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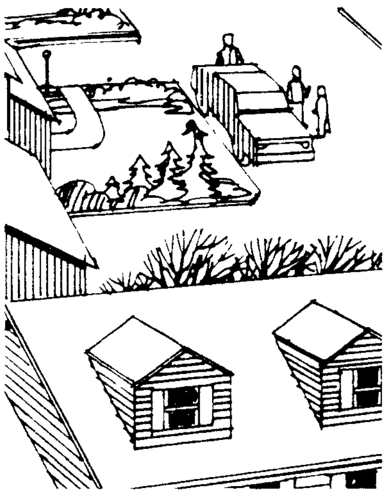
Residential Wood Combustion Study

Task 4
Technical Analysis of Wood Stoves



TECHNICAL ANALYSIS OF WOOD STOVES

Combustion Principles

Design Considerations

Operating Techniques

RESIDENTIAL WOOD COMBUSTION STUDY TASK 4

Technical Analysis of Wood Stoves

Combustion Principles

Design Considerations

Operating Techniques

<u>FINAL REPORT</u>

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THIS REPORT CONSISTS OF SEVERAL DIFFERENT PARTS.

THEY ARE LISTED BELOW FOR YOUR CONVENIENCE.

EPA 910/9-82-089a	Residential Wood Combustion Study Task 1 - Ambient Air Quality Impact Analysis
EPA 910/9-82-089b	Task 1 - Appendices
EPA 910/9-82-089c	Task 2A - Current & Projected Air Quality Impacts
EPA 910/9-82-089d	Task 2B - Household Information Survey
EPA 910/9-82-089e	Task 3 - Wood Fuel Use Projection
EPA 910/9-82-089f	Task 4 - Technical Analysis of Wood Stoves
EPA 910/9-82-089g	Task 5 - Emissions Testing of Wood Stoves Volumes 1 & 2
EPA 910/9-82-089h	Task 5 - Emissions Testing of Wood Stoves Volumes 3 & 4 (Appendices)
EPA 910/9-82-089i	Task 6 - Control Strategy Analysis
EPA 910/9-82-089j	Task 7 - Indoor Air Quality

DISCLAIMER

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Design and operation of residential wood combustion devices influence both performance and emissions. Important design considerations include mechanisms to increase thermal efficiency and improve combustion efficiency. Both these efficiencies must be relatively high to have an overall efficient residential wood combustion (RWC) device. Until the last five years or so, levels of residential wood combustion were low enough that there was no real demand for improved stove designs which increase efficiencies and decrease emissions. There remains considerable room for improvement in the design of stoves. Some of these improved units are beginning to appear, but emission test results from these units are limited. It is expected that in the next few years the emerging stove technology will result in substantial emission reductions, possbily by as much as 75%. However, design alone is not sufficient to assure an efficient operation and reduce emissions from RWC devices. The overall efficiency of all these devices is ultimately determined by the operator. Variables such as fuel, charging rate, and combustion air regulation greatly impact performance and emissions.

In order to obtain the highest overall efficiency while still minimizing air contaminant emissions, the following practices must be observed.

1. Stoves should be sized to encourage operation at a moderate to high burning rate (greater than 32 $kg/hr\text{-}m^3$, or 2 $lb/hr\text{-}ft^3$, dry fuel basis)*. Automatic regulation of combustion air to facilitate an even and

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*The recommended burn rate is expressed as mass of wood consumed per hour per volume of combustion chamber; e.g., for a stove with a firebox of 1.5 ft^3 this is a burn rate of 3 lb/hour.

moderate burning further improves overall efficiency.

2. Charging a stove with an excessive amount of wood decreases efficiency. When this occurs, combustion air must be restricted to maintain the desired output or the heat generated must be wasted which reduces the overall efficiency. Overnight banking of fires should be discouraged since the resulting combustion is poor and excessive amounts of pollutants are generated.

3. Seasoning the fuel properly increases the usable heat of the fuel. Therefore, less seasoned fuel is required to operate the appliance to provide the same amount of heat.

4. Operate fireplaces only during mild weather (temperature) conditions. Use doors to close off heated room air losses during low fires or during periods when the fireplace is not in use. Burn fireplace with full hot fires to maximize efficiency and reduce emissions. Existing information is contradictory on whether or not fireplace doors in conjunction with outside combustion air significantly improves efficiency.

5. Add-on (retrofit) devices such as catalysts and automatic thermostats can improve efficiencies and reduce emissions in some instances. However, improvements in operator firing techniques appear to have a far more significant impact on efficiencies and emissions for existing units.

Continued effort needs to be undertaken to investigate new stove designs. There appears to be considerable room to improve both combustion and thermal efficiency while reducing air contaminant emissions. It is expected that some of the currently emerging units with advanced engineering designs will enable significant emission reductions to be achieved. Nonetheless, it appears that a considerable reduction in contaminants from existing units could be realized by providing more public information and education on proper firing techniques.

I. INTRODUCTION

Fire has been used as a source of heat for thousands of years. During that time, wood heating has progressed from the open pit to a semi open pit (a fireplace) to an enclosed pit (a wood stove). When fuel was plentiful and air pollution of no concern, there was little need for an efficient fireplace or stove with reduced air pollution.

It was recognized that wood heating provided only a local source of heat and warmth. They also required great care and abundant labor to minimize fire danger and supply sufficient fuel. As new fuels and heating systems were developed, the use of the fireplace and wood stove as a primary heat source diminished.

It was not until this past decade, when conventional fuel prices escalated, that wood heating started to be more popular. People who had switched away from wood heat as a fuel are now starting to switch back. The popular trend to use wood, either as a primary or auxiliary fuel, has been gaining momentum. This is placing a demand on the availability of fuel and a burden on our air quality.[23] In an effort to reduce fuel demand and improve air quality, numerous studies have been instituted on wood heating systems, particularly on wood stoves. Although wood heating systems include fireplaces, stoves, fireplace inserts, central furnaces and boilers, this report will emphasize data regarding fireplaces and stoves. An overview of general information in provided in this report. Basic combustion principles, efficiencies and combustion variables are discussed in Section II. The influence of design configurations on combustion with the resultant formation of pollutants is investigated in Section III.

Modification to the combustion system and the heat transfer mechanism by design or retrofit is explored in Section IV.

Many of the technical reports analyzed in reference to this task stressed the need for good operating practices and the use of quality fuel to improve operation and reduce emissions. The impact of fuel species, fuel moisture content and operational variables are, therefore, discussed in detail in Section V.

It also became apparent that proper stove selection is critical to reduce emissions and improve efficiencies. Section VI is provided to assist in making this selection. Section VII serves to summarize the design parameters and firing techniques recommended to operate a stove or fireplace with minimum emissions.

