. For example, the amount of fresh air required for proper ventilation by a family of four has been established at 1400 cubic feet per hour. Thus, a standard fireplace will cause the displacement of over twice the amount of air required for optimum ventilation. This extra air is usually heated to room temperature by the time it reaches the fireplace. Thus,

the use of the fireplace causes the net amount of heat needed to keep the house warm to increase.

2) Another source of heat leakage is the fireplace damper itself. According to the National Electrical Manufacturers Association the average fireplace experiences up to 38.5 percent heat loss with the damper open and the fireplace not in use.

3) The fireplace is an ineffective device other than for heating immediate space. The fireplace is largely limited to heating by radiant energy. There is some contribution made by the materials of fireplace re-radiating absorbed infrared radiation. If air at room temperature comes into contact with these heated surfaces, it rises and forms a heated layer of air adjacent to the ceiling surface. This, in combination with air movement towards the fireplace (draft), provides temperature differentials between floor and ceiling which results in thermally uncomfortable surroundings.

The following section deals with correcting the shortcomings of the fireplace and transforming it into a more effective heating device.

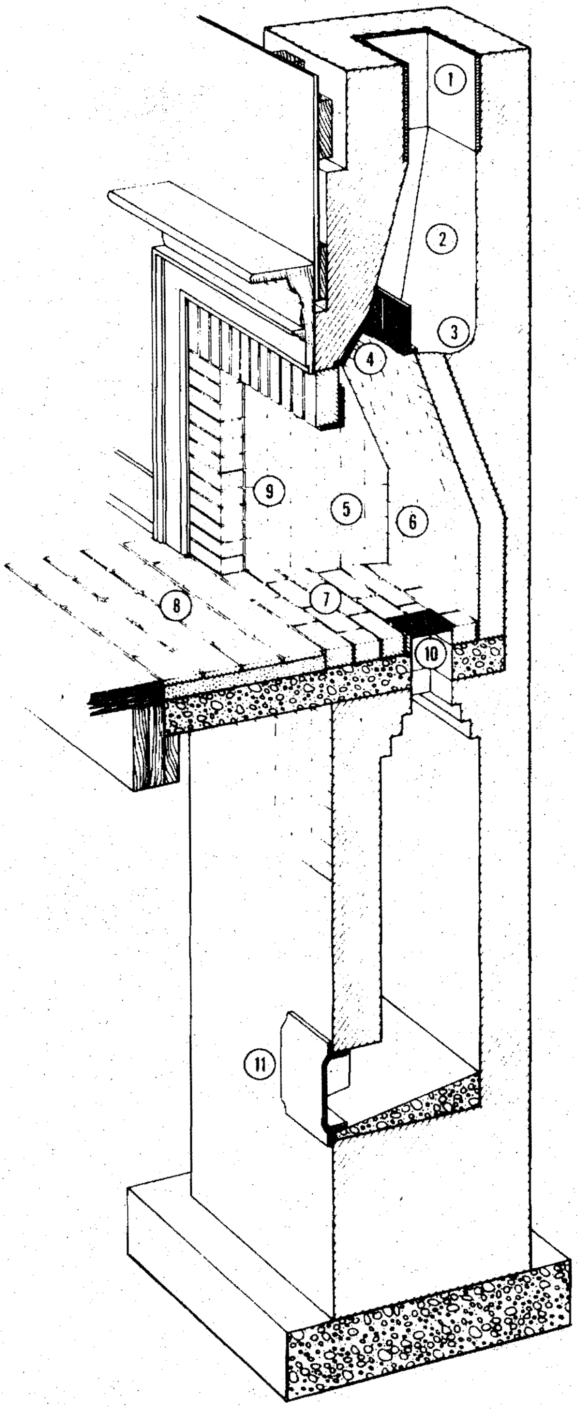
3.4-2 Increasing Fireplace Efficiency

To be simply stated, an energy-efficient fireplace should:

1) maximize the amount of radiation it emits, and

2) minimize the amount of excess air up the chimney.

To better understand how the aforementioned can be achieved, a discussion of the fireplace and its component parts has been included. (See Figure 3.1)



1. Flue
2. Smoke Chamber
3. Smoke Shelf
4. Damper
5. Fire Chamber
6. Fire brick
7. Back Hearth
8. Front Hearth
9. Fireplace Opening
10. Ash Dump
11. Cleanout Door

Figure 3.1 The Fireplace and Its Component Parts

3.4-2a Fireplace Opening

The fireplace opening should always be in the form of a lying rectangle; in other words, it should be wider than high. If it is topped by an arch, the height is determined by the distance between the hearth and the vertex of the arch. If an arched section is involved, the width is equal to the length of the cord.

Altering the size of the fireplace changes the proportion of the other components. Table 3.2 gives the basic relationships between room size, fireplace proportion, and flue size for various chimney heights.

Glass doors can be fitted into frames which seal against the fireplace opening such that when the doors are closed, very little air can enter the fireplace except through explicit air inlet dampers at the bottom of the unit. (See Figure 3.3)

With the doors open the operation and performance of the fireplace remains the same as any ordinary fireplace. With the tempered glass doors closed the operation of the fireplace has these three main effects: first, only a small amount of air sufficient for the burning of the fire flows through the air inlet dampers at the bottom of the glass enclosure, thus, greatly reducing the amount of room air that is carried up the chimney; secondly, by providing adjustable air inlet dampers, this allows the rate of combustion to be adjusted; and thirdly, much less radiant heat from the fire gets into the room, and somewhat more will be given off by the chimney walls. Thus, there are opposing effects with respect to overall net efficiency with the use of glass doors on a standard masonry fireplace.

Table 3.2 Fireplace Proportions in Relation to Room Volume

Source: <u>Der Offene Kamin</u>, Julius Hoffman Verlag.

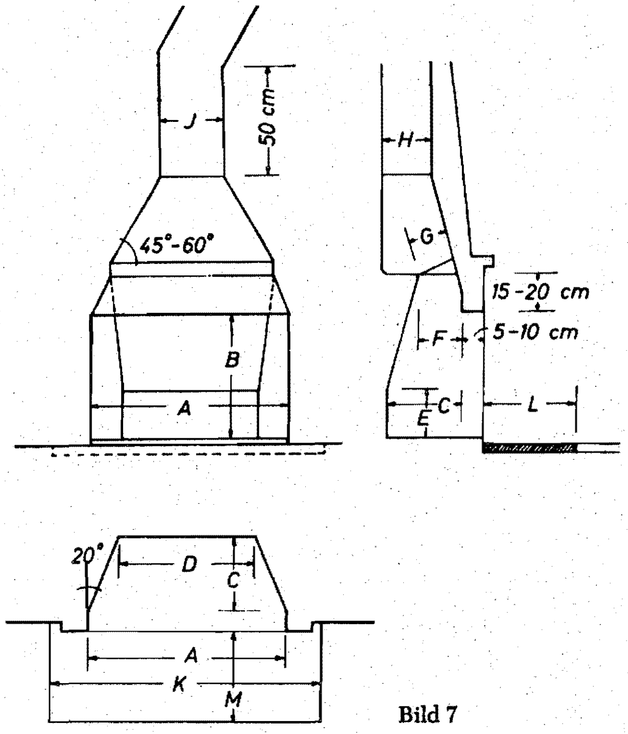


Bild 7

Room		Fireplace opening			Depth of hearth	Backwall		Width of Neck	Width of Throat	Flue			Front hearth	
Floor space sq. ft.	Volume cb. ft.	width in.	height in.	area sq. in.	in.	width in.	vertical part in.	in.	in.	depth in.	width in.	area sq. in.	width in.	lengt in.
		A	B		C	D	E	F	G	H	J		K	L
170—240	1400—2100	24	20	480	13	14	10	8	$4^{3}/_{4}$	8	8	64	40	20
		26	22	572	14	16	10	8	$4^{3}/_{4}$	8	8	64	41	20
240—320	2100—3200	28	23	644	14	17	10	8	$4^{3}/_{4}$	8	8	64	43	20
		30	24	720	15	19	10	8	$4^{3}/_{4}$	8	8	64	45	20
		31	25	775	15	21	11	8	$4^{3}/_{4}$	8	$10^{1}/_{4}$	82	47	20
320—430	3200—4200	33	26	858	15	23	11	8	$4^{3}/_{4}$	8	$10^{1}/_{4}$	82	49	20
		35	27	945	16	24	11	8	$4^{3}/_{4}$	8	$10^{1}/_{4}$	82	51	20
		37	28	1036	16	26	12	8	$4^{3}/_{4}$	$10^{1}/_{4}$	$10^{1}/_{4}$	105	53	20
430—540	4200—6400	39	29	1131	17	27	12	8	$4^{3}/_{4}$	$10^{1}/_{4}$	$10^{1}/_{4}$	105	55	20
		41	30	1230	17	29	12	8	$4^{3}/_{4}$	$10^{1}/_{4}$	$10^{1}/_{4}$	105	57	20
		43	31	1333	18	30	12	10	$4^{3}/_{4}$	$10^{1}/_{4}$	15	154	59	20
540—750	6400—8800	45	32	1440	18	32	13	10	6	$10^{1}/_{4}$	15	154	61	20
		47	33	1504	19	34	13	10	6	$10^{1}/_{4}$	15	154	63	20
		49	34	1666	19	35	13	10	6	$10^{1}/_{4}$	15	154	65	20
750—970	8800—12400	51	35	1787	20	36	13	10	6	$10^{1}/_{4}$	15	154	67	20
		53	36	1908	20	38	13	10	6	$10^{1}/_{4}$	15	154	69	20
> 970	> 12400	55	37	2035	21	39	13	10	6	15	15	225	71	20
		57	38	2166	22	40	13	10	6	15	15	225	73	20
		59	39	2301	23	43	13	10	6	15	15	225	75	20

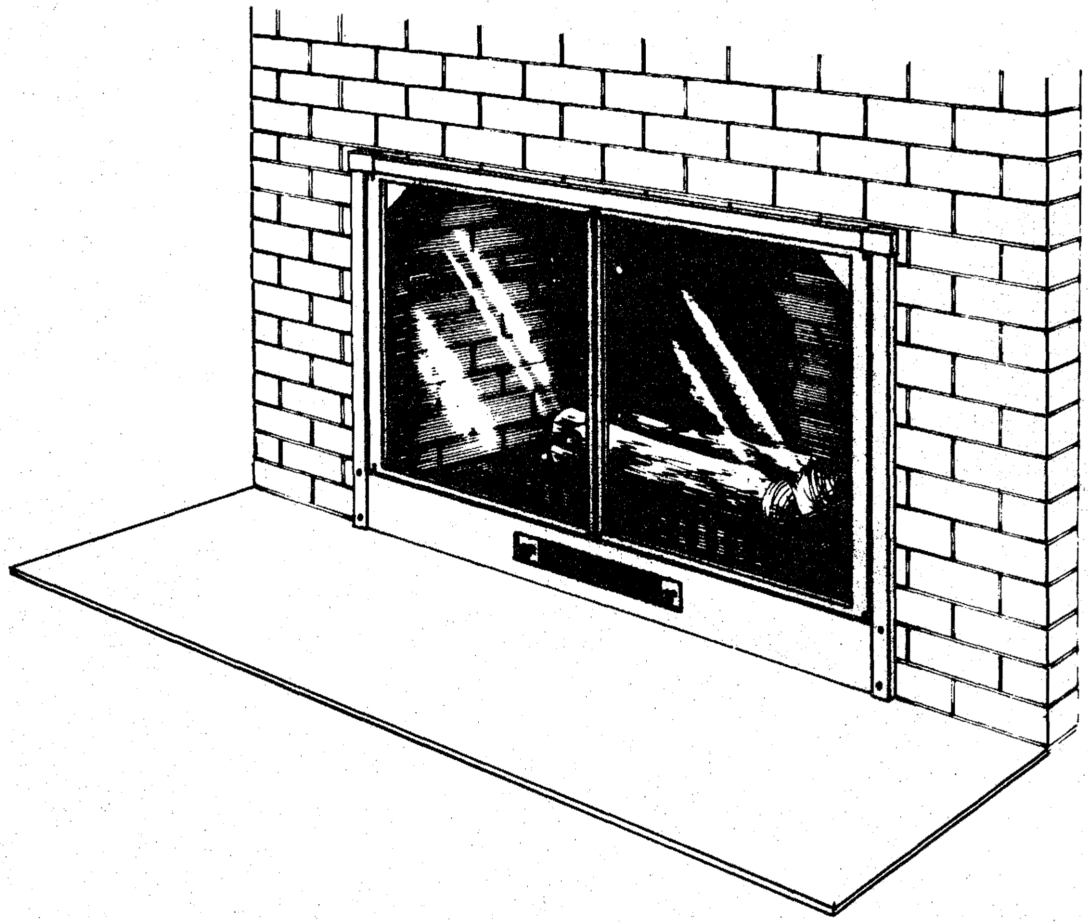


Figure 3.3 Use of Tempered Glass Doors

Most of the heating from an ordinary fireplace is largely due to radiation received from the flames, coals, and warmed surfaces. Virtually all kinds of tempered glass which are practical for use in fireplace doors absorb most of the radiation from the fire. The glass itself, when warmed, re-emits some radiation, but the net effect is a large reduction in the direct heat output of the fireplace. However, the properties of enclosing the combustion chamber with glass doors does suggest its use with warmed-air circulating fireplaces which pass air around the back and sides of a metal insert that fits into a standard fireplace opening. (See Section 3.4-2b) Here the majority of heating is done with warm, natural convected air or by forced circulation and not by radiation as in a standard fireplace.

Use of glass doors can cut back on excess air entering the fireplace without decreasing the wood combustion rate. Thus, with the same amount of heat being generated, but less air diluting the combustion products, the flue gases are hotter. The increased heat of the flue gases suggests the use of heat exchangers past the combustion chamber (See Section 3.4-2e) One such device, the Thriftchanger Heat Recovery Fireplace consists of an enclosed combustion chamber connected to a heat exchanger comprised of parallel steel tubes. (See Figure 3.4) When the heating cycle is desired, a diversion damper located above the smoke shelf is closed, allowing the combustion gases to be pulled by chimney vacuum down through the distribution plenum and into the heat exchange module giving up a partial amount of heat. Once through the heat exchanger, the gases continue on through to the chimney. Floor air is heated by the tubes in the heat exchanger to be convected to a desired

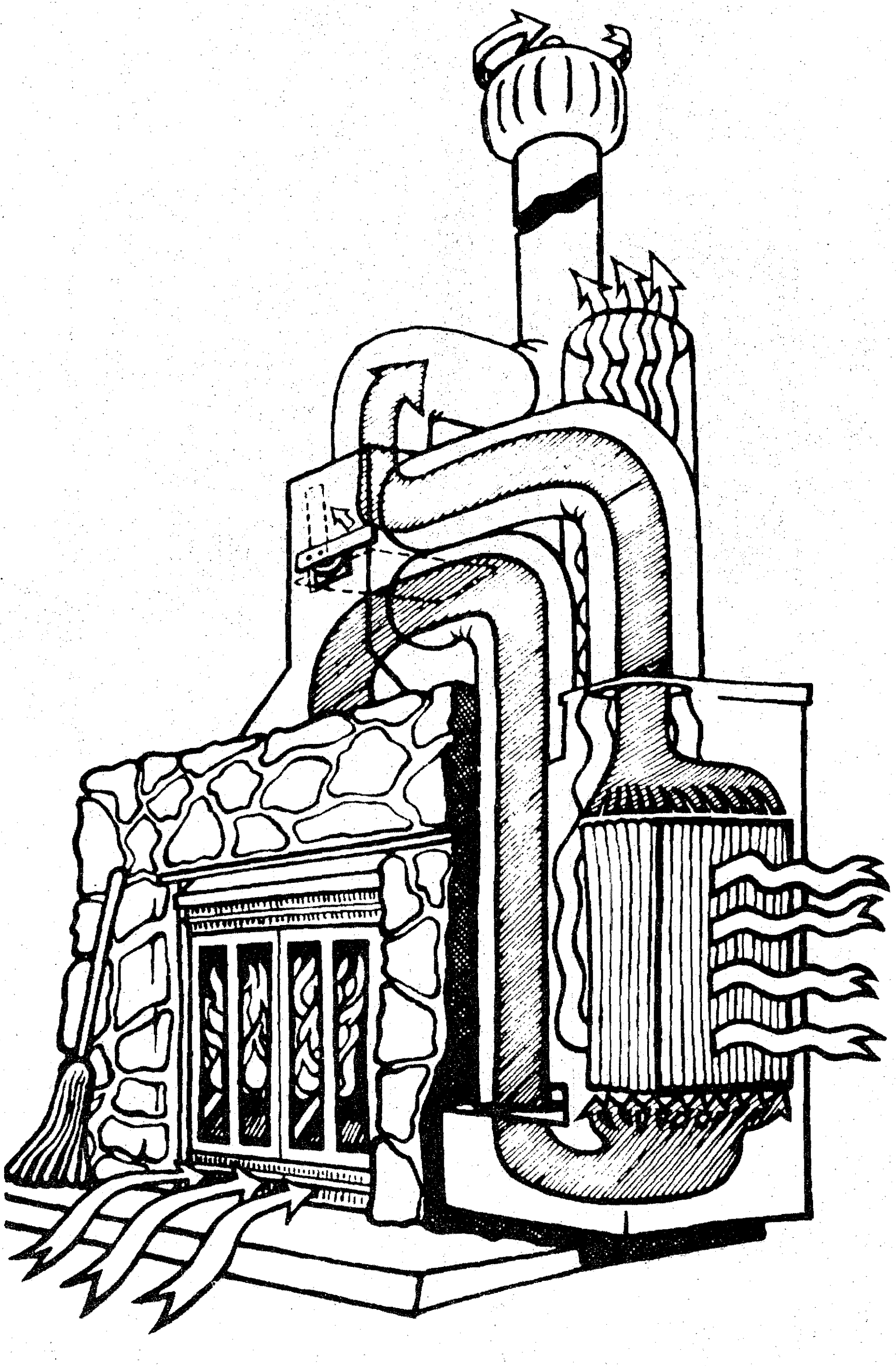


Figure 3.4 Thrift-Changer Heat Recovery Fireplace

outlet by a riser pipe. Claimed efficiency for the device is over 60 percent.

The use of glass doors also has the added benefit of closing down the fireplace at night while still venting fumes from the remains of an earlier fire. Without the doors to cut off the air supply, heated room air would escape through the chimney or until a new fire was started.

3.4-2b Combustion Chamber

The floor of the combustion chamber on the hearth within the fire area is usually built of fire brick but it may be other types of hard brick, concrete, stone, tile or other noncombustible, heat-resistant materials. The outer hearth is built of the same type of materials and extends a minimum of eight inches on each side of the fireplace opening and sixteen inches in front.

Some consideration can be made as to lowering the hearth below floor level. A twelve inch sunken fireplace puts the heat radiation at floor level where it is most needed. It also creates a possible seating arrangement and lessens the danger of flying sparks.

The depth of the combustion chamber is dependent on two factors. One, the depth should be such to maximize radiant energy and, secondly, there should be adequate space for combustion to occur. There are basically two origins for radiant energy coming out of a fireplace; primarily, radiation coming directly from the coals and flames of the fire into the room, and secondary radiation which is reflected or emitted from the fireplace walls. Direct radiation is maximum from fireplaces which are especially shallow, tall and wide since less radiation is intercepted by the fireplace walls. According to the aforementioned, the depth of the combustion chamber must not exceed one-half to two-thirds the height of the fireplace opening.

Secondary radiation or that radiation which is reflected or emitted from the combustion chamber walls can be maximized by doing two things. First, the back wall of the combustion chamber should be vertical up to a point one-third of the height of the fireplace opening and slope forward 4 to 8 inches; the sides should not be perpendicular to the back, but angled outward to deflect the radiant heat forward into the room. Secondly, the temperature of all the surfaces will be higher if insulating fire brick is used in the construction of the combustion chamber. This makes the surfaces hotter by decreasing the heat conduction into the structure of the fireplace.

The proportions of the inside combustion chamber are important in providing adequate space for combustion gases to burn completely. Deep chambers produce more smoke than shallow ones since there is inadequate air for combustion in the rear of the chamber.

A properly designed grate is important if complete combustion is to occur. A grate is far superior to a fire simply bedded on the floor of the combustion chamber. A grate is used to raise the firebed a few inches above the hearth. This allows for the passage of air through and over the fuel bed providing an intimate mixture of the combustible gases and air. The grate should be sized so that wood charcoal which forms during combustion attains sufficient depth to cover the grate.

There are a few specially manufactured grates which provide a platform for the combustibles along with acting as heat extractors. One "C-shaped" grate made of hollow pipes is used to circulate room air by natural convection. (See Figure 3.5) The heat of the hot coals on the base in combination with the flames coming into contact with the upper portions of the pipe cause the air inside each pipe to expand and to flow out into the room. Another grate, inclined in design, allows for ashes to build up on the floor of the combustion chamber so that heat can radiate into the room.

The most effective, as well as most expensive, fireplace accessory is a heat circulating, metal combustion chamber insert. (See Figure 3.6) A metal heat chamber will emit quantities of conductive heat that would otherwise be lost through absorption in the surrounding masonry or lost to the atmosphere via the chimney.

The operation of a heat circulating chamber is such that air at floor level is drawn into the unit, constantly coming into contact with the back and sides of the combustion chamber. The air is then discharged into the room as warm air from a convenient place somewhere above the fireplace opening.

This natural convective air circulation draws air from the room, heats and circulates it back again into the room. Thus, dust-laden room air is brought to the heating surface and re-circulated into the room containing still more dust produced by carbonization. Consequently, a fresh-air intake which draws in air from the outside is much more advantageous. The fresh air is channeled to the metal heat chamber through ducts which can be closed off. Upon heating, the air is discharged into the room in the same way and in the same place as other

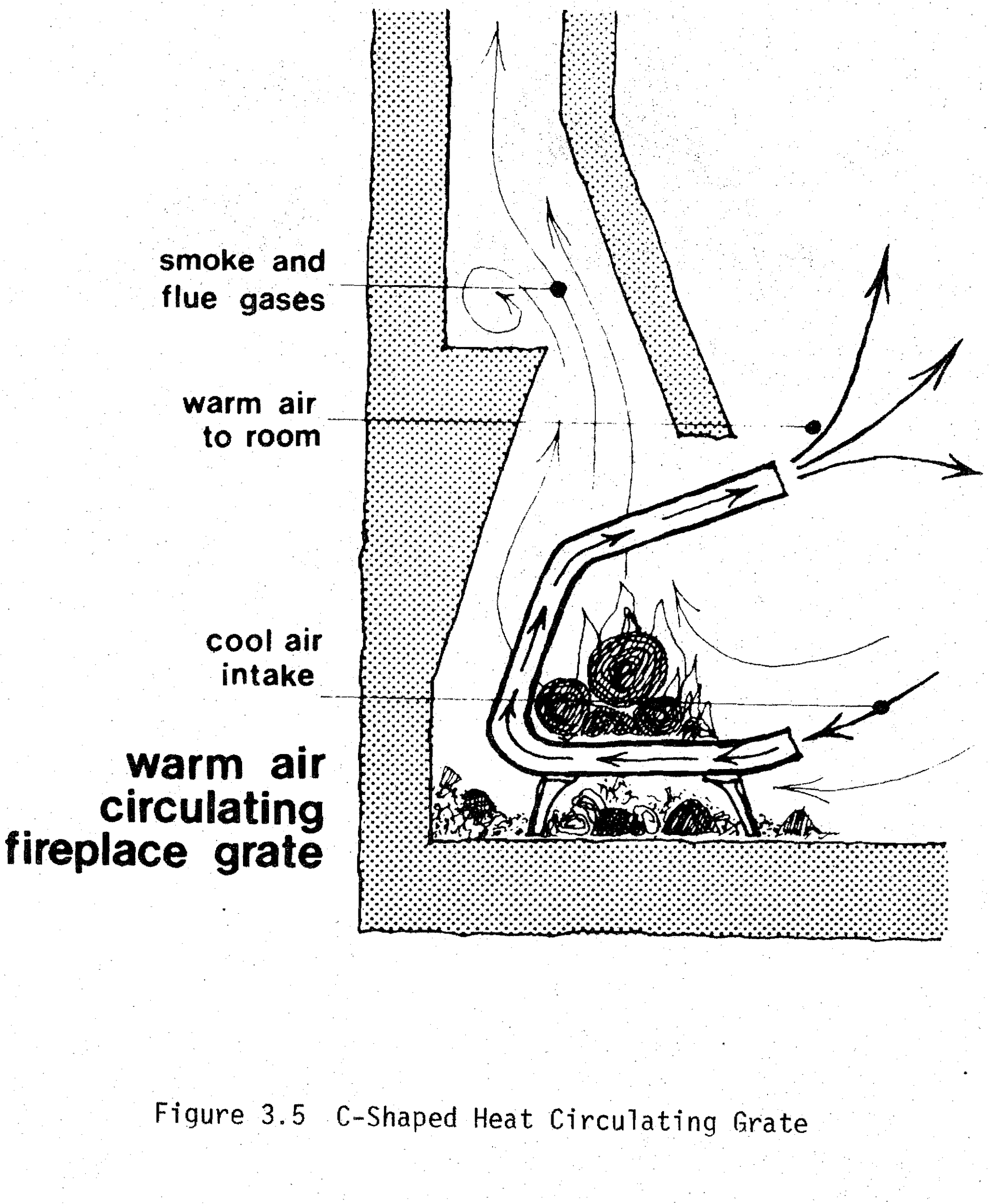


Figure 3.5 C-Shaped Heat Circulating Grate

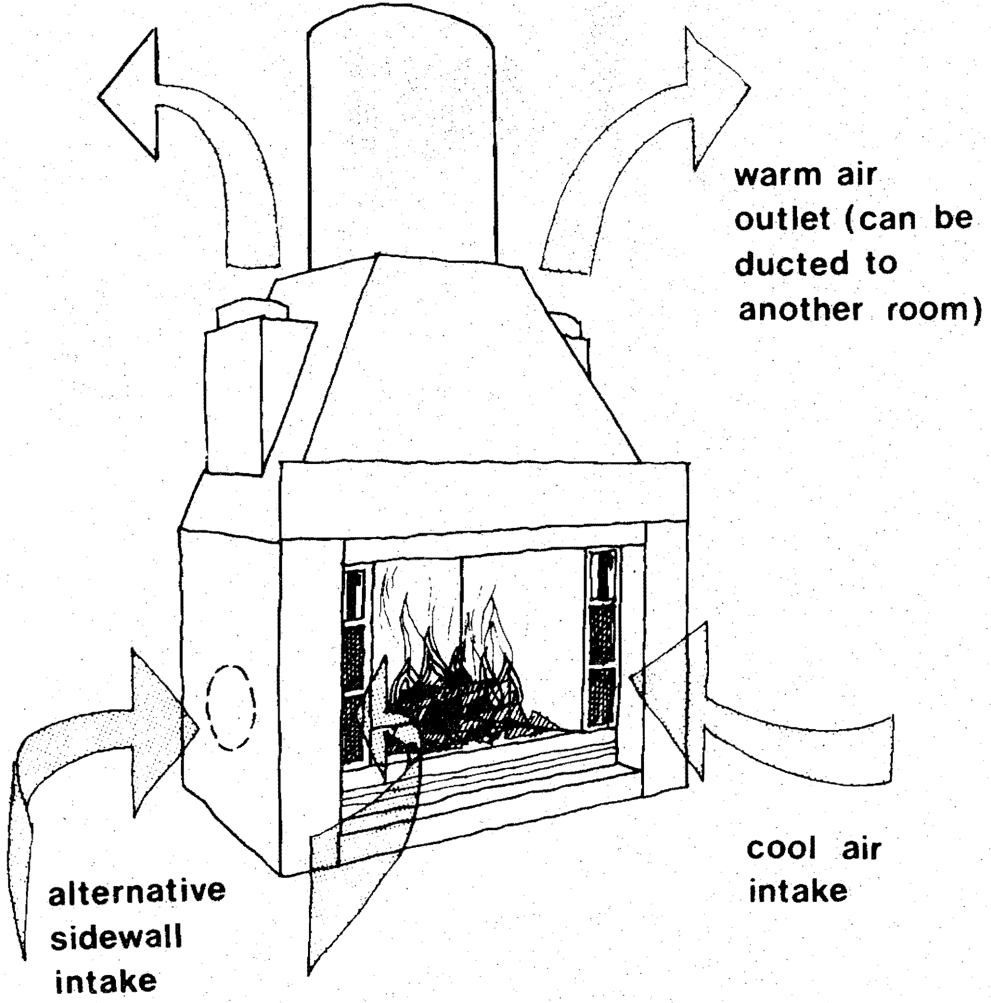


Figure 3.6 Heat Circulating Fireplace

re-circulated air.

When a metal fireplace liner is employed, bricks or masonry are no longer used in the construction of the combustion chamber. Therefore, the fireplace is no longer capable of the heat-retaining properties provided by the thermal mass of the bricks. In spite of this absence, open fireplaces with the capability of warm-air heating feature a higher degree of thermal efficiency than ordinary fireplaces. In Great Britain a series of thorough investigations have been conducted by the British Building Research Station to ascertain the thermal efficiency of various open fireplaces. The investigations were carried on in thirty-nine different homes with equal conditions and circumstances and included fireplaces of normal design as well as fireplaces with heat-circulating inserts. In these investigations the fuel consumption was determined as well as the distribution of heat in lined-in rooms. The investigations ascertained that fireplaces with heat-circulating inserts consume twenty-one percent less fuel. In the ordinary fireplace constructed of masonry approximately twenty-five percent of the BTU value of wood was all that was emitted into the room by radiation. In the heat-circulating fireplaces this figure was thirty-six percent, one third of which was emitted by convection. With the typical fireplace 6,000 to 7,500 cubic feet of combustion air was drawn from the room per hour, while with heat-circulating fireplaces these figures were only 2,100 to 2,500 cubic feet per hour.