A bibliography of technical reports reviewed in conjunction with this task also is provided (Section VIII) to assist in additional detailed investigation where desired.

II. COMBUSTION PRINCIPLES

Combustion of wood is a process in which the hydrogen and carbon in the fuel are chemically combined with oxygen to form combustion products and release heat energy.[12] Complete combustion is dependent on the "Three T's" of combustion: time for the combustion reaction to occur, a high enough temperature to maintain combustion, and enough turbulence to allow sufficient oxygen to mix with the fuel. If combustion is complete, carbon dioxide and water vapor are formed. When complete combustion does not occur, which is common in wood burning appliances, particulate matter, carbon monoxide, hydrocarbons and other gases also are formed. The latter are emitted as air contaminants and represent an energy loss to the user. As combustion becomes more complete, less contaminants are formed. With proper heat transfer, this means more usable heat energy is available.

STAGES OF COMBUSTION

Combustion of wood involves four basic processes: moisture evaporation, pyrolysis, gas vapor burning, and surface char burning. The rate of heat release and the formation of pollutants is dependent on these processes and the rates at which they occur. In the wood stove, these processes are all occurring simultaneously within the combustion chamber.[11]

MOISTURE CONTENT

As wood is heated, moisture in the wood is evaporated to form a vapor (steam). This evaporation of water uses energy rather than releasing it, unlike the combustion processes of gas vapor and surface char burning. Since the vaporation uses energy released from the combustion processes, it lowers the temperature in the combustion zone which retards the combustion process. In wood fired boilers, for example, it has been found that the combustion process cannot be maintained if the wood moisture content exceeds 68% - this is, the wet wood requires so much energy to evaporate the water that temperatures are reduced below the minimum temperature required to sustain combustion.[12] Consequently, fuel moisture content (seasoned vs "green" wet wood) is an important variable.

PYROLYSIS

Pyrolysis involves a chemical decomposition of the original molecules into other molecular species because of high temperature. Combustible gases evolve from the wood as the temperature rises. Wood will not burn until this chemical change occurs.[26]

GAS VAPOR BURNING

Initially these gases near the surface of the wood are not ignited due to the high concentration of carbon monoxide and water vapor. However, as the rate of pyrolysis and the temperature increases combustion can occur in the presence of oxygen. Thus with an increase in temperature and turbulence to mix with oxygen, combustion becomes more rapid and heat is generated.

CHAR BURNING

In a wood stove the charred surface of wood does not usually burn until well into the combustion process. Charcoal does not vaporize at the temperature achievable in a wood stove. Consequently, combustion can occur only when oxygen is available and can come in direct contact with the charcoal on the wood surface. Oxygen can get to the surface only when the flow of gases coming out of the wood has subsided.[49] This occurs after moisture evaporation and pyrolysis.

COMBUSTION CHEMISTRY

The chemical reactions involved in the combustion process are complex due to the complex chemical nature of wood. However, for the purpose of this section, a simplistic approach to this subject will be utilized.

Wood consists basically of cellulose fibers and lignin with water trapped within its structure. The weight of the trapped water in green wood can equal the weight of the dry wood[35] (50% water).

When dry wood burns completely, the following basic reaction occurs:

$$C_6H_{10}O_5 + 6\ O_2 \rightarrow 6\ CO_2 + 5\ H_2O + \text{Heat}$$

(cellulose) + (oxygen) → (carbon dixoide) + (water) + Heat

Simply stated, when wood vapors mix with oxygen present in the air at a temperature sufficient to promote combustion, carbon dioxide and water are formed and heat is generated. Table 1 summarizes the energy involved in the various stages of combustion involving one pound of wood.

In theory, the amount of moisture in the wood does not affect the available energy, but it drastically affects the ease of burning[35] and the <u>usable</u> energy. With wet wood, more of the heat released during combustion must be used to vaporize water within the wood thus reducing the heat output of the appliance. The relationship of moisture content to efficiency is discussed in more detail in Section V.

EFFICIENCY

The design of a wood heating appliance has considerable effect on combustion efficiency, the resultant emissions, and heat output. Many reports and sales

TABLE 1

The Four Stages of Wood Combustion[35]

	Temp Range °F	lb Air/ lb Wood	Energy[a] BTU/lb
1. Water vaporizes	200-250	0	-100[b]
2. Wood pyrolysis to make charcoal, wood gas, and wood oil vapors	500-750	0	- 43
3. Wood-gas and vapors burn	Above 1100	5	+1600
4. Charcoal burns in air	1200-1800	1	+3200

[a] Negative value represents a required energy input; positive value represents an energy output.

[b] For wood containing 10% moisture. These numbers are for oak, but are quite similar for all woods. See Table 3, page 34 for heat values of other species.

brochures are quick to report the efficiency of an appliance without defining what is meant by efficiency. Efficiency can be defined as a ratio of output to input.

However, heating a home with any combustion device involves two basic processes, each with its own efficiency. These processes are combustion and heat transfer. The combustion of these two yield the overall efficiency.

COMBUSTION EFFICIENCY

Combustion efficiency is defined as the heat energy generated during combustion divided by the wood energy input.[55] Combustion efficiency is affected by parameters that affect the basic combustion process. These include fuel, air supply, and temperature in the combustion zone. Combustion efficiency is a measure of how well combustion is occurring.

HEAT TRANSFER EFFICIENCY

Heat transfer efficiency is used to describe how well heat is transferred from the combustion zone to the area being heated. This is dependent on the design of the heating appliance. Factors that affect heat transfer efficiency include such items as mass of the stove, its ability to retain or transmit heat, and loss of heat out the appliance exhaust stack.

OVERALL EFFICIENCY

The product of the combustion efficiency and heat transfer efficiency determines the overall efficiency. These efficiencies in turn affect air contaminant emissions from the stove. Overall efficiency can be defined as the useful heat energy output divided by the wood energy input.[55]

Both combustion and heat transfer losses can be measured by the movement of combustion exhaust gases out the stack. These stack gases contain energy in the form of unburned gases and particulate matter which results through incomplete combustion. Heated excess combustion air and hot combustion products represent a heat transfer energy loss.

In any stove design, both the combustion and the heat transfer efficiency are extremely important considerations. Ideally, both efficiencies should be very high to provide an overall efficient stove. However, there are certain practical considerations which must be taken into account. As heat transfer increases, stack gas temperature decreases. Certain minimum stack temperatures must be maintained to prevent condensation and provide adequate draft. If there were no condensible gases in the exhaust stream other than the water formed by combustion and through evaporation from the fuel, stack temperature could, as a practical matter, be reduced until condensation of the water vapor in the stack occurred. However, the condensible hydrocarbon gases produced from incomplete combustion cannot be ignored in normal operation. Unless these are removed from the gas stream they condense on the walls of the exhaust stack causing a creosote buildup and a safety hazard. Current operating practices stress the need to maintain stack temperatures high enough to reduce this formation and buildup of creosote. Furthermore, as the temperature in the stack is reduced thermal buoyance is reduced, decreasing draft and air flow through the combustion zone.