With the combination of a heat-circulating insert and tempered glass doors, the fireplace has the potential of becoming nearly as energy efficient as stoves.

Correct air-intake is the key to efficient fireplace combustion. In an average fireplace a large volume of air is withdrawn from the living space to support its combustion. This volume of air is supplied from unheated air infiltrating from natural leaks in and around closed windows and doors. A large percentage of the 5,000 to 30,000 ft^3 of air per hour drawn by the fireplace originates from these sources. This volume of unheated air can cause as much as a doubling of the heating needs of a house. The exact increase depends on how much the actual fireplace draws and how susceptible the house is to air infiltration. We can also go to the other extreme where fireplaces are installed in tightly constructed, efficiently weather-stripped houses, where the amount of infiltrated air is insufficient for supplying the chimney draft.

Both situations, that of extreme air infiltration and that which is insufficient, can be alleviated by supplying the air needed for combustion from fresh air drawn from the outside. Air can be supplied to the fire by duct-work located below the floor and extended to the outside. These ducts must be protected from insects and vermin by screens and must be inclined toward the inside to prevent the entrance of water. Fresh air is supplied to the fire through air registers in the hearth directly in front of the fire or in the sides immediately above the hearth. (See Figure 3.7a) If an ash dump is available, it can also be combined with supplying combustion air. (See Figure 3.7b)

The size or area of the air supply duct should be roughly the same as the flue. Provisions should be made to include a damper or an adjustable register to enable regulation of the air supply, including

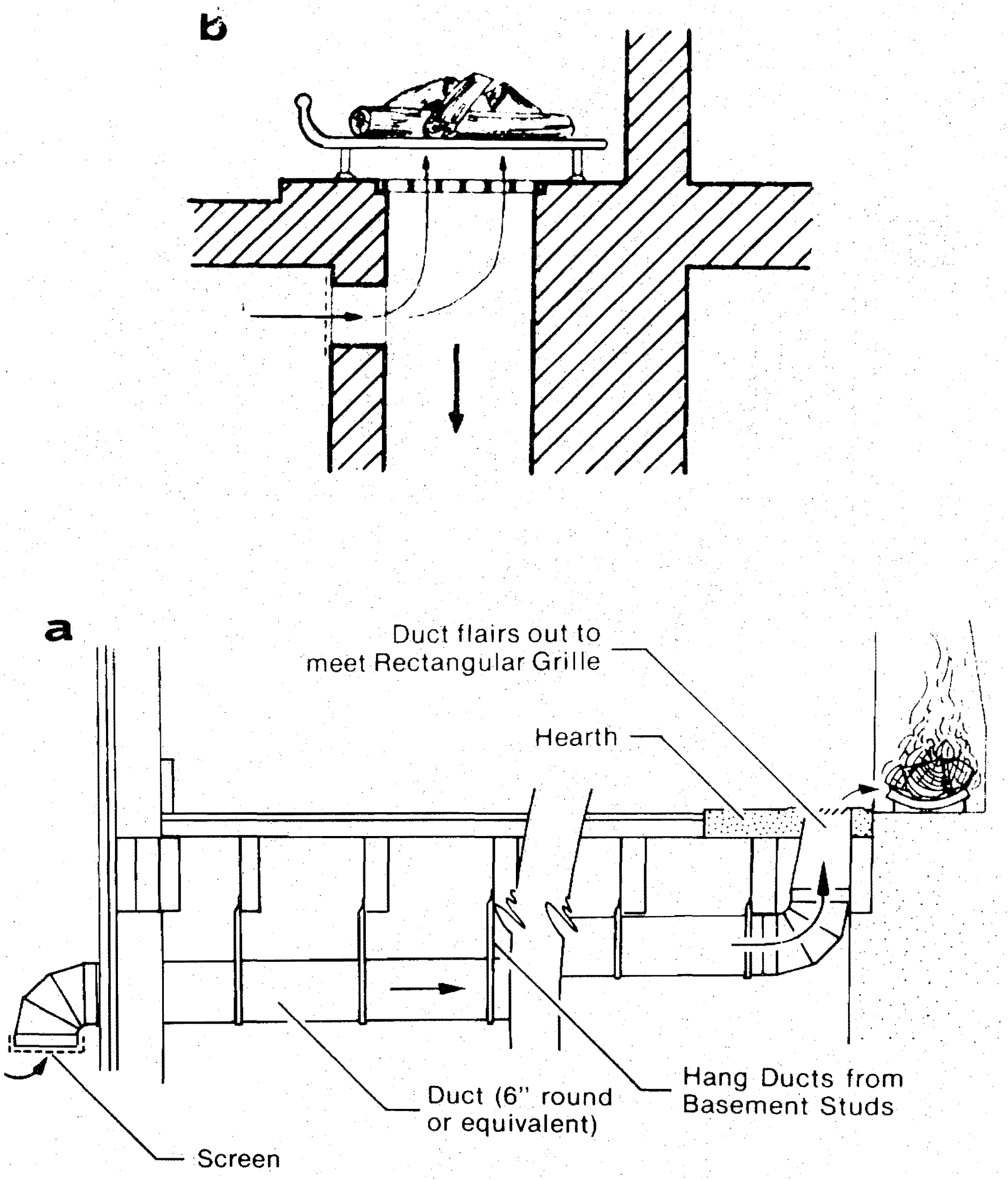


Figure 3.7a & b Outside Air Supplied to Combustion Chamber

closing it off when not needed.

Combustion efficiency can be increased if the incoming air is preheated before it reaches the firebed. The object being, is to maintain a high combustion zone temperature without diluting it by admitting cold outside air. This can be accomplished by routing the new air supply duct under the firebed with the exit at the fireplace grate. (See Figure 3.8)

Using the arrangement of ducted outside air also has the benefit of minimizing cold air drafts, particularly those at floor level, within the room.

3.4-2c Throat and Damper

By sloping the back of the fireplace forward, the top of it is narrowed to leave a small gap approximately 4 to 6 inches in width, This is known as the throat of the fireplace; its purpose is to constrain the escaping flue gases at a speed high enough to discourage downdrafts (Venturi effect). If the chimney throat is too large, then some cool air that does not participate in ignition or combustion will be drawn over the fire. This results in increased smoke emission.

A damper control with adjustable settings is instrumental in meeting the varying conditions of fireplace use. A properly designed damper allows the adjustment of the throat opening in order to regulate the draft. This, in turn, offers the control over the rate of combustion to suit the type of fire. For example, a roaring pine fire may require a full throat opening, but a slow-burning hardwood log fire may require an opening of only 1 or 2 inches. Closing the damper to suit the rate

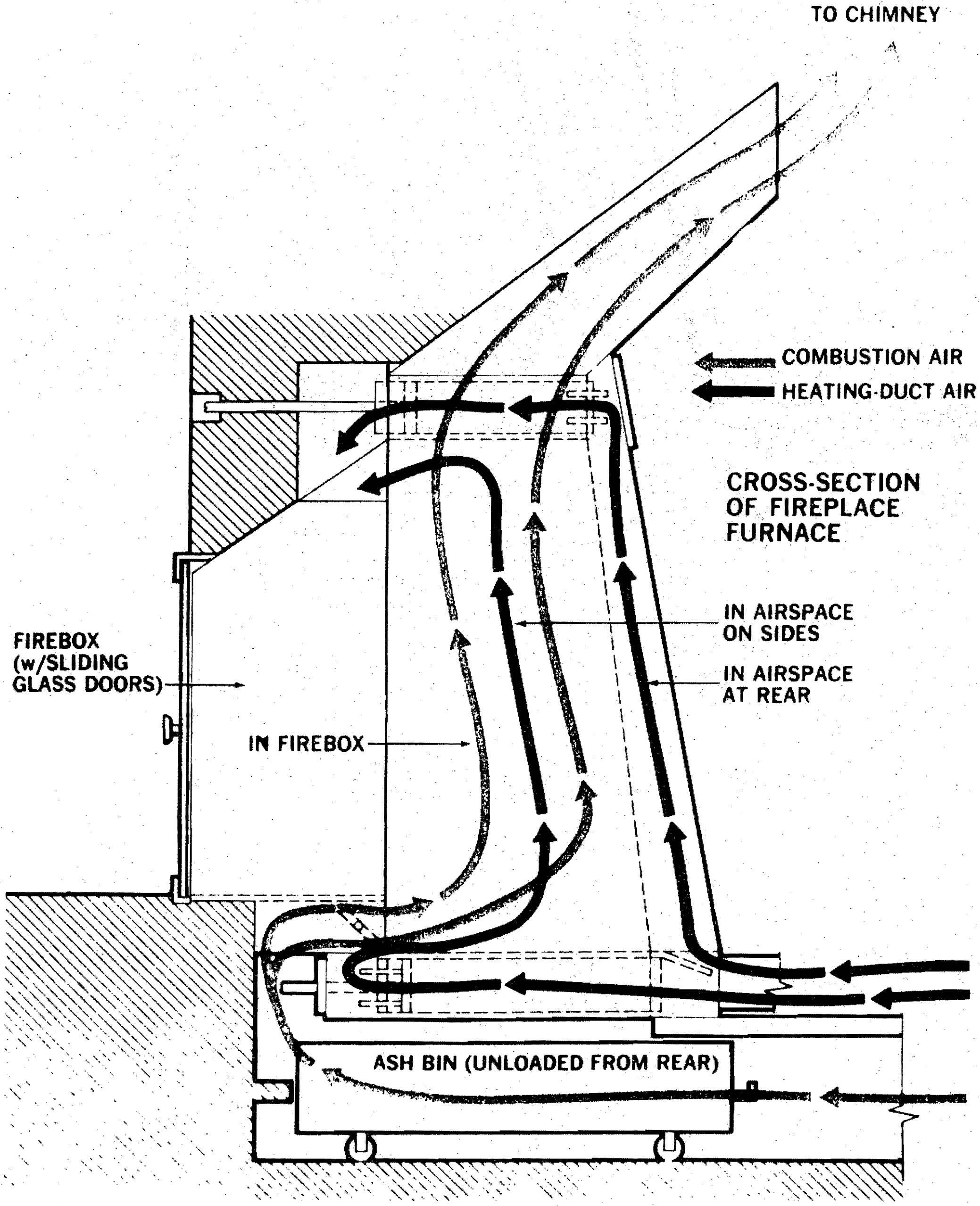


Figure 3.8 Combustion Chamber Air-Preheat

of combustion reduces the amount of heat loss up the chimney. A properly sealed damper also allows the flue to be completely sealed off to prevent heat loss when the fireplace is not in use.

3.4-2d Smoke Shelf and Smoke Chamber

There are varying opinions as to the usefulness of the smoke shelf. Its intended purpose is to prevent downdrafts and at the same time improve the drawing power of the fireplace. Its existance is based on the premise that cold air is always descending down the back wall of the chimney; when it hits the smoke shelf, it "bounces" forward and upward, mixing with the hot flue gases and helping to lift them up the chimney. As an anti-downdraft deterrent, smoke pushed down the chimney by a gust of wind is supposed to bounce off the shelf and not cause the fireplace to smoke.

The smoke chamber is located above the smoke shelf and throat damper as a sloped compartment across the entire width of the fireplace opening. Due to the considerable expansion of flue gases, compared to the area of throat, the smoke chamber, supposedly thwarting the influx of downdrafts, provides storage for the rising gases.

It is important that the slope of the sides of the chamber be identical with the flue located in the center. Otherwise, the draft would have an irregular effect in the fireplace opening, which would lead to smoke ejected into the room as well as unequal flame formation and combustion. Above the level of the smoke chamber, the first part of the flue should be constructed vertically for at least twenty inches should sloping of the flue be necessary.

3.4-2e Chimney and Flue

The two functions of a chimney are to carry the by-products of combustion out of the house and to supply the draft necessary to support combustion.

In the flue there is a column of air which has a temperature, usually higher than that of an equally high column of outside air, consequently, its specific weight is lower and it is displaced by the heavier outside resulting in draft.

The lift or the amount of draft is dependent on the height of the chimney along with the temperature differential between the exhaust gases and the outside temperature. With equal temperatures present, the exhaust gases of the fireplace are up to ten percent heavier than the outside air. With increasing temperature the gases expand and are reduced in weight so that they become buoyant.

The average temperature loss of the exhaust gas is approximately 1 to 9 degrees fahrenheit for every three feet of chimney height, so in order to maintain sufficient draft the flue must be insulated to maintain a high temperature and a near consistent temperature from top to bottom. The masonry of which a chimney is normally constructed does not serve this purpose as it is a poor insulator. If a masonry chimney is used, a noncombustible insulation should be installed between the exterior and the flue lining. Double-wall, factory-built chimneys with high temperature insulation packed between the walls (*i.e.*, metalbestos) are approximately four times better as insulators than normal chimneys. Not only do insulated chimneys improve draft, they also retard the condensation of tar and creosote. Minimizing condensation in chimneys is important for the following reasons. The condensate is highly corrosive and thus reduces the life expentancy of the chimney system. Creosote is highly flammable and can become a potential fire hazard by providing fuel for chimney fires.

In the case of uninsulated chimneys, they should be located in the interior of the house; the heat loss is less because the temperature differential between the inside and outside of the chimney is less; also, much of the heat loss from the chimney is a heat gain for the house, which, in turn, improves the heating efficiency of the whole system.

Another factor which influences the amount of draft is the amount of friction that the exhaust gases come into contact in their upward movement. The inside of the flue should be as smooth as possible as any projecting parts such as a mortar joint will have the effect of reducing the capacity of the flue area. Whenever possible, the sloping of the flue should be avoided as any change in direction increases friction and also increases the total amount of surface area that the exhaust gases come into contact with, thereby reducing their temperature. If a slope cannot be avoided, it should never be more than thirty degrees off of the vertical.

Aside from the height of the flue, the form of its cross section, round, square, rectangle, plays an important role in draft efficiency. The cross-sectional area of the flue should be 1/10 to 1/12 the net area of the fireplace opening. Depending on the height of the flue (approximately 14 times the height of the hearth), it will be more or less. However, the flue area should never be less than 8 inches by 8 inches.

The height of the flue is usually the result of the building height; it should extend at least 3 feet above the roof, plus any additional footage required to clear the top of the flue from any obstructions within an approximate radius of 10 feet.

3.4-2f Chimney Cap

The use of a chimney cap is a remedy against katabatic winds which occur in the proximity of high buildings or other obstructions where the chimney outlet is below the ridge of the roof, or where the building is erected on the slope of a steep hill.

There are two types of chimney caps: those that arrest downdraft or backdraft by a baffle arrangement (Figure 3.9a), or those which provide an operable closure (Figure 3.9b). The latter operates as a damper unit controlled by a chain or by a low voltage motor, allowing the chimney to be completely closed off or to be used in intermediate positions for adjustable draft. This is one possible solution for those fireplaces which are constructed without throat dampers.

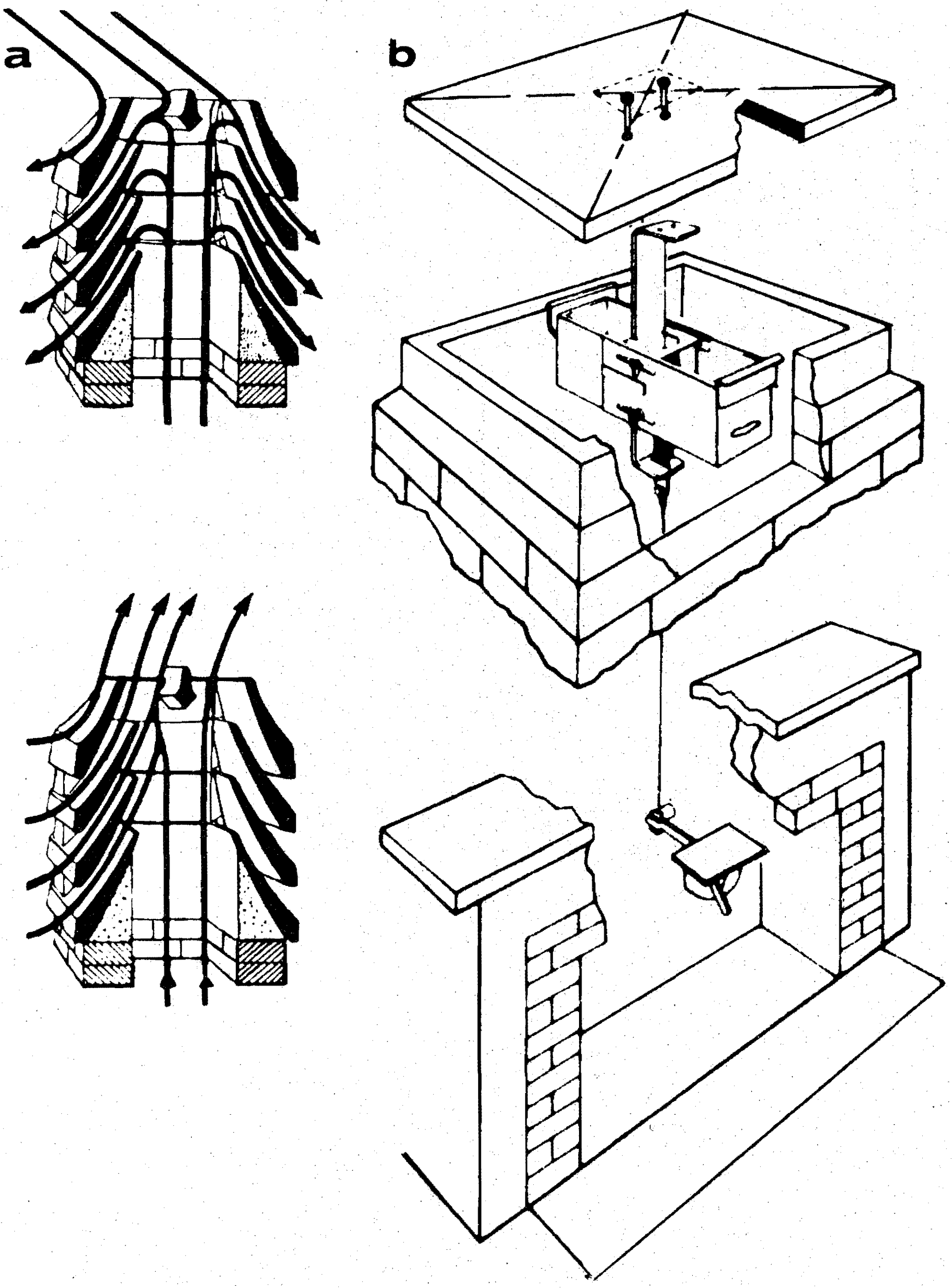


Figure 3.9a & b Chimney Cap with Baffles and Operable Chimney Cap

CHAPTER FOUR: HEAT DISTRIBUTION SYSTEMS

4.0 Introduction

Air temperature is by far the single most important aspect of a person's thermal environment. There are, however, three other factors that influence one's feeling of adequate warmth: the air's humidity, its motions, and the amount of radiant energy traveling through the surrounding space.

Where fireplaces and thermal comfort are concerned, we are primarily interested in the latter two: air movement and infrared radiation.

The effect of infrared radiation is particularly important since so much of the heat output of a fireplace is radiant. Demonstrating the influence of a fireplace on the energy balance of a house, appears something like this: for every 100 units of wood energy put into the fire, 15 units enter the room as radiation from the fireplace, 7 units conduct through the chimney walls and become useful heat if the chimney has its wall surface exposed to the living space, and 8 units of energy leave the house in the air which goes up the chimney.[1]

In a space heated only with an open fireplace there will be extremes in thermal comfort. This is largely due to unequal amounts of radiation coming from two directions, i.e., a person's back located away from the

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[1] Estimate extrapolated from: W.S. Harris and J.R. Martin, "Heat Transmitted to IBR Research Home from the Inside Chimney," Transactions of ASHVE, 1953, pp. 97-112. Re: Jay Shelton, The Woodburners Encyclopedia, Vermont Crossroads Press, 1976.

radiant source will feel much cooler than his front; this is also compounded by the drafts induced by the fireplace.

Drafts or the movement of air influences thermal comfort by enhancing both conduction of heat out of the skin and evaporation, both of which have a cooling sensation for the individual. For example, at typical room temperatures and relative humidities, an air velocity of 3 feet per second makes the air feel about 4^{o}F cooler than stationary air at the same actual temperature.

Taking a pinpoint radiation source such as the fireplace and incorporating it with a distribution system can greatly enhance its comfort conditioning capability by eliminating uneven radiant heat and drafts. It also has the added benefit of increasing net energy heating efficiency as well as reducing the need for constant refueling.

4.1 Heat Distribution Systems - Air

In order to design a fireplace to be incorporated in a heat distribution system it is important that we understand the ways in which a fireplace influences the energy balance in a house. First, radiant energy from the fireplace heats the room it is in. Secondly, heat in the hot flue gases may conduct through the chimney walls into the house, and thirdly, warm house air is pulled into the fireplace and up the chimney.

As reflected by the latter variable, a tremendous amount of air is infiltrated into the house, increasing the actual heat load. (See Section 3.4-1) Use of glass doors can cut back on this excess air entering the fireplace without decreasing the wood combustion rate.

For example, in a particular situation in which the outdoor air temperature is $30^{\circ}F$ and the room temperature is $70^{\circ}F$ and the use of glass doors reduces the air flow from 1,500 to 500 pounds per hour (approximation), the savings realized in heat would be 9,600 BTU per hour.[2]

By reducing the infiltration heat load by the use of glass doors, the first component or the amount of infrared radiation emitted into the room is greatly decreased. As stated previously, most of the heating from an ordinary fireplace is due to radiation received from the flames, coals and warmed surfaces inside the fireplace. Virtually all kinds of glass which are suitable for use in fireplace doors absorb a large percentage of the radiation from the fire. The glass itself, when warmed, re-emits some radiation, but the net effect is a large reduction in the direct heat output; however, the reduction of net radiation emitted provides combustion chamber temperatures which are much hotter than normal. In order to take full advantage of these high combustion temperatures and therefore the use of glass doors, there is a need to extract this heat.

There are several ways in which this can be done. One is to introduce a fluid (Section 4.1, Air and Section 4.2, Water) into a double wall construction located in the fireplace's combustion chamber. This fluid can circulate under natural convection or can be assisted by a blower or pump to transport heat into the immediate space or deliver it to some remote area.

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[2] $.24 \frac{BTU}{^{\circ}F} \times 1000 \text{ lb} \times (70^{\circ} - 30^{\circ}F) = 9{,}600$ BTU/hr.

The most common heat circulating fireplace design in use is the "Heatilator." (See Section 3.4-2b and Figure 3.6) The operation of this device is such that air at floor level is drawn into the unit constantly coming into contact with the back and sides of the combustion chamber. The air is then discharged into the room as warm air from a convenient place located above the fireplace opening.

Figure 4.0 represents several methods whereby the heat discharged into the room can be circulated throughout a multilevel space. The heated air is circulated by natural convection through vents located in the ceiling. Return vents are located on the external wall areas so that cold air can return back to the fireplace combustion chamber. Uncomfortable floor drafts produced by the returning air are eliminated by channeling this air under the floor by way of a duct. This underfloor duct has the added advantage of providing access for incoming outside air.

Heat conduction from the chimney core can be further increased with the addition of glass doors on the fireplace. These doors cut back on excess air entering the fireplace without decreasing the combustion rate. As a result, there is the same quantity of heat produced but less air diluting the combustion products, so, in turn, the flue gases are hotter. With hotter flue gases, the masonry around the fireplace core, as well as the entire chimney, are hotter. Consequently, more heat will enter the house by conduction through the fireplace and chimney walls. The increased heat transfer from an exposed interior masonry chimney is significant, somewhere in the order of 50 percent or more, than chimney heat contribution without glass doors. The addition of a closeable

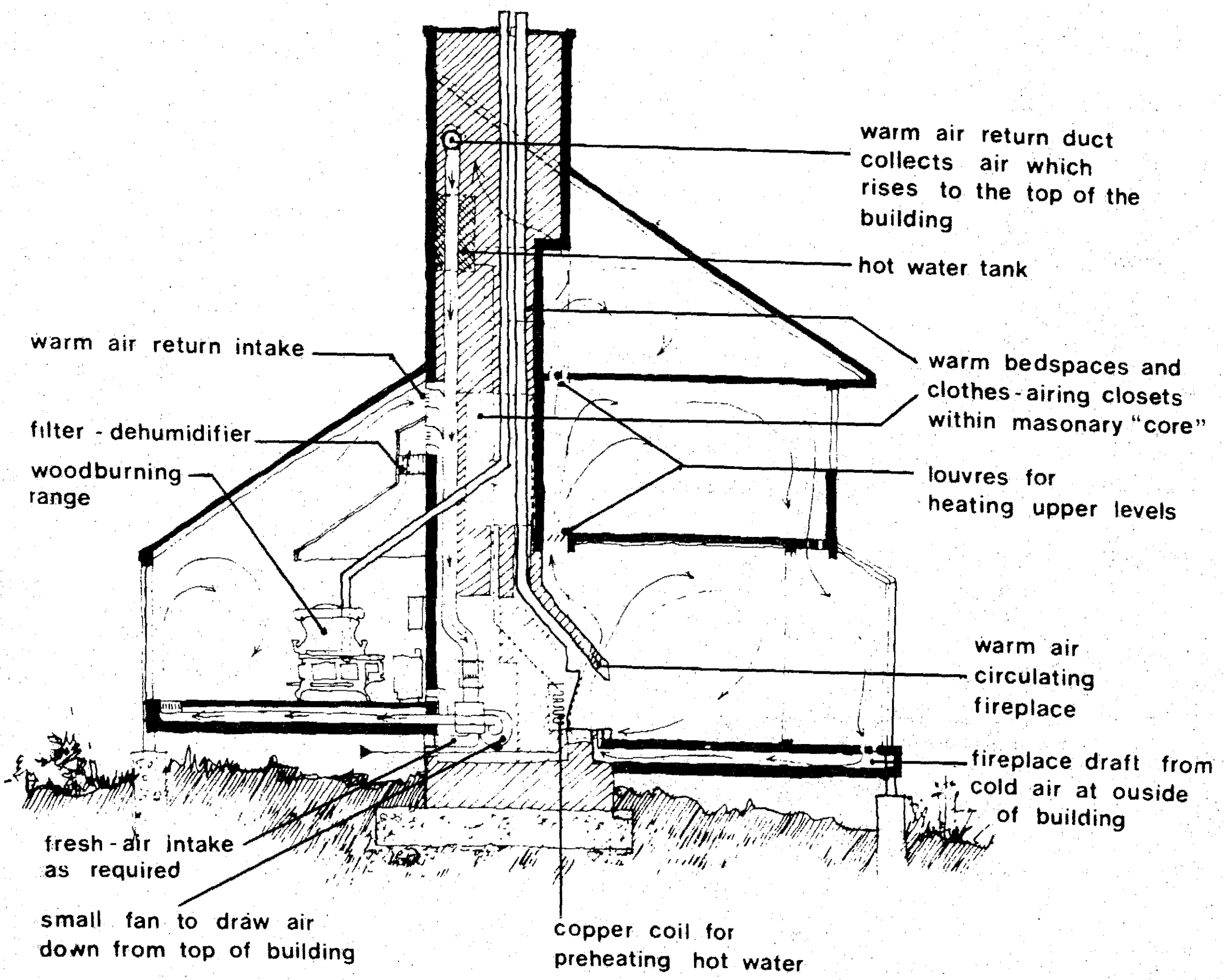

Figure 4.0 Heat Distribution - Natural Convection Air Flow

Source: Energy for the Home, Garden Way Publishing.

chimney cap (Section 2.4-2f) has the added advantage of reducing heat loss from the masonry core via the flue by preventing cooler outside air from entering when the fire is extinguished.

To best utilize the heat transfer from the fireplace, the chimney should be centrally located with all surfaces exposed. An open plan is better suited to obtain a balanced heat effect than one in which the rooms are isolated from each other.

A small fan located at the base of the chimney can be used to recirculate heated air that has collected at the peak of the ceiling. This air, drawn down through the masonry core, will give up a portion of its heat to be stored in the thermal mass of the chimney. This heat reclamation system not only has the ability to capture heat from the fireplace but it also has the added advantage of capturing waste heat produced by cooking as well as heat produced by south facing windows. Normally, heat produced by these solar-oriented windows goes unused because there is no way to circulate it to other parts of the house as well as to store it. With an air circulating system of this type, south facing windows can make a major contribution to the total heating demands.