If heat transfer efficiency is going to be increased significantly with a resulting decrease in stack gas temperatures, the condensible organic hydrocarbons must be removed from the stack gases to eliminate the creosote problem; this is achieved through more complete combustion.

COMBUSTION VARIABLES

Combustion is dependent upon the characteristics of the fuel and the adequate supply of oxygen. To enhance the combustion process, the combustion air must mix with the fuel (turbulence) at an adequate temperature to ignite and must remain in the combustion zone for a long enough time to complete the chemical reaction. This is often referred to as the 3T's of combustion (time, temperature, and turbulence).

Combustion efficiency increases with an increasing fuel burn rate.[25] However, this is not to be confused with the size of the charge or with the overall efficiency. The fuel burn rate represents how rapidly the charge is being burned, and the combustion efficiency represents the completeness of the combustion reaction. A rapidly burning fire increases both the temperature and the turbulence and, therefore, combustion efficiency normally increases.

Turbulence is necessary to provide mixing of the fuel with the combustion air (oxygen) permitting the oxidation (burning) process to proceed. The temperature of the gases must also be sufficient to allow the reaction to continue. Therefore, the location of the draft air inlet on an appliance is very important and should be located to provide combustion air preheating.[21] The quantity of air supplied to the combustion process also is important. Too little air supply limits the reaction resulting in incomplete combustion. Air must be supplied in proper proportion to the fuel to provide for proper combustion. Theoretically it requires 5.7 pounds of air to burn 1 pound of dry wood.[35]

Air which is supplied to promote the primary combustion process is referred to as primary combustion air. Although it requires 5.7 pounds of air to burn 1 pound of wood, additional air must be supplied to make up for the incomplete mixing of the fuel and oxygen. This "extra" air is referred to as excess air. One problem that exists, however, is that as excess air increases, overall efficiency decreases[26] due to a decrease in thermal efficiency.

In an attempt to reduce the amount of primary air required for complete combustion, some combustion appliances introduce secondary combustion air. Secondary combustion refers to the ignition of the volatile gases which are released by the burning fuel and not ignited directly in the fire. This ignition is accomplished by adding the secondary air to the primary combustion products, thus providing the oxygen needed for combustion of these hot gases. To maintain secondary combustion there must be sufficient fuel to mix with the incoming oxygen at a high enough temperature to support combustion.[49] This process provides the dual benefit of reduced emissions, as well as a reduction of heat that would otherwise escape out the chimney with excess primary air. Unfortunately, secondary combustion is difficult to attain and maintain. To support secondary combustion, very high gas temperatures are needed[49] (at least 1100°F), which generally require the stove to be operated at a very high temperature. In concept secondary combustion should be very effective, yet secondary combustion is very difficult to obtain at the lower burning rates due to the reduced operational temperature that is typical of consumer operation.[7] Unless the stove is properly sized (i.e., small enough to maintain a hot fire without generating excessive heat output), the heat output becomes uncomfortable to the homeowner and operator and the firing rate is reduced which results in lower combustion temperatures causing the secondary combustion to cease.

Other important combustion variables include the fuel and the firing techniques used by the operator. Variables in these areas include the species, moisture content, size, and frequency of the fuel charge. These are discussed in detail in Sections V and VI of this report.

The effects of reduced heat transfer and combustion efficiencies on air contaminant emissions is still being investigated. According to Harper[26] emissions of CO, THC, and NO_x decrease as overall efficiency increases. He further states that creosote is a result of incomplete combustion. Findings by Shelton[19, 31] indicate that combustion is more complete in hotter fires and that more creosote is formed in low temperature fires. Another study by Stockton[20] indicates that at higher temperatures particulate emissions are reduced. Hubble's[42] results indicate that CO, particulate, and creosote emissions increase with a decreasing fuel combustion rate (i.e., slow burning fires with low combustion efficiencies produce more emissions); however, for Hubble's study the highest thermal efficiencies were calculated to occur at the low burn conditions. Emission tests conducted under Task 5 of this study[41] also indicated that emissions are inversely proportional to the burn rate.

It must be remembered that overall efficiency includes both combustion and thermal efficiencies. A proper combination of efficiencies, therefore, is desirable to obtain the minimum air contaminant emissions. Theoretically, by maximizing the combustion efficiency, to maintain the highest overall efficiency, emission rates (g/BTU) can be reduced. Conversely, reducing the combustion efficiency and improving the thermal efficiency may result in higher emissions with no resulting increase in overall efficiency.

However, this limited data precludes any definitive answers regarding emissions as a function of overall efficiency. It appears that emissions decrease as combustion efficiency increases and that emissions increase as thermal efficiency increases (mass per mass of fuel consumed; g/kg fuel). Note, however, that as the thermal efficiency of an appliance increases, the amount of fuel which must be consumed is decreased; therefore, the net emissions to the atmosphere may decrease. Section V discusses creosote formation and operating efficiencies in more detail.

III. RESIDENTIAL WOOD COMBUSTION SYSTEMS

RWC has been in use for centuries. However, until recently its use had been rapidly fading. Consequently, research into improved RWC appliance was virtually non-existent. Now that additional importance is being placed on RWC systems to provide heat, research is beginning. This research includes investigating systems with respect to heating characteristics, effects of fuel variables, and identification of air contaminant emissions as to type and amount.

Three basic RWC systems are in use. These include central heating systems, fireplaces, and wood stoves.

The central heating system involves combustion of wood with a simple combustion appliance and then distribution of the heat generated to other areas of the home. Typically this involves a central furnace or boiler where sawdust or logs are used as the fuel. The hot combustion gases are then used to heat either air, which is routed to other areas of the home, or water that is pumped to other areas of the home for heat. A significant feature of central heating systems is that they utilize a sophisticated (relative to stoves) heat transfer system, and often include heat storage systems.

A second system used to generate local heat is the fireplace. The fireplace is an open combustion appliance without means to effectively regulate the combustion air. Consequently, these generally operate with 500-600% excess air. Although originally constructed of masonry, many are now manufactured of metal and may be of free standing design.

The third system is the s tove where combustion occurs in a closed combustion chamber. Consequently, combustion air can be regulated by draft controls or by inlet air restrictions. These airtight or semi-airtight appliances operate in the range of -25 to 100% excess air.[26] These units are customarily manufactured from iron, steel, or ceramics.