4.2 Heat Distribution - Water

Heat distribution efficiency can be further increased by the use of water as a heat extraction fluid because of its greater heat exchanging capabilities. One form of heat circulating fireplace which utilizes water (Figure 4.1) does so by circulating the fluid through a double wall construction liner or water circulating grate. The water

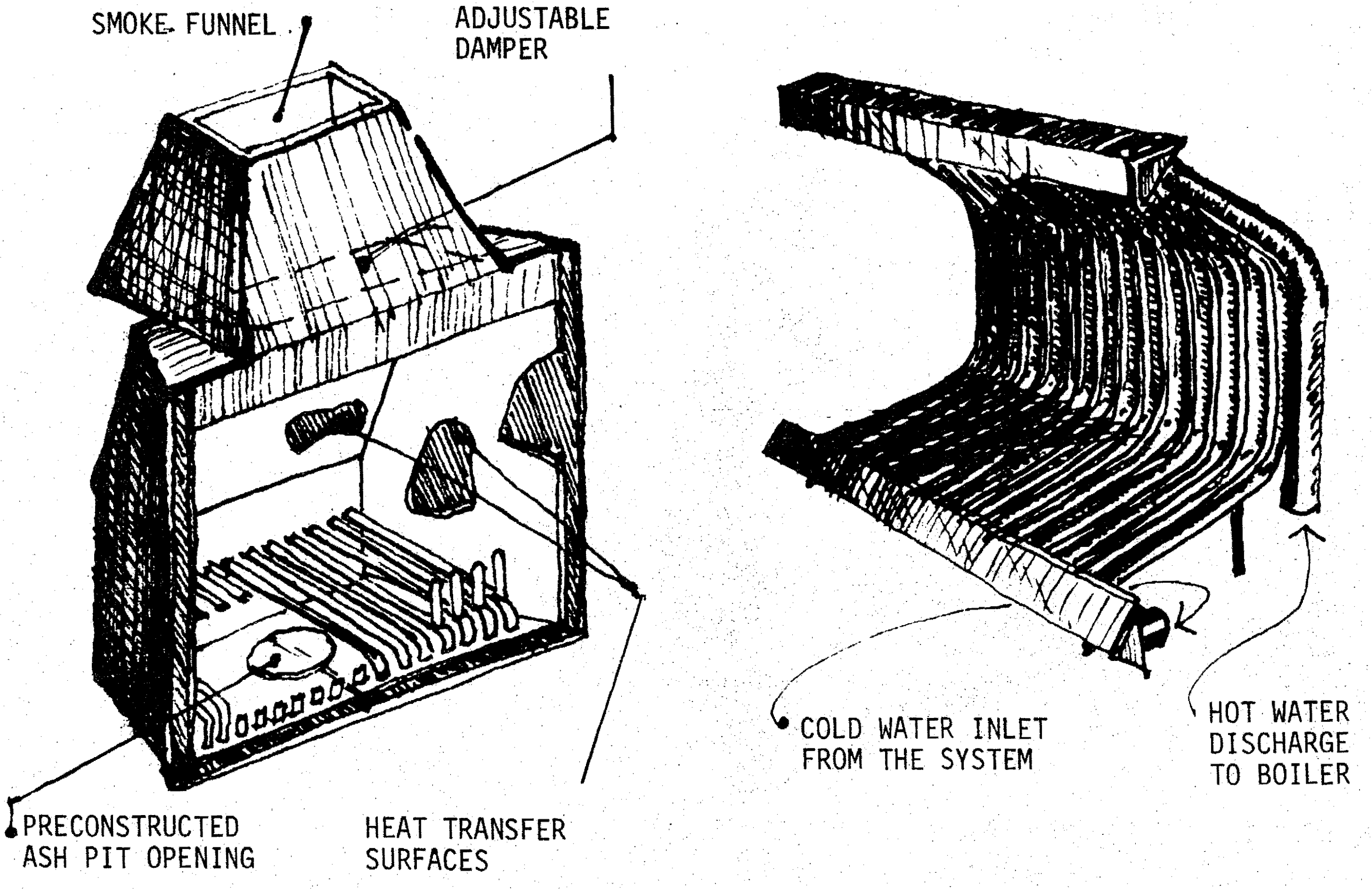

Figure 4.1 Water Circulating Fireplace and Grate

can then be transported to an already existing distribution system whether forced air or radiant.

If a water circulating grate is used, it can also be used in conjunction with an air circulating insert discussed previously.

A water circulating insert couples readily with existing central heating systems, in particular, forced - hot - water systems (Figure 4.2). The fireplace heat exchanger is merely an auxiliary loop tapped into the return line from the baseboard convectors using the already existing furnace circulator pump to transport the water. The only modifications that are required involve connecting the heat exchanger inlet to the existing hot water system return line and from the outlet side of the exchanger to the circulator pump. These connections are made with pipe tees and gate valves so that the original return line is left intact. The advantage of the system is that the conventional oil-burner operation is in no way affected and continues to function normally whenever needed. The household thermostat is set to the desired temperature. If the fireplace heater fails to deliver sufficient heat to keep the space at the pre-set level the oil burner automatically gives added heat as long as necessary.

The only other modification to the already existing system requires putting the circulator pump on a separate circuit so that the pump will operate with the normal burner off. This can be done simply by installing a by-pass switch so that when flipped the pump runs continuously to circulate water from the fireplace coil through the house whether the oil burner is activated or not. With the switch in the other position the pump resumes its original operation.

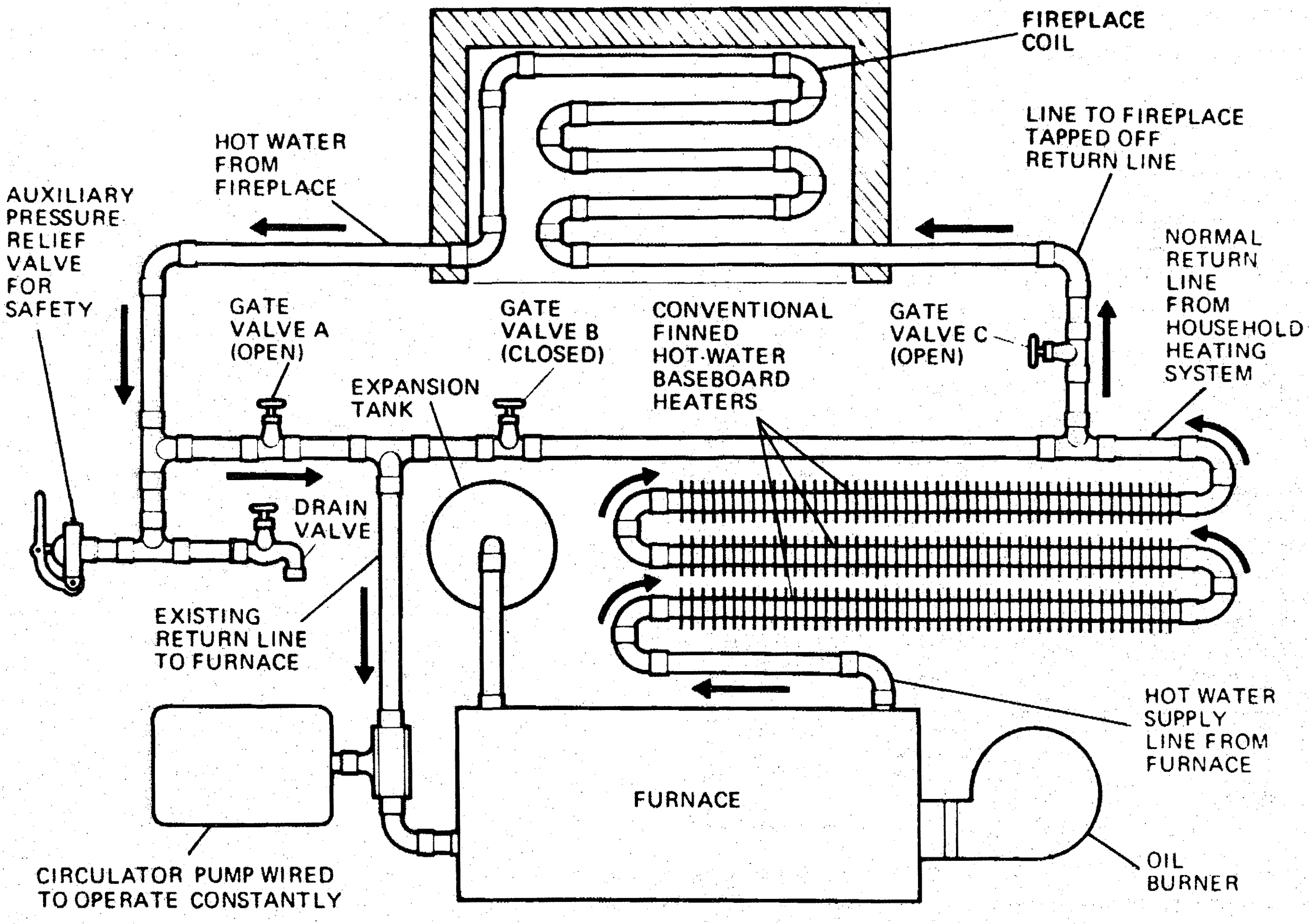

Figure 4.2 Water Circulating Fireplace Heat Extractor Coupled with an Existing Hydronic System

An alternative to this manual switching would be to locate a temperature sensor in the fireplace combustion chamber that would control a switching relay that in turn controls the circulating pump.

In a closed system of this type it cannot be overstressed to include a pressure relief valve (around 125 p.s.i.). This valve will release excess pressure should unusually high temperatures exist, such as in a stagnant or no flow rate situation.

Incorporating a water circulating heat exchanger into an already existing forced air system is somewhat more complex (Figure 4.3). The fireplace circulator is connected to a heat exchanger located in the system's cold air return duct. Water is circulated through the system by a separate pump connected to an expansion tank and pressure relief valve. Because the heating loop is a closed system, an expansion tank must be provided to compensate for the expansion of the water. The tank is partially filled with air which compresses when the heated water expands. The need for this tank as well as the separate circulating pump is eliminated from the previous example because these components are an integral part of the original system. Control logic is the same as with the hydronic system, with the exception of the added pump which is wired in parallel with the furnace blower.

Figure 4.4 shows a fireplace heat exchanger coupled with a storage tank. This system provides flexibility of operation by storing heat in the tank to be later released when a demand exists. Heat does not need to be released immediately as with the previous systems discussed.

This system has the added advantage of operating under no pressure so there is no way for steam to build up to dangerous levels. The

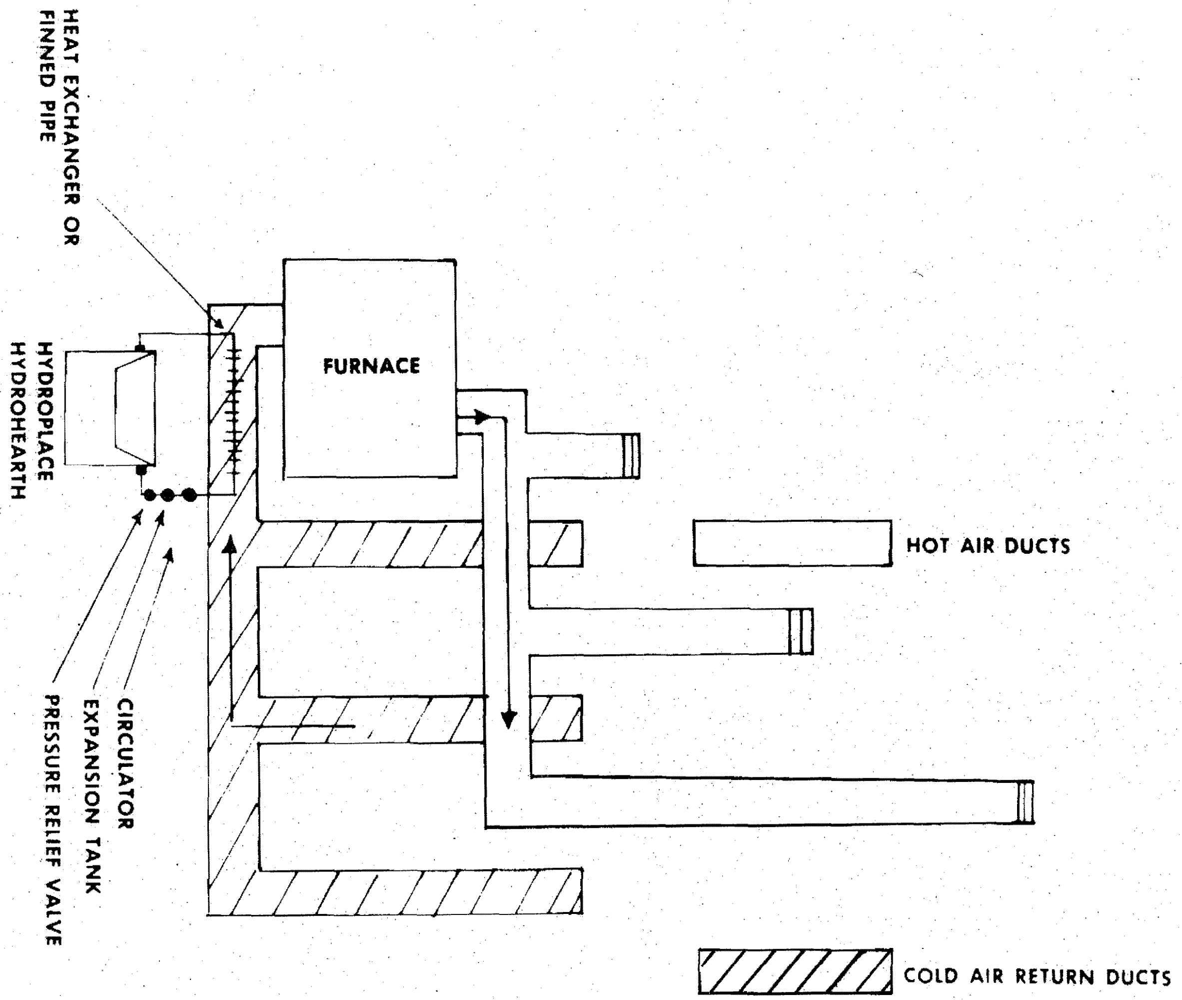

Figure 4.3 Water Circulating Fireplace Heat Extractor Coupled with an Existing Forced Air System

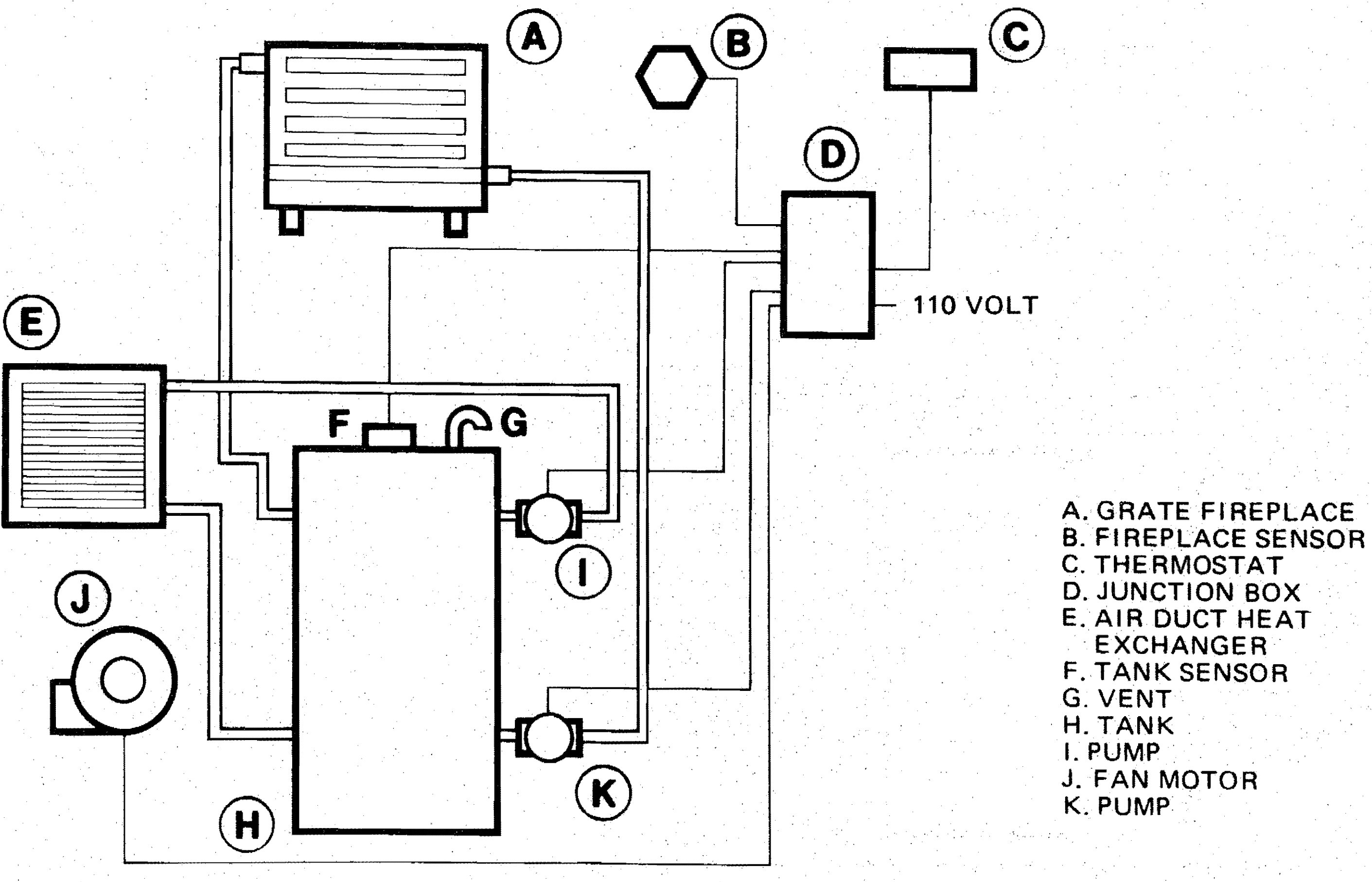

Figure 4.4 Fireplace Heat Extractor Combined with Storage Tank

storage tank, since it is vented, eliminates the need for both a pressure relief valve and expansion tank; however, since this is an open system, provisions must be made to provide automatic water make-up.

The system operation is as follows: when a fire is built in the combustion chamber, sensor B activates pump K which circulates water through the fireplace heat exchanger and to the storage tank H. This operation continues until the fire is no longer delivering any useful heat; at this point pump K ceases its operation. When room thermostat C indicates a heating demand, pump I circulates water through a heat exchanger (18" X 18" X 2") located in the cold air return duct; at the same time the forced air fan blower J is operating. If the tank temperature (sensed by F) is below that of the ambient room temperature (sensed by C), pump K is left inoperable with blower J acting as it normally would with the conventional system.

The control logic is much more involved than the previous examples and requires a differential thermostat D to integrate sensors B, C and F and to make decisions based on the system's operating parameters.

The performance involved with the various systems range from additional heat outputs of 16,000 BTU's per hour to 50,000 BTU's per hour.[3] These variations in heat output are largely due to differences in heat exchange surface area as well as circulating flow rates.

By modifying a standard fireplace (rated at 10-30 percent steady state performance) to include an enclosed fireplace chamber with an

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[3] Based on manufacturers data: A Glow Heat-X-Changer, Inc./Heat-X-Changer, 16,000 BTU; Shenandoah Mfg. Co./Firegrate FG-7, 50,000 BTU.

apparatus for extracting heat by circulating water, the system's performance is increased to 65 - 80 percent or by factors greater than 3.[4]

Price ranges for the fireplace modifications start at $125.00 for owner fabricated and installed water grate heat exchange systems to $700.00 for the fireplace heat exchanger/storage tank systems. Cost effectiveness clearly rests with the owner fabricated unit in that there is a greater BTU output per dollar invested.

4.3 Fireplace As an Auxiliary to a Solar System

Conventional auxiliary systems are designed to meet the heating demands of a space when the solar system can no longer deliver the required heat. This situation usually occurs after the system has experienced long periods of cloudy and overcast days or unusually extreme temperature variations. Moreover, conventional auxiliary systems (gas, electric, oil) act independently of the solar system in such a way that when the storage system can no longer supply the heating needs, it is isolated and replaced by the auxiliary system. This relationship necessitates the auxiliary to be fully-sized to be capable of meeting the total heating demands of the building so that at any point in time there are two systems fully-sized to heat a particular space. Furthermore, depending upon the relationships of the size of the collector, the storage volume and the thermal characteristics of the building, the auxiliary system only operates 25 percent to 40 percent of the time.

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[4] Putnam, J.P., op.cit.

It becomes increasingly apparent that there is a need for a low-cost back up system that can be easily coupled with solar systems.

Fireplaces modified for heat extraction are particularly attractive as an auxiliary source to a solar system for the following listed reasons:

- They are lower in cost than conventional systems.
- Moreover, the wood fuel source can be obtained at lower costs than conventional fuels. (See Section 2.6)
- Because of wood's wide range of availability, it can be classified as a decentralist fuel; therefore, it cannot be controlled by large interests. This provides a fuel source that has a stable price base and low escalation rate.
- The wood fuel draws from a renewable resource base, thus putting a minimum strain on finite fossil fuel resources.
- The environmental impact from woodburning devices is much lower than other fuels. (See Section 2.4)
- Because of the inherent simplicity of woodburning devices, they are extremely reliable and easy to maintain.
- Woodburning devices can operate at different levels of energy demand, therefore providing a tremendous amount of flexibility in the sizing of the solar components (i.e., the overall collector area can be reduced by the amount of dependency on the woodburning device and user participation.

With the aforementioned reasons supported by the environmental impact statements in Section One, it is fair to say that woodburning devices provide methods which are more cost-effective and environmentally sound than what is presently being used as auxiliary systems.

As yet, the largest potential of woodburning devices as an auxiliary to a solar system has not been discussed...that being, when combined with heat storage, the need to constantly fuel and regulate the output is eliminated. Instead, the heat given off by the device, rather than being circulated all at once is then stored until called for to heat the building.

Figure 4.5 shows a simplified piping diagram of a water circulating grate combined with a solar storage system. The operation as well as the control logic is very similar to the example of the open storage system (Figure 4.4). The storage tank is the central organizing element for the entire system. Water is circulated from the tank to the solar collectors B by pump E. In this particular configuration the panels require no inhibitor or antifreeze because the system is designed to automatically drain down when the temperature approaches freezing. The fireplace grate C supplies heat to the storage tank through water to a water heat exchanger H. The other side of the heat exchanger is connected to the already existing electric furnace or forced air system. In this type of installation we are also providing a form of background heat to the space by radiant heating panels. Hot water from the storage tank is circulated by pump F through pipes concealed in the floor. Heat is transmitted through the pipes to the floor and then to the room by radiation and convection. With the radiant panels we are able to utilize low water temperature in the storage tank that could not normally be used in a conventional forced air system. Use of low water temperature with forced air provides a feeling comparable to that of a draft.

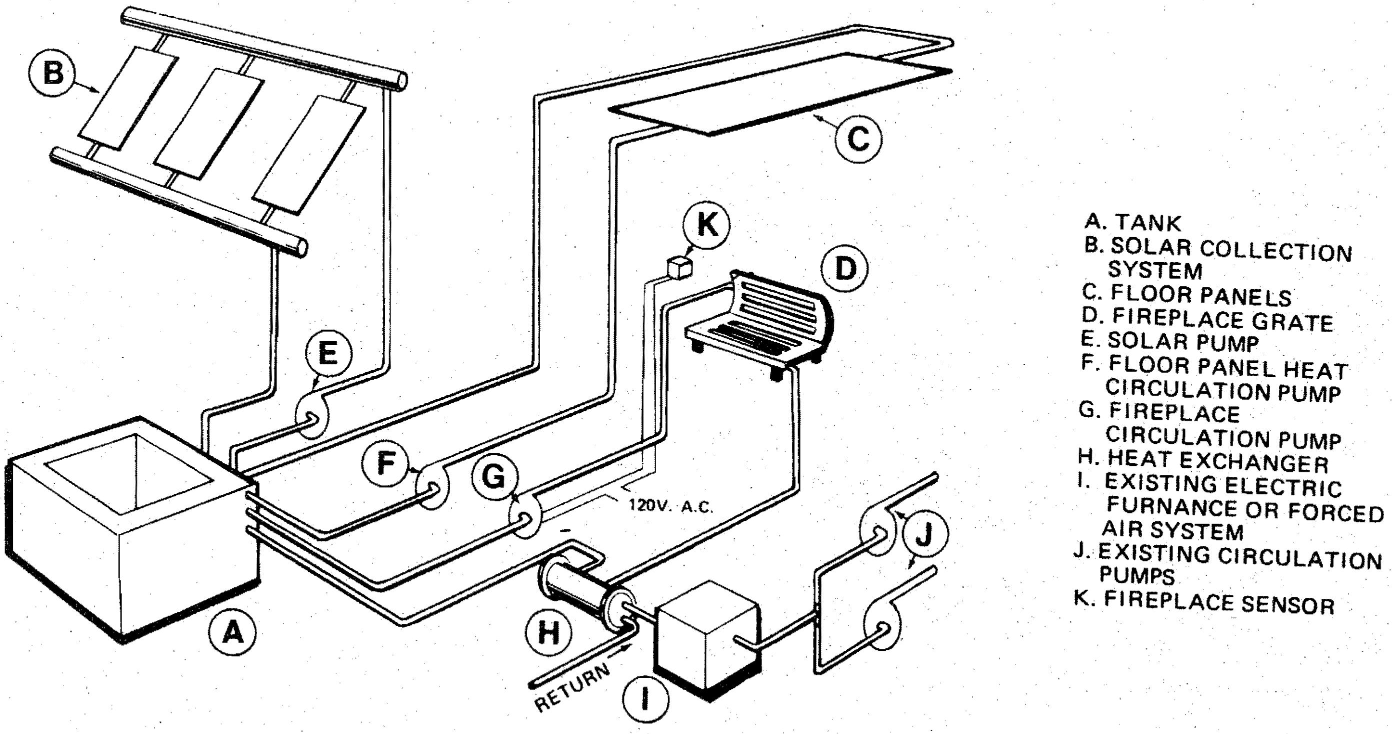

Figure 4.5 Fireplace Heat Extractor Combined with a Solar System

The success of this arrangement lies with the split-system configuration in which the distribution system is matched to the temperature range of each heat-producing component. Since the temperature produced by the fireplace heat exchanger is instantaneous and at a higher level compared to that produced by the solar system, it is directly connected to the forced air system through a water to water or water to air heat exchanger. After the water has passed through the heat exchanger and given up a large portion of its heat, it enters the storage tank at approximately the same temperature as the heated water from the solar collector. If water entered the tank in excess of those temperatures produced by the solar collector, the net effect would be a reduction in collection efficiency. Collector performance is a direct component of the temperature differential between inlet and outlet water temperature. The further apart these two are, the greater the collection efficiency; by the same token, the closer the differential, less collection efficiency is realized. If excess temperatures in comparison to those produced by the solar system were introduced into the storage tank, the overall effect would be to raise the temperature level. This, in turn, would increase the temperature of the collector inlet water lowering solar collection efficiency.

The use of a floor slab for a radiant heat exchanger not only has the benefit of low temperature utilization but also has the advantages of increasing the overall storage capacity, which in turn reduces the size of the water storage tank needed as well as reducing the capacity of the forced air system.

The combination radiant floor slab with a forced air system provides a comfortable as well as thermally efficient system.

Figure 4.6 shows yet another combined fireplace/solar system configuration. This particular system was installed in the residence of Michael L. Connell located near Big Island, Virginia designed by Gregory and Associates of Roanoke, engineered by Owen Engineering of Lynchburg, Virginia and contracted by Solar Structures of Lynchburg.

The 2,600 square foot house has a calculated heat loss of 45,000 BTU/hr. The south facing collectors (336 sq.ft.) are roof mounted and inclined at 53°. The collectors used are Sunworks liquid collectors which consist of copper tubing soft soldered to a copper absorber plate which is coated with a selective black surface.[5] A single piece of 3/16" tempered glass covers the collector. Total cost for the collectors was $3,040 or $9.05 per square foot.

In addition to the solar collector is a fireplace heat exchanger which consists of a water circulating grate constructed of 1/2" diameter, schedule 80, wrought iron pipes with a 1" diameter supply and return manifold. Even though the grate is tested to withstand pressures in excess of 500 p.s.i., a 125 p.s.i. pressure relief valve was installed for protection against superheated water. Water from the fireplace heat exchanger is transported to the storage by a 1/6 hp. water circulating pump. The estimated heat recovery capability of the fireplace heat exchanger is 22,000 BTU per hour which is adequate to provide space heating needs of the house during moderate weather.

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[5] Sunworks, Division of Euthone, Inc., Box 1004, New Haven, Conn. 06508. Manufactured by Solar Structures Inc., Lynchburg, Virginia.

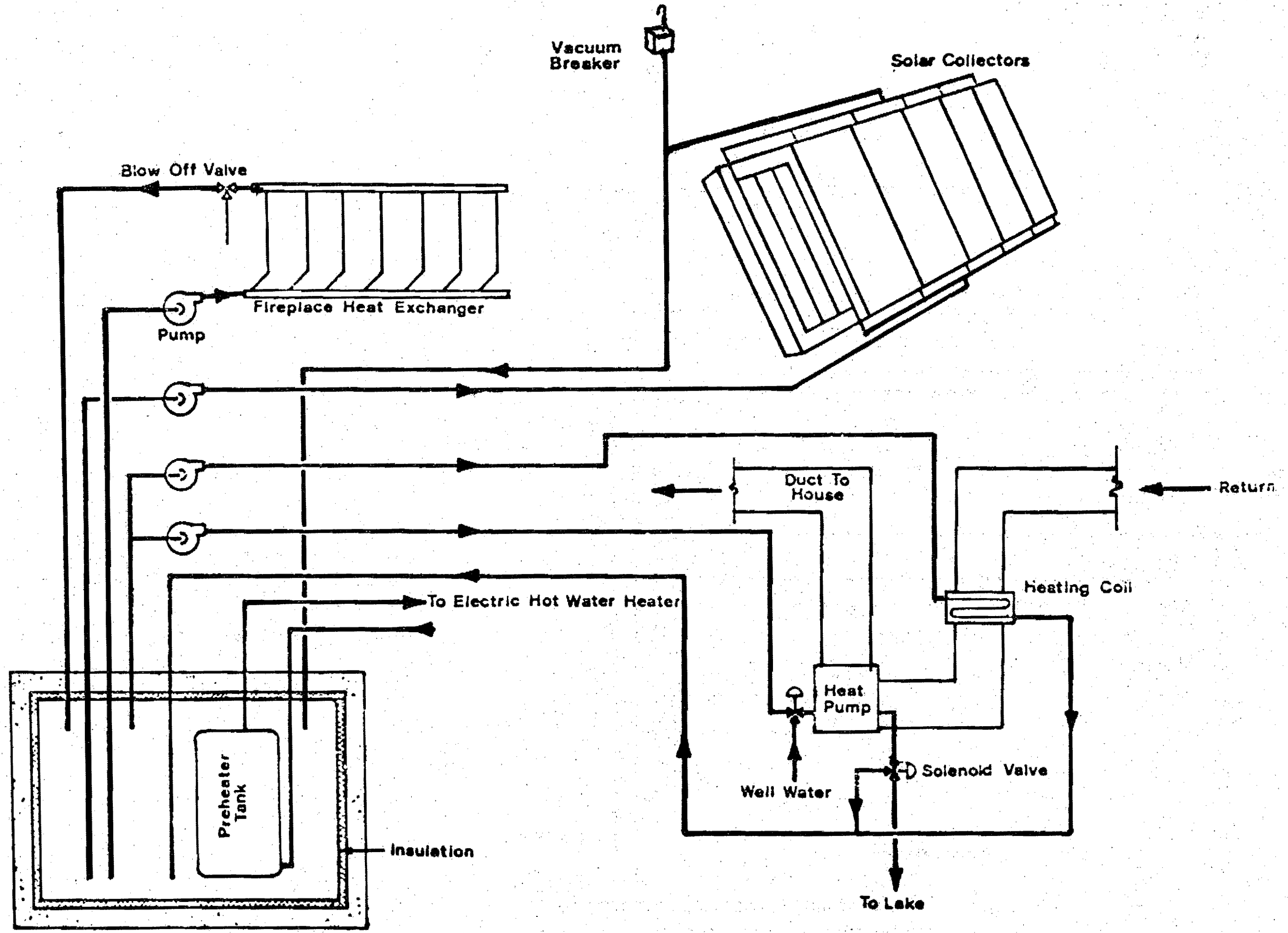

Figure 4.6 Combined Wood and Solar System Piping Diagram (Connell Residence)

The 2,000 gallon precast concrete storage tank is located below grade outside the foundation wall. The tank, a reinforced septic tank with welded steel wire mesh, is insulated on the interior with polyurethane foam (4" in the top half, 2" in the bottom half). The internal application of the urethane eliminates damage to the insulation during transportation of the tank to the site and also isolates the concrete from thermal stresses. The urethane is sealed with 25 mil Butyl rubber. Heat loss calculations show that with an initial 180^{o}F water temperature and a 35^{o} constant ground temperature, there will be a 3^{o} heat loss in the first 24 hours.