Although these are the three basic systems utilized for RWC, there are a multitude of hybrids. Fireplace inserts are commonly installed in existing fireplaces. These units are stoves that use the chimney rather than a stove exhaust pipe, and are operated in a similar manner to regular wood stoves. Some fireplaces are being modified to incorporate some design characteristics of the wood stove (i.e., glass doors to partially control excess air) in an effort to increase efficiency, while some wood stoves are being modified to operate like fireplaces to retain the "romance of a fireplace" (e.g., wide open doors). Both systems are being modified to extract additional thermal energy by including air to air heat exchangers and in some cases, hot water heat exchanger coils. Only the basic systems are discussed in any detail in this task with emphasis placed on fireplaces and wood stoves.

CENTRAL HEATING SYSTEMS

Central heating systems are designed to include a heat transfer system within the overall system. They also are designed to be operated on a nearly continuous basis since they are often the primary source of heat for the home. According to the RWC survey conducted as part of this project, it is estimated that these systems account for only 1-2% of the current RWC.

Central furnace systems operate with an overall efficiency of 40 to 75%.[50] This is a slightly higher efficiency than typical wood stoves and much higher efficiencies than associated with fireplaces.

LOCALIZED HEATING SYSTEMS

A fireplace or wood stove is a localized heat source. Although some units may employ fans to move heat away from the appliance or even a hot water coil to assist in heat transfer, they are really designed to add heat to their immediate surroundings only. If the appliance is to be used as a central heating system, some other heat transfer system must be added to accomplish this task.

FIREPLACES

The efficiency of a fireplace is quite low. Typical masonry fireplaces have an overall efficiency of 20%.[31] Other sources have reported efficiencies to range from -10 to +10%[26] and from 20 to 42%.[34] The apparent wide range in efficiencies may be caused in part by the lack of standardized operating and testing conditions. However, due to the high volume of excess air associated with a fireplace, the outside temperature has a significant effect on overall efficiency. When in operation, the draft created from the fire draws in large volumes of cold air through leaks under doors and around windows. The cooling from the outdoor air drawn into the heated space may actually result in a net heat loss from an open fire. A decrease in efficiency of 3% exists for each 10°F difference between outside and inside air temperature.[2] Thus, assuming most fireplaces are only 20% efficient, most fireplaces will consume more energy than they produce when the outdoor temperature is below 0°F (a temperature difference of 70 degrees between the outside and inside air results in an efficiency reduction of 21%).

However, some energy efficient fireplaces have been designed which may have efficiencies as high as 30 to 35%.[26] At an efficiency of 35% this means the best factory built energy efficient metal fireplaces have efficiencies as good as the worst wood stoves.

Emissions from fireplaces have become of more concern since their apparent increase in usage. A study[8] by J.L. Muhlbaier indicates that the most important parameter controlling emissions is the average burning rate. As the burning rate increases, the emissions of particulate matter and hydrocarbons decrease. The study further indicates that there is no obvious correlation between fuel moisture content and emissions, although particulate emissions increased greatly with large log sizes. Based on this study, to minimize emissions from fireplaces (pounds emissions vs burning rate) hot full fires are necessary. In this study, there was no attempt made to correlate emissions as a function of heat output delivered to the surrounding room. However, these results are consistent with other findings[31] and recommendations; in short, to maximize energy efficiency, full, hot fires should be built and also should be maintained for long periods of time. Obviously, when the fireplace is not in use, the dampers should be closed to prevent loss of warm air up the chimney. It was further recommended that on cold days, the fireplace should not be used since an actual energy loss may result.

WOOD STOVES

Stoves may be classified by the heat transfer technique utilized. Useful heat energy can be transmitted by radiation, convection, or by a combination of these two. Although all stoves utilize both forms of heat transfer they are generally classified as radiators or circulating (convection) stoves depending on the principle mode of heat transfer. These are illustrated in Figure 1. Some literature states that circulators do not perform as well (do not have a high overall efficiency) as radiant stoves, with circulators having a 40 to 50% efficiency and radiant stoves having a 45 to 70% efficiency.[50] Other studies[21] indicate that over a range of conditions, a difference cannot be statistically determined. In any event, the overall efficiency of the wood stove exceeds the fireplace but is still relatively low in relation to conventional methods of home heating.

Radiating Stoves

Radiating stoves supply most of their useful heat by radiation from the stove's surface. Therefore, heat transfer from the combustion chamber to the surface of the stove is essential. If this is done improperly, the temperature of the combustion chamber may be significantly reduced adversely affecting combustion efficiency.

Circulating Stoves

Convection units, or circulating stoves typically use hot air circulation as their principle form of heat release. Air passes or is forced over the stove's surface between an outer shell and the shell containing the combustion chamber, resulting in the warming of the air before it is blown into the room.

Stoves also are classified on the basis of air flow paths through the combustion chamber. Five basic classifications commonly are sold, with numerous combinations or modifications of these classifications available. The airflow of the primary combustion air determines whether the stove is an updraft, down draft, cross draft, diagonal, or "S" draft stove. These designs are illustrated in Figure 2. The path the air follows in relation to the combustion zone would