Domestic hot water is provided by placing a 42 gallon glass lined preheater tank in the main storage tank. This tank is then connected to a standard hot water heater. With this combination, 70 percent of the domestic hot water needs will be provided by solar.

Hot water from the storage tank is pumped through a heat exchange coil located in the return side of the duct system. This method should provide sufficient heat for the house during most moderate weather conditions or approximately 65 to 70 percent of the time. When the solar storage tank temperature drops below 100^{o}F and heating can no longer be supplied, a York-4 ton water-to-air heat pump is used to supply the space heating requirements. The heat pump can then use the remaining temperature in the storage tank to assist its operation. When the tank temperature drops below 55^{o}F the heat pump switches over to well water to augment its operation.

The control system for the mechanical equipment package involves a differential thermostat manufactured by Deco-Labs. In its normal operation the unit senses the collector plate temperature as well as the water storage tank temperature. When these two temperatures differ by as much as 10°F, the collector circulating pump is cut on. The system continues to operate until the differential between the collector plate and the storage temperature is 5°F and then cuts off.

A computer analysis (F-CHART, see Appendix B) was performed on the Connell residence to determine what percentage the 336 sq. ft. of solar collector supplied to the total heating demand.

With a 5,668 degree-day per year the 2,600 sq. ft. house requires 111 million BTUs to meet the total heat demand. This includes space heating as well as the hot water heating load. According to the program, the specified collector area supplies 49.9 percent of the heating demand leaving a deficit of 55 MBTU to be supplied by the auxiliary. If we were to supply the heating deficit by with wood, it would be equivalent to 1½ cords of hickory at 30.8 MBTU per cord (20 percent moisture content) or $193 in fuel costs assuming delivered wood costs $70 per cord. This is also assuming a fuel conversion efficiency of 65 percent. If the same quantity of heat were to be supplied by an unmodified fireplace with a steady state conversion efficiency of 20 percent, the amount of wood needed would be equivalent to 9 cords or 277 million BTUs or $625. The increased wood consumption and increased fuel cost is due to inefficient combustion in a standard fireplace. The difference in operating fuel costs of $432 makes a strong case for modifying a fireplace to increase its heat-producing capabilities.

If the heat pump were to supply the same equivalent of auxiliary fuel, it would amount to $382 per year. This is assuming an average coefficient of performance of two and electric fuel costs at $.045/kwh.

The solar energy system is supplying energy equivalent to $770 of electricity or $194 of wood (modified fireplace) per year. It becomes increasingly apparent that the economic justification of solar is much easier when electricity is the comparison fuel rather than wood.

The aforementioned figures are representative fuel costs, and they neither reflect the change due to local fuel rates, nor do they reflect fuel escalation rates. These varying relationships can best be determined with the aid of Appendix A.

CHAPTER FIVE: CONCLUSION

Energy use in the 70 million homes in America is substantial, taking about one-fifth of the national total for all sources of energy and about one-third of all electricity generated. Forty-two percent of this total evolves from space heating which is the single largest energy consumptive process in the house.

An estimated 50 percent of the already existing 70 million homes have some form of wood conversion device. Moreover, this device takes the form of a fireplace. The fireplace, as it stands, is terribly inefficient at fuel conversion. Estimated net operating efficiencies range from -5 to 10 percent. In order for the fireplace to make a useful contribution to space heating, simple modifications have to be made. These modifications include: reducing the amount of air the fireplace infiltrates, improving its combustion efficiency, and maximizing the amount of extracted heat.

Once these modifications have been performed and the operating efficiencies attained, they will equal, if not exceed, those of existing fuel conversion devices (excluding electric heat).

In practice, supplementing a conventional heating system with wood can result in a lower usage of total heat, and because fireplace heat extraction devices retrofit readily with these conventional systems, they offer the homeowner an economic alternative to increasing fuel costs.

For those considering the installation of a solar system, a modified fireplace with heat extraction capabilities combined with solar storage can provide an auxiliary fuel source that allows a considerable amount of flexibility in the sizing of the components. The percentage of the heat load that the wood auxiliary provides determines the size of the solar collection system, and this, in turn, becomes a product of convenience and the amount of dependency on the woodburning device.

Wood, as a fuel source, offers some outstanding advantages compared to other sources of energy. First and foremost are their renewability. Secondly, wood energy is a form of solar energy collection and storage that is protected from energy degradation due to the plant's natural protective mechanisms. Thirdly, the air pollution aspects of wood combustion is virtually superior to all fossil fuels. Fourthly, the use of wood as a fuel will not interfere with the carbon dioxide balance of the earth. Fifthly, there is presently an abundance of wood in the United States particularly suited for wood combustion. The careful use and extraction of this wood can actually improve forest ecology. And finally, wood can prove to be a more economic fuel alternative depending on conversion efficiency as well as comparative fuel costs.

Woodburning devices are not the sole answer to total energy reduction. Combined with conservation efforts and a more sensitive approach to energy use, however, reduced consumption can occur.

APPENDIX A: ECONOMICS[1]

This section is included to assist in determining what the net annual savings in fuel costs will amount to if wood is used as a fuel source.

Figure A-1 summarizes the fuel cost comparison of wood to oil, natural gas, electricity, and liquified petroleum (LP) gas. The solid line in each graph represents the break-even fuel prices in the average case of a modified fireplace (or wood stove) with an efficiency of 50 percent, a furnace or boiler efficiency of 65 percent (or 100 percent for electric heat) and wood with a 22.5 million BTU per cord heat value. Under these assumptions, wood heat is less expensive (in terms of fuel costs) if the point on the graph corresponding to the actual prevailing fuel prices falls to the left of the solid line.

The solid line corresponds to the case of average wood, and average efficiencies for the stove and for the furnace. In practice, most people's situations are not average in all three of these respects. The dashed lines represent the break-even fuel prices for a variety of other conditions. To estimate which line is appropriate for a particular case, assess whether each of the three critical characteristics is high, average, ow low; assign the appropriate number to each; and total the numbers.

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[1] Shelton, J.W. <u>The Woodburners Encyclopedia</u>, Vermont Crossroads Press, 1976, p. 88.

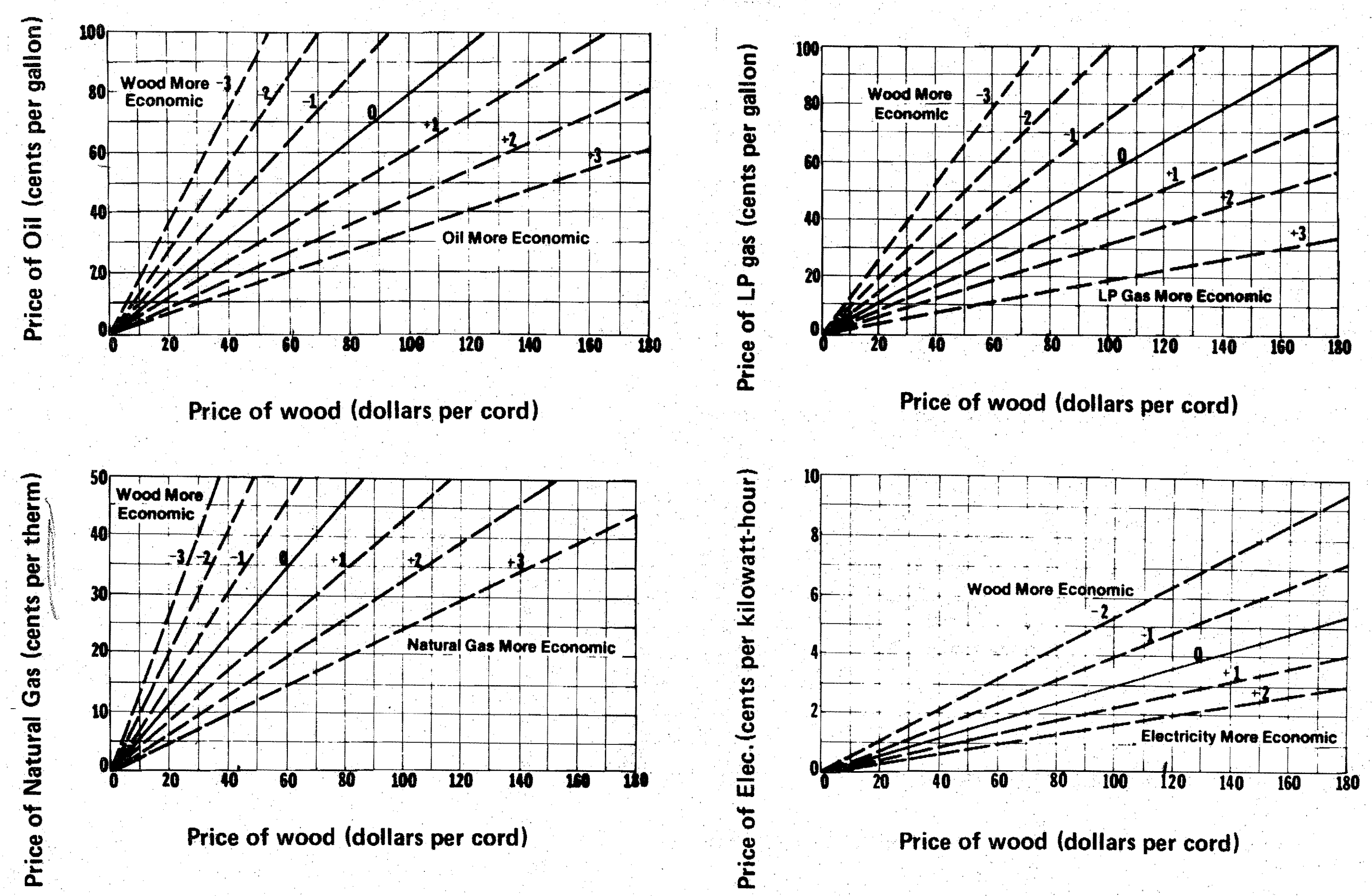

Figure A-1 Fuel Cost Comparisons of Wood to Oil, Natural Gas, Electricity, and Liquified Petroleum

Source: The Woodburners Encyclopedia, Vermont Crossroads Press.

Fireplace net efficiency	high	65%	+1
	average	50%	0
	low	40%	-1
Wood energy content per cord	high	30 MBTU	+1
	average	22.5 MBTU	0
	low	17 MBTU	-1
Conventional heating system net efficiency (use 0 for electric heat)	high	85%	-1
	average	65%	0
	low	50%	+1

For example, if the fireplace is unmodified and has a low energy efficiency, the corresponding number for this category is -1. If the available wood has a high energy content (such as hickory or oak), +1 is the score for this category. If the conventional heating system is old or poorly maintained, the number for this category would be +1. The sum of these three numbers would be +1. Wood is the more economic fuel in this case if the point on the graph corresponds to the actual prices of the comparison fuel and wood falls to the left of the dashed +1 line.

In order for a wood system to be economical overall, the annual savings in fuel costs must be enough to pay for the system's initial cost. This typically requires the annual fuel-cost savings to be about 10 percent of the initial investment. If the price of wood is very near the break-even price, the savings will never be large.

APPENDIX B: F-CHART

The computer program, F-CHART, was developed by the Solar Energy Laboratory, University of Wisconsin. The program, written in standard FORTRAN II for use in interactive mode, can be used to determine the annual performance and economic assessment of a specified collector or to find an economic optimum collector area for a given location. The latter case is the most beneficial for our purposes. When the computer is asked to optimize the collector area in terms of economics, it weighs several variables, among which is the cost of meeting the heating demands with the solar system to meeting the heating demands with existing fuels and determining the correct solar to auxiliary relationship.

For example, if auxiliary fuel costs are inexpensive in comparison to the cost of solar, the collector will be sized to carry a smaller portion of the heating load or vice versa.

Table B-1 shows the variable description as well as the sample data input for each run. Run #1 shows the data input used for the Connell residence discussed in Chapter 4. Run #2 represents the input data required to optimize the collector area to the available auxiliary fuel, wood. Finally, Run #3 is an optimization of collector area using electric heat as the auxiliary fuel.

Sample data output showing a thermal analysis for each run as well as what percentage of the total heating load the solar system is supplying can be found in Table B-2.