FIGURE 1

Basic Stoves

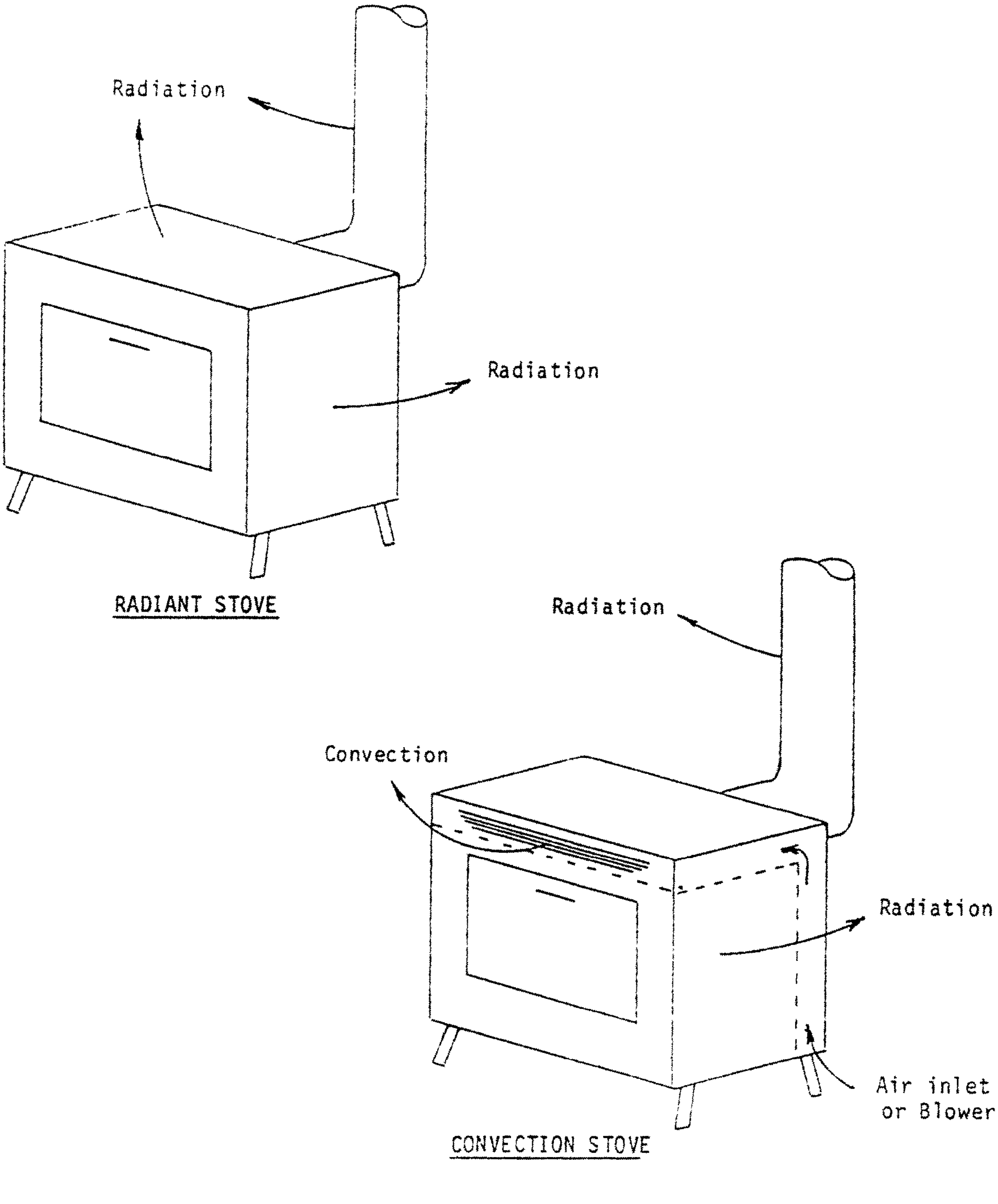
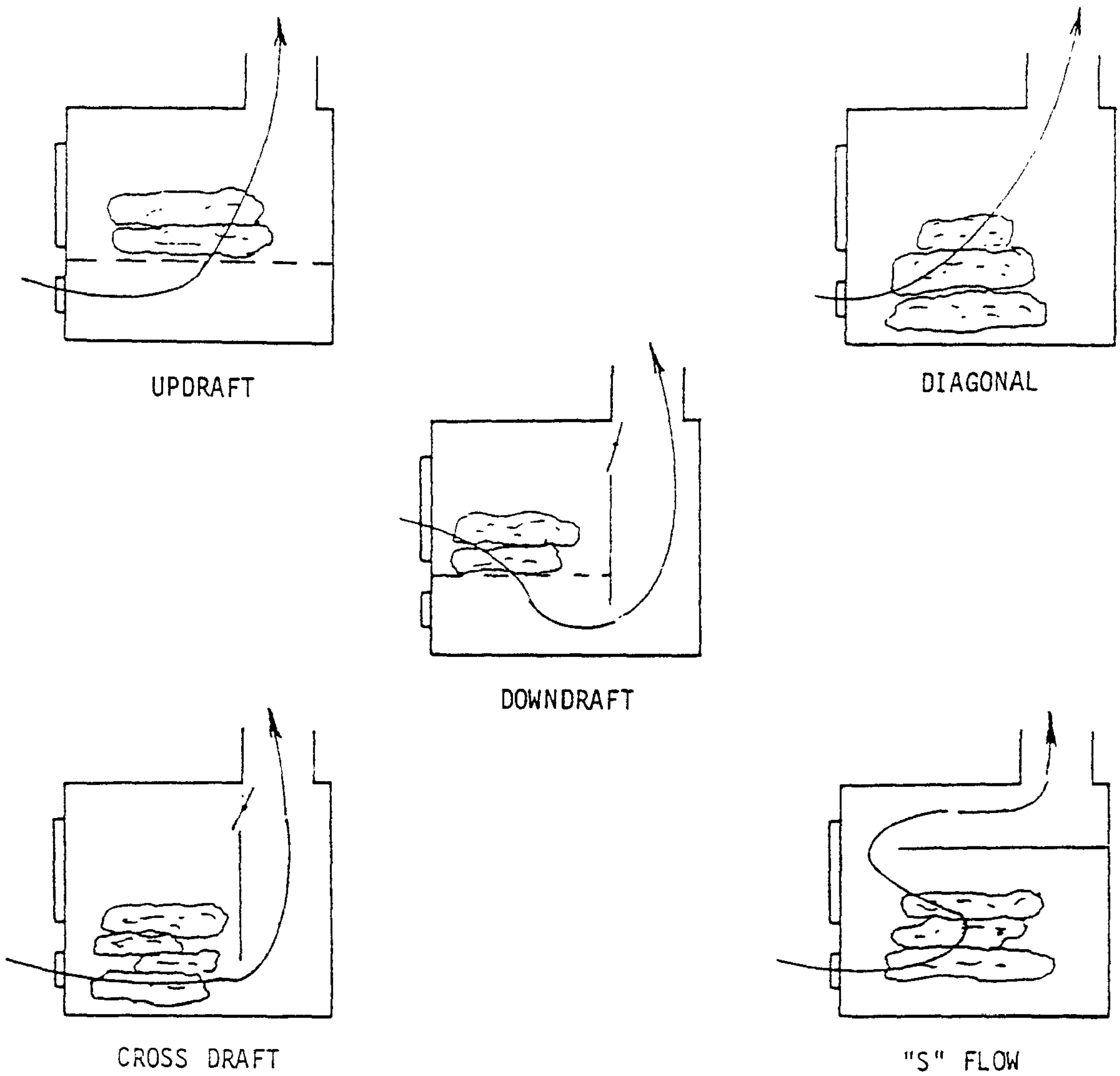


FIGURE 2

Air Flow Patterns



appear to be extremely important. It would appear to affect pyrolysis rates, oxygen availability and mixing, combustion temperatures, and consequently, combustion efficiencies. In addition the air path would appear to influence the heat transfer within the stove and therefore, its overall efficiency. However, data[16] indicate that the air flow path has negligible effect on the wood stove overall efficiency.

•Down Draft

Combustion air is drawn down through the charge of wood to the grate area where combustion is occurring. The gases generated in the pyrolysis process are carried with the primary air to the area of combustion facilitating more thorough combustion and improving combustion efficiency.[11] Heating of the primary air, which occurs with the air being drawn through the fire, also reduces emissions[11] by increasing the combustion efficiency.

•Updraft

In this design, the primary air flow passes upward through the burning wood. Heating of the air occurs under the grates providing the fuel with preheated air. This results in the heating and pyrolysis of some of the wood in an oxygen deficient environment since these gases have already passed through the combustion zone[11] and the oxygen consumed. This effectively limits the rate of combustion. Combustion which occurs in an oxygen deprived atmosphere is incomplete and, therefore, higher in air contaminants.

•Cross Draft

In the cross draft or side draft stove, the primary air in introduced at one side of the charge and leaves at the base of the charge. The pyrolysis products are not released directly into the primary air stream but into the fuel magazine. The air is heated by radiation and convection before being drawn into the primary combustion area.

•Diagonal Flow

This flow pattern is typical with many box stove designs. Air enters near the base of the charge and travels directly to the stack. It travels across the face of the burning area as overfire air. There is little mixing of the incoming air with the fuel to promote complete combustion.

•"S" Flow

This design permits the slower "end burning" of the charge. Air is introduced at the base of the charge with the combustion products leaving the combustion chamber on the same side. This design is conducive to a very slow burning rate since the effective surface area of the fuel log is relatively small.[11]

•Ceramic Stoves

Stoves which utilize a ceramic combustion chamber in lieu of metal or firebrick lined also are on the market. There was little technical data available in reference to this type of design. Sales literature[9, 33] indicates improved overall efficiencies resulting from the massive structure designed to accumulate the heat and release it slowly. This heat "accumulation" theoretically increases the combustion temperature resulting in increased combustion efficiencies and reduced emissions. The sales literature claims very little heat loss up the stack. Limited test data conducted in RWC Task 5 of this project[41] indicates low mass emissions but very high stack temperatures (i.e., high heat loss).

•Fireplace Inserts

Stoves which are manufactured to be installed in existing fireplaces are defined as fireplace inserts. Basically the inserts are designed and operated like the stoves previously discussed. The major difference is that they use an existing fireplace chimney rather than a "stove pipe". Theoretically combustion principles and the combustion efficiency would be the same as wood stoves. However, the heat transfer efficiency should be lower than that of wood stoves since no stove pipe exists (considerable heat is transmitted through a stove pipe). When comparing the insert to the fireplace much higher overall efficiencies are expected from the insert, since the combustion air can now be regulated.

Table 2 is a summary of overall efficiencies as reported by T. Burch.[50] In summary it should be noted that fireplace and non-airtight stove efficiencies ranged from negative to 40%. Airtight stoves had higher efficiencies, ranging from 35 to 70% which was little different than the central heating systems. The overall efficiency appears to be directly related to the ability of the appliance to regulate combustion air. RWC appliances that regulate combustion have higher overall efficiencies.

TABLE 2

Typical Overall Efficiencies
of
Wood Burning Appliances *

Appliance	Efficiency Range
Masonry Fireplace	-10% to 10%
Manufactured Fireplace with heat circulation and	-10% to 10%
outside combustion air	15% to 35%
Free-Standing Fireplace	20% to 40%
Fireplace Stove	20% to 40%
Non-Airtight Stoves	15% to 40%
Radiant Stoves	45% to 70%
Circulator Stoves	49% to 55%
Fireplace Inserts	35% to 55%
Supplement Furnaces	40% to 60%
Central Furnaces	40% to 75%

* From Wood Burning Safety & Efficiency by Burch et al.[50] The sources of these efficiency ranges are not cited in this reference, and may conflict with other data presented in this report. Nonetheless, this table is useful for comparing efficiency ranges for the various devices.

IV. MODIFICATIONS AND RETROFIT

A variety of stove and fireplace features can affect operation, heat output, and emissions. Several possible combustion modification techniques appear feasible to reduce emissions and improve combustion efficiency. Many of these techniques are operator and fuel dependent. Physical modification to existing fireplace and stove installations is possible by retrofit.

The retrofit devices currently on the market are used to regulate air flow, improve combustion, treat the exhaust gases or improve heat transfer efficiency. Many of the retrofit units are designed with the intent of influencing more than one of the above traits in a positive manner. However, little data exists that either supports or refutes the claims made on these units.

WOOD STOVE MODIFICATIONS

DRAFT CONTROLS

Controlling combustion air to the fire is one of the design features that can most readily be modified. Draft control has a significant effect on wood stove efficiencies and wood usage.[16] Draft control can be accomplished at the stove by regulating the area which allows the combustion air into the firebox or can be accomplished at the stack through the use of a barometric damper. The barometric damper allows room air to be bled into the stack which simultaneously reduces the air flow through the combustion zone. For non-airtight stoves, only the barometric damper type control will work. Draft control is important because the amount of primary air introduced into the wood stove acts as a throttle and determines burning rate.[35]

The combustion air can be regulated through the use of a damper controlled manually or automatically by a thermostat. Typically a thermostat is installed on the stove. A bi-metallic spring attached to a butterfly damper closes off or opens up the primary air intake passage thus regulating the air flow. The thermostat acts automatically to regulate the primary air damper after the stove reaches a certain temperature. According to the manufacturer[16], overall stove efficiency increases when controlled by an automatic thermostat. As the amount of primary air reaching the fire is reduced the rate of combustion decreases due to oxygen starvation. After the stove starts to cool, the damper opens which allows additional oxygen to reach the fuel increasing the rate of combustion. Through the use of a damper, the temperature of the stove is kept relatively constant. Since the stove temperature can be automatically maintained at the peak of the stove's efficiency curve[16], the net thermal efficiency of the stove is increased. The increased thermal efficiency requires less wood to be burned and, therefore, results in less emissions to the atmosphere. In Barnett's study[16], the actual stove emission factor (mass emissions/mass fuel) was not reduced by the automatic damper. These data should not be construed to indicate that restricted air flow conditions improve efficiency. Instead, the data indicate that regulated air flow improves thermal efficiency over non-regulated air flow.

Utilization of outside combustion air ducted directly to the combustion chamber has been suggested as a means to improve overall efficiency (i.e., the unit is not consuming warmed room air and, therefore, not using energy already transmitted to the room). However, the use of outside combustion air for air-tight wood stoves apparently does very little toward saving energy.[56]

AFTERBURNERS AND CATALYSTS

Afterburners and catalysts are used to promote additional combustion of the exhaust gases. Theoretically the improved combustion will provide more heat and at the same time reduce emissions. The afterburning process can be accomplished through the addition of a secondary fuel into the gas stream to promote and maintain combustion or by the placement of an active catalyst into the exhaust.