Table B-1 Variable Description for F-CHART and Sample Data Input for Run #1 - Run #3

CODE	VARIABLE DESCRIPTION	Run #1	Run #2	Run #3	Units
1	AIR SYSTEM=1, LIQUID SYSTEM=2....................	2			--
2	COLLECTOR AREA.................................	336			FT2
3	FRPRIME-TAU-ALPHA PRODUCT(NORMAL INCIDENCE).......	0.70			--
4	FRPRIME-UL PRODUCT.............................	0.83			BTU/H-F-F2
5	NUMBER OF TRANSPARENT COVERS......................	1			--
6	COLLECTOR SLOPE................................	53			DEGREES
7	AZIMUTH ANGLE (E.G. SOUTH=0, WEST=90)............	0			DEGREES
8	STORAGE CAPACITY...............................	49.58			BTU/F-FT2
9	EFFECTIVE BUILDING UA............................	692			BTU/HR-F
10	CONSTANT DAILY BLDG HEAT GENERATION..............	0			BTU/DAY
11	HOT WATER USAGE................................	80			GAL/DAY
12	WATER SET TEMPERATURE............................	120			F
13	WATER MAIN TEMPERATURE...........................	51			F
14	CITY CALL NUMBER................................	68			--
15	THERMAL PRINT OUT BY MONTH=1, BY YEAR=2..........	1			--
16	ECONOMIC ANALYSIS ? YES=1, NO=2..................	1			--
17	USE OPTMIZD. COLLECTOR AREA=1, SPECFD. AREA=2.....	2	1	1	--
18	PERIOD OF THE ECONOMIC ANALYSIS..................	20			YEARS
19	COLLECTOR AREA DEPENDENT SYSTEM COSTS............	10			$/FT2 COLL
20	CONSTANT SOLAR COSTS.............................	1500			$
21	DOWN PAYMENT(_ OF ORIGINAL INVESTMENT)...........	25			%
22	ANNUAL INTEREST RATE ON MORTGAGE.................	8.75			%
23	TERM OF MORTGAGE.................................	20			YEARS
24	ANNUAL NOMINAL(MARKET) DISCOUNT RATE.............	8			%
25	EXPENSES(INSUR.,MAINT.) OF SYSTEM IN 1ST YEAR.....	0			$
26	ANNUAL _ INCREASE IN ABOVE EXPENSES..............	6			%
27	PRESENT COST OF AUXILIARY FUEL (CF)..............	13.88	3.30	13.88	$/MBTU
28	CF RISE' LINEAR=1,_/YR=2,SEQ. OF VALUES=3.........	2			--
29	IF 1, WHAT IS THE SLOPE OF CF INCREASE?..........	0			--
30	IF 2, WHAT IS THE ANNUAL RATE OF CF RISE?.........	10			%
31	ECONOMIC PRINT OUT BY YEAR=1, CUMULATIVE=2........	2			--

Table B-1 Variable Description for F-CHART and Sample Data Input for Run #1 - Run #3 (Continued)

CODE	VARIABLE DESCRIPTION	Run #1	Run #2	Run #3	Units
32	EFFECTIVE FEDERAL-STATE INCOME TAX RATE............	30			%
33	TRUE PROP. TAX RATE PER $ OF ORIGINAL INVEST.......	.0192			%
34	INCOME PRODUCING BUILDING? YES=1, NO=2.............	2			--

Table B-2 Thermal Analysis

Specified Collector Area
336 sq. ft./electric heat auxiliary

```
****THERMAL ANALYSIS****
 TIME PERCENT INCIDENT HEATING WATER DEGREE AMBIENT
       SOLAR     SOLAR     LOAD   LOAD   DAYS     TEMP
                (MBTU)   (MBTU) (MBTU) (F-DAY)  (F)
 JAN    28.0     11.76    18.39   1.41  1107.    30.
 FEB    41.1     14.53    15.99   1.28   963.    32.
 MAR    47.7     15.39    13.54   1.41   815.    37.
 APR    67.0     14.46     7.51   1.37   452.    50.
 MAY   100.0     15.61     3.04   1.41   183.    59.
 JUN   100.0     14.53     0.38   1.37    23.    68.
 JUL   100.0     15.06     0.0    1.41     0.    72.
 AUG   100.0     14.47     0.10   1.41     6.    70.
 SEP   100.0     15.06     1.33   1.37    80.    64.
 OCT    81.9     14.98     5.66   1.41   341.    54.
 NOV    47.9     13.03    11.06   1.37   666.    41.
 DEC    32.3     12.57    17.14   1.41  1032.    32.
 YR     49.9    171.43    94.14  16.64  5668.
```

Optimized Collector Area
253 sq. ft./wood heat auxiliary

```
****THERMAL ANALYSIS****
 TIME PERCENT INCIDENT HEATING
       SOLAR     SOLAR     LOAD
                (MBTU)   (MBTU)
 JAN    21.7      8.84    18.39
 FEB    32.2     10.93    15.99
 MAR    37.7     11.57    13.54
 APR    54.4     10.88     7.51
 MAY    90.9     11.74     3.04
 JUN   100.0     10.93     0.38
 JUL   100.0     11.33     0.0
 AUG   100.0     10.88     0.10
 SEP   100.0     11.33     1.33
 OCT    68.1     11.76     5.66
 NOV    37.9      9.80    11.06
 DEC    25.1      9.46    17.14
 YR     41.4    128.94    94.14
```

Optimized Collector Area
1094 sq. ft./electric heat auxiliary

```
****THERMAL ANALYSIS****
 TIME PERCENT INCIDENT HEATING
       SOLAR     SOLAR     LOAD
                (MBTU)   (MBTU)
 JAN    70.0     38.28    18.39
 FEB    92.2     47.32    15.99
 MAR    98.5     50.11    13.54
 APR   100.0     47.10     7.51
 MAY   100.0     50.82     3.04
 JUN   100.0     47.31     0.38
 JUL   100.0     49.03     0.0
 AUG   100.0     47.11     0.10
 SEP   100.0     49.06     1.33
 OCT   100.0     48.77     5.66
 NOV    97.0     42.42    11.06
 DEC    77.6     40.94    17.14
 YR     89.1    558.27    94.14
```

Tables B-3 through B-5 show an economic summary of all three runs. The summary or life-cycle cost benefit analysis concludes with the total cost of operating the solar system over a 20-year span versus total cost of operation without solar.

Table B-3 Economic Analysis/Specified Collector Area 336 sq. ft. with Elect Heat Auxiliary

```
****ECONOMIC ANALYSIS****
SPECIFIED COLLECTOR AREA =  336. FT2
INITIAL COST OF SOLAR SYSTEM($)=   4860.
      MORT      INTRST DEPRC  PRP.TX INC.TX    FUEL   MISC      TOTAL   SOLAR
YR    PAYMT      PAID  DEDUCT  PAID   SAVED  EXPNSE EXPNSE      COST  SAVNGS
 1      392.     319.      0.     1.     96.    770.     0.     1067.    470.
 2      392.     313.      0.     1.     94.    847.     0.     1146.    545.
 3      392.     306.      0.     1.     92.    932.     0.     1233.    627.
 4      392.     298.      0.     1.     90.   1025.     0.     1328.    718.

 5      392.     290.      0.     1.     87.   1127.     0.     1433.    818.
 6      392.     281.      0.     1.     85.   1240.     0.     1549.    927.
 7      392.     271.      0.     1.     82.   1364.     0.     1676.   1048.
 8      392.     260.      0.     1.     78.   1501.     0.     1815.   1181.
 9      392.     249.      0.     1.     75.   1651.     0.     1969.   1327.
10      392.     236.      0.     1.     71.   1816.     0.     2138.   1488.
11      392.     223.      0.     1.     67.   1997.     0.     2323.   1665.
12      392.     208.      0.     1.     63.   2197.     0.     2527.   1859.
13      392.     192.      0.     1.     58.   2417.     0.     2752.   2073.
14      392.     174.      0.     1.     53.   2658.     0.     2999.   2309.
15      392.     155.      0.     1.     47.   2924.     0.     3270.   2568.
16      392.     134.      0.     1.     41.   3217.     0.     3569.   2853.
17      392.     112.      0.     1.     34.   3538.     0.     3898.   3167.
18      392.      87.      0.     1.     26.   3892.     0.     4259.   3513.
19      392.      61.      0.     1.     18.   4281.     0.     4656.   3892.
20      392.      32.      0.     1.     10.   4709.     0.     5093.   4310.
PRESENT WORTH OF YEARLY TOTAL COSTS WITH SOLAR($)=       21473.
PRESENT WORTH OF YEARLY TOTAL COSTS W/O SOLAR($) =       34085.
```

Table B-4 Economic Analysis/Optimized Collector Area, 253 sq. ft. with Wood As Auxiliary

```
****ECONOMIC ANALYSIS****
OPTIMIZED COLLECTOR AREA =  253. FT2
INITIAL COST OF SOLAR SYSTEM($)=   4027.
     MORT    INTRST DEPRC  PRP.TX INC.TX   FUEL   MISC    TOTAL   SOLAR
YR   PAYMT    PAID  DEDUCT  PAID   SAVED  EXPNSE EXPNSE    COST  SAVNGS
 1     325.    264.     0.     1.   80.    214.      0.     460.   -95.
 2     325.    259.     0.     1.   78.    235.      0.     483.   -81.
 3     325.    253.     0.     1.   76.    259.      0.     509.   -66.
 4     325.    247.     0.     1.   74.    285.      0.     536.   -50.
 5     325.    240.     0.     1.   72.    313.      0.     567.   -32.
 6     325.    233.     0.     1.   70.    345.      0.     601.   -12.
 7     325.    225.     0.     1.   68.    379.      0.     637.    10.
 8     325.    216.     0.     1.   65.    417.      0.     678.    34.
 9     325.    206.     0.     1.   62.    459.      0.     723.    61.
10     325.    196.     0.     1.   59.    505.      0.     772.    90.
11     325.    185.     0.     1.   56.    555.      0.     825.   123.
12     325.    172.     0.     1.   52.    611.      0.     885.   158.
13     325.    159.     0.     1.   48.    672.      0.     950.   198.
14     325.    144.     0.     1.   44.    739.      0.    1021.   241.
15     325.    129.     0.     1.   39.    813.      0.    1100.   288.
16     325.    111.     0.     1.   34.    894.      0.    1186.   341.
17     325.     93.     0.     1.   28.    984.      0.    1281.   398.
18     325.     72.     0.     1.   22.   1082.      0.    1386.   462.
19     325.     50.     0.     1.   15.   1190.      0.    1501.   532.
20     325.     26.     0.     1.    8.   1309.      0.    1627.   609.
PRESENT WORTH OF YEARLY TOTAL COSTS WITH SOLAR($)=      8352.
PRESENT WORTH OF YEARLY TOTAL COSTS W/O SOLAR($) =     8104.
--
```

Table B-5 Economic Analysis/Optimized Collector Area, 1094 sq. ft. with Electric Heat Auxiliary

```
****ECONOMIC ANALYSIS****
OPTIMIZED COLLECTOR AREA = 1094. FT2
INITIAL COST OF SOLAR SYSTEM($)=  12442.
      MORT      INTRST DEPRC  PRP.TX INC.TX    FUEL   MISC      TOTAL    SOLAR
YR    PAYMT      PAID  DEDUCT  PAID   SAVED   EXPNSE EXPNSE      COST    SAVNGS
 1     1004.      817.     0.     2.   246.     167.     0.       928.     610.
 2     1004.      800.     0.     2.   241.     184.     0.       949.     742.
 3     1004.      782.     0.     2.   235.     202.     0.       973.     887.
 4     1004.      763.     0.     2.   230.     222.     0.       999.    1047.

 5     1004.      742.     0.     2.   223.     245.     0.      1028.    1223.
 6     1004.      719.     0.     2.   216.     269.     0.      1059.    1417.
 7     1004.      694.     0.     2.   209.     296.     0.      1094.    1630.
 8     1004.      667.     0.     2.   201.     326.     0.      1131.    1865.
 9     1004.      637.     0.     2.   192.     358.     0.      1173.    2123.
10     1004.      605.     0.     2.   182.     394.     0.      1218.    2407.
11     1004.      570.     0.     2.   172.     433.     0.      1268.    2720.
12     1004.      532.     0.     2.   160.     477.     0.      1323.    3064.
13     1004.      491.     0.     2.   148.     524.     0.      1383.    3443.
14     1004.      446.     0.     2.   134.     577.     0.      1449.    3859.
15     1004.      397.     0.     2.   120.     634.     0.      1521.    4318.
16     1004.      344.     0.     2.   104.     698.     0.      1600.    4822.
17     1004.      286.     0.     2.    87.     768.     0.      1687.    5377.
18     1004.      223.     0.     2.    68.     844.     0.      1783.    5986.
19     1004.      155.     0.     2.    47.     929.     0.      1888.    6660.
20     1004.       81.     0.     2.    25.    1022.     0.      2003.    7400.
PRESENT WORTH OF YEARLY TOTAL COSTS WITH SOLAR($)=       14645.
PRESENT WORTH OF YEARLY TOTAL COSTS W/O SOLAR($) =       34085.
```

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1977 - Solar Heating Applied to Wood Processing Workshop, Blacksburg, Virginia

1976 - New England Solar Energy Society Conference, Amherst, Massachusetts

- Passive Solar Heating and Cooling Conference, Albuquerque, New Mexico

1975 - Virginia Solar Energy Society Organizational Meeting, Richmond, Virginia

- Solar Energy Storage Subsystems for the Heating and Cooling of Buildings Workshop, Charlottesville, Virginia

1974 - 95th Winter Annual Meeting, ASME, Solar Energy Conference, New York, New York

- International Solar Energy Society, U.S. Section, Colorado State University, Fort Collins, Colorado

- NSF/RANN Workshop on Solar Heating and Cooling of Buildings, Washington, D.C.

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1977 - Speaker: Solar Energy Applied to Wood Processing Techniques, Blacksburg, Virginia

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- Consultant: William Heald, solar and wood heated residence, Newport, Virginia

- Lecturer: Descriptive Environmental Systems/Alternative Energy Sources, College of Architecture, Virginia Polytechnic Institute and State University

1975 - Consultant: Virginia Science Museum on Energy Futures, Educational Mobile Exhibit

- Speaker: Tennessee Valley Alternatives Workshop/ Natural Energy Systems, Knoxville, Tennessee

- Graduate Research Assistant in the Professional Division, College of Architecture, Virginia Polytechnic Institute and State University

- Lecturer: Alternative Natural Energy Sources in Building Design, presented to third-year College of Architecture, Virginia Polytechnic Institute and State University

- Partner: Passive Energy Systems Consulting Firm, Blacksburg, Virginia

- Consultant: Land and Building Research Corporation, Blacksburg, Virginia. Solar energy and site adaptation of 200 low-income housing units

- Consultant: Marvin C. Meador, private solar and wood-heated residence, Smith Mountain Lake, Virginia

- Information exchange with project leaders of NASA Solar Energy Residence

- Current Project: Production of an educational film utilizing a thermographic camera to increase one's energy awareness by visually indicating thermal energy flaws

- Current Project: Development of low cost solar and wood-heating systems for single and multiple family residences

1974 - Topic leader on energy conservation and alternatives at Programming and Site Planning Workshop of the Science Museum of Virginia, Roanoke, Virginia

- Consultant: Neal Gross, Low Cost Energy Self-Sufficient Residence, Paint Bank, Virginia

FIREPLACE ANALYSIS FOR EFFICIENT FUEL CONVERSION AS AN AUXILIARY SYSTEM FOR SPACE HEATING

by

Robert Paul Schubert

(ABSTRACT)

Existing fireplaces are extremely inefficient in fuel conversion and space heating capabilities. Simple modifications can be performed to improve the combustion efficiency of fireplaces to equal, if not exceed, those of existing fuel conversion devices.

This study investigates ways in which the fireplace can be designed to effectively withdraw the heating potential from a given amount of wood and distribute this heat effectively to climatize a space.