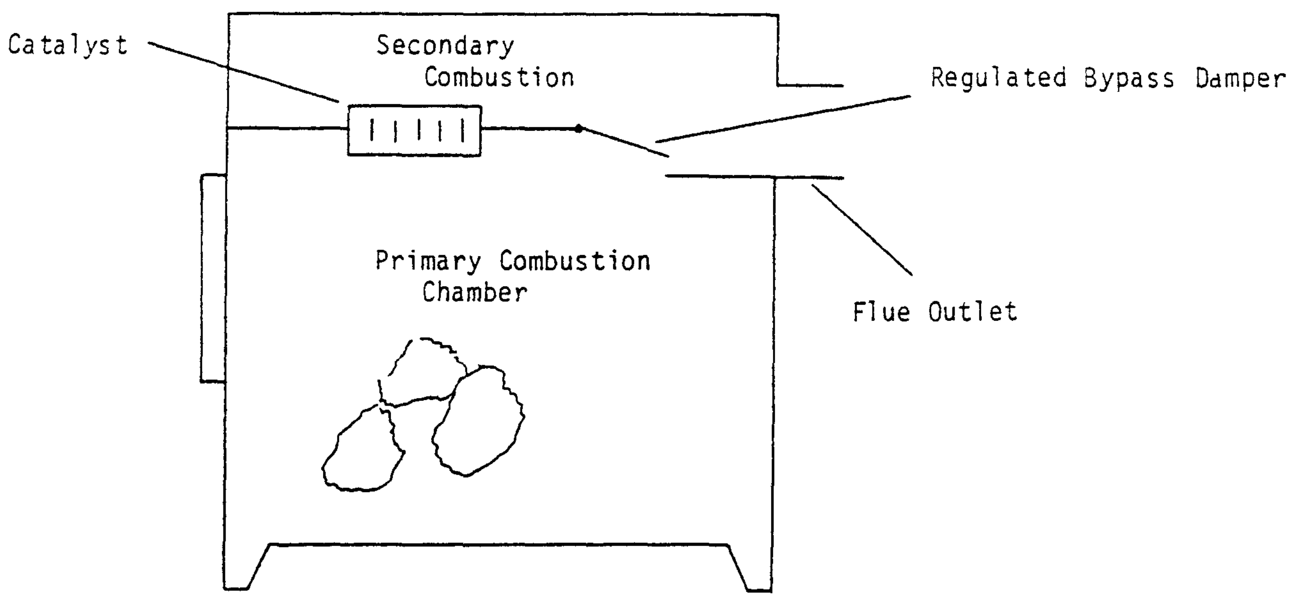
There were no data available regarding the introduction of a secondary fuel to promote additional combustion and there is only limited data in reference to use of catalysts on wood stoves. A typical catalyst consists of a ceramic support in a configuration which permits the combustion gases to pass over or through the support (e.g., a honeycomb structure); the support is coated with platinum or other metal catalyst. Figure 3 shows one installation. The catalyst acts by substantially reducing the temperature at which the unburned combustion gases will ignite and burn. For example, combustion gases from a wood stove typically will combust at 1100°F but in the presence of a catalyst would combust at 500°F (given adequate oxygen, mixing, and residence time).

Proper operation of the catalyst requires that it be operated in a hot exhaust stream. At temperatures below 400°F a noble metal catalyst becomes inefficient.[32] Some catalysts require a minimum operating temperature of 500-550°F.[3] Temperaturs below 400°F do occur at low burn settings or at the end of the burn cycle for typical stoves.

In order to effectively use a catalyst system, the operator must be more attentive to stove operation since catalysts are designed to work in temperatures above 400°F. In addition to contacting the catalyst, the flue gases also must

FIGURE 3

Catalyst Installation



contain sufficient oxygen in order to undergo additional combustion. Since the combustion gases must contact the catalyst in the presence of oxygen, catalyst surface area, residence time of the gases with the catalyst, oxygen content, and mixing of the combustion gases all become important considerations. According to one study[5] conducted by a catalyst manufacturer, catalysts can reduce total emissions.

It has been reported by the manufacturers[5, 18] that as the loading (uncombusted emissions) to the operating catalyst increased, catalyst combustion efficiencies increased since more "fuel" was being provided to complete the combustion reaction. Emissions that continued through the catalyst were reported[5] to be more soot-like than tar-like, indicating volatile organics had been oxidized. Other tests[41] conducted on catalyst equipped stoves indicated little or no reduction in emission rate compared to emission rates typically expected from non-catalytic stoves.

The effectiveness of a catalyst appears to be very dependent on the proper operation of the stove, as well as stove design. This includes proper location of the catalystic combustor within the appliance and properly designed secondary air inlets for adequate combustion air distribution. The catalyst must be operated in a hot environment with fuel and oxygen present in proper amounts in order to promote additional combustion and reduce emissions. It is important that the stove be properly sized so that it can be operated at high enough temperatures for catalytic action without overheating the house. Using catalysts on wood stoves is relatively new technology. Many potential problems and unanswered questions remain. One significant question involves the amount and type of secondary pollutants which may be generated during the catalytic combustion process, particularly hazardous or toxic emissions.[32] Among secondary pollutants that theoretically could be formed in the presence of a catalyst are ammonia and hydrogen cyanide, although tests have not confirmed the formation of such pollutants.[32] Operating the catalyst in an excessively rich exhaust stream below the ignition temperature may cause fouling of the catalyst[32] and possibly plugging of the pathway for combustion gases resulting in a safety hazard if a bypass around the catalyst is not available. In addition, combustion of certain products such as magazines and some pressed wood products containing metals in the ink and glue resins may poison the catalyst and eliminate its effectiveness. The expected life of a catalyst will be an important consideration in the success of the new technology.

DESIGN MODIFICATIONS

A properly designed wood burning stove would include bricklining to promote high combustion temperature, preheated primary and secondary air to promote combustion, baffling to increase retention time of the combustion gases, combustion air regulation, and an efficient means of extracting the useful heat.[15] Design considerations such as these are present in the more efficient stoves.[26]

Fire Brickliners

Theoretically fire brick liners can decrease air pollution emissions by helping to maintain higher temperatures in the firebox, thus promoting more complete combustion. The stove takes longer to attain its heating temperature due to its increased mass but once attained, the temperature of the stove is more uniformly maintained.

Baffles

Baffles are used to keep the hot gases in the stove longer, rather than allow their immediate escape at the exhaust. Theoretically this causes the heat to be released to the room through the stove instead of lost out the chimney. The baffles also theoretically act to decrease emissions by allowing extra time for more complete combustion to occur in the firebox. However, there is insufficient data available to provide any indication as to the effectiveness of baffles.

Pollution Control Equipment

Only one system to date has been identified as being designed specifically to reduce air contaminant emissions. This system utilizes a stainless steel mesh which is inserted in the exhaust stack. When operated at low temperatures, contaminants theoretically condense and agglomerate on the mesh. At elevated temperatures, this accumulation would provide a fuel source to promote combustion. Based on one test[36], this system was 50% effective in particulate control. However, it must noted that one other study[41] indicated no decrease in emissions nor significant increase in overall stove efficiency associated with the use of this unit.

FIREPLACE MODIFICATION

As previously discussed, the overall efficiency from a fireplace is very low (-10% to 20%) because of the large amounts of cold air drawn into the house by the fire's draft. Modifying an existing masonry fireplace can be very difficult. However, many retrofit devices are becoming available which claim to improve overall efficiency on these units. This improvement in overall efficiency typically is accomplished by improving the thermal efficiency (heat transfer) of the fireplace. Improvements in thermal efficiency should result in a corresponding reduction in air pollution since less fuel would need to be consumed to generate the same amount of heat. Some of the more common retrofit devices include glass doors or tube grates.

COMBUSTION AIR REGULATION

Fireplaces typically operate with 500 to 600% excess air. This means that for each pound of wood burned, approximately 37 pounds (500 ft^3) of air is used. To control the loss of this heated room air, outside combustion air preheated by the fireplace, should be utilized. One report[2] states this is the most effective means of increasing fireplace efficiency. However, another report[31] is quick to point out that no hard evidence exists that use of outside air is beneficial. The latter report also identifies many potential negatives, when using outside air, such as heat loss through these ports when the fireplace is not in use.

A second means to reduce the loss of preheated room air is by using glass fireplace doors. However, these doors, when closed, reduce the gross heat transfer to the room of the fireplace by 50 to 55%.[2, 31] To eliminate this high heat loss, the fireplace should be operated with the doors open. The doors should be closed when the fire burns down or when the fireplace is not in use. The doors are more effective at eliminating heat losses after the fire then improving efficiency of operating during the fire.

HEAT TRANSFER SYSTEMS

Fireplaces can be built with air to air heat exchangers incorporated into their design. Typically these are an envelope placed behind the fire pit that allows air to come into contact with the metal back of the fireplace. These are similar to the convection stove illustrated in Figure 1. Heat transfer in this form is not high. When not in use, it may in fact provide a source of heat loss. When used with a fan to promote movement of heated air an improvement of 8.6% may occur.[2] Other studies[31, 34] report that fans help but only by about 5%. Without fans, the increase in efficiency is only about 2.5%.[2] Fireplaces that do not have these heat exchangers built in may receive some of the same benefits by installing tube grate systems or forced air heat exchange systems. Tube grates (hollow tubes which support the burning logs and are shaped to draw in room air, heat it, and return it directly to the room) may increase efficiencies 5 to 8 percentage points when these units are equipped with a fan.[31] Without fans, this increase is more in the neighborhood of 1 percentage point.[2]

Improving fireplace efficiency appears extremely difficult to accomplish whereas reducing recurring heat losses during non-burning periods through the installation of glass doors or other fireplace sealers may be quite feasible.

HEAT STORAGE SYSTEMS

Wood stoves are designed to produce usable heat during the combustion process. The combustion process must be regulated to meet the required heating demand. This requires considerable operator attention to match the output to the demand. When the operator is not available to regularly tend the fire it must be "banked". Frequently this involves placing large charges of wood on the fire and reducing the combustion air in an effort to sustain a long burning period. In such a case, little attention is given to the actual heat output or the efficiency of operation; the primary concern is simply to sustain a fire that gives off some heat until the operator can return to properly tend the fire.

Theoretically overall stove efficiencies could be significantly increased if heat storage principles could be utilized to first efficiently accumulate the heat generated during ideal combustion and then later dissipate the heat as needed. This would allow the operator to operate the appliance at its highest overall combustion efficiency. The concept of massive rock or water heat sinks to provide this accumulation capacity appears to be the idea most frequently voiced. No technical data were available that provided comparison of efficiencies or emissions when using these systems for wood stoves. However, wood burning furnaces designed according to these principles of operation and intended for use with central heating systems have been tested and shown capable of attaining low emission rates; heat transfer efficiencies were not measured during the study.

V. FUEL SELECTION AND PREPARATION

The chemical composition of dry wood as measured in percent carbon, hydrocarbon and oxygen is very similar for hardwoods and softwoods. All wood has approximately the same energy content on a per pound basis.[49] The elemental content typically is about 40-52% carbon, 6% hydrogen, and 40-44% oxygen.[11] The cellulose content does vary however, with the hardwoods containing more volatile hemicellulose and less char-forming lignin than the softwoods.[11] Due to hardwood's higher density it has a higher heating value on a volume basis. Wood is usually purchased by the cord which is a volume measurement. Thus, there are more BTU's per cord which makes them a more desirable fuel from an operator's standpoint. Furthermore, softwoods burn more rapidly, therefore, requiring more frequent charging.

The utilization of a high quality fuel that has been properly prepared for use in the wood stove is essential. Species, moisture content, and log size all must be considered in maximizing heat output while minimizing air pollution. These aspects also play an important role in creosote buildup and potential fire problems.

FUEL SPECIES

Species selection is limited by the geographic area and the availability of the desired species. If several species are available, price often is used as the sole consideration when purchasing firewood. This can be a serious error since the heat output among species varies significantly. The relative heating value can vary by up to 50%, as illustrated in Table 3. Based on heating value

TABLE 3

Relative Heating Value Per Cord[4] of Wood

(Millions of BTU's per Cord)

HIGH (24-31)	MEDIUM (20-24)	LOW (16-20)
Live oak	Holly	Black spruce
Shagbark hickory	Pond pine	Hemlock
Black locust	Nut pine	Catalpa
Dogwood	Loblolly pine	Red alder
Slash pine	Tamarack	Tulip popular
Hop hornbean	Shortleaf pine	Red fir
Persimmon	Western larch	Sitka spruce
Shadbush	Juniper	Black willow
Apple	Paper birch	Large-tooth aspen
White oak	Red maple	Butternut
Honey locust	Cherry	Ponderosa pine
Black birch	American elm	Noble fir
Yew	Black gum	Redwood
Blue beech	Sycamore	Quaking aspen
Red oak	Gray birch	Sugar pine
Rock elm	Douglas fir	White pine
Sugar maple	Pitch pine	Balsam fir
American beech	Sassafras	Cottonwood
Yellow birch	Magnolia	Basswood
Longleaf pine	Red cedar	Western red cedar
White ash	Norway pine	Balsam popular
Oregon ash	Bald cypress	White spruce
Black walnut	Chestnut	

along, a significant price differential could be offset rapidly. Other considerations, such as residual ash and creosote generation, make the use of high quality fuel very desirable.

MOISTURE CONTENT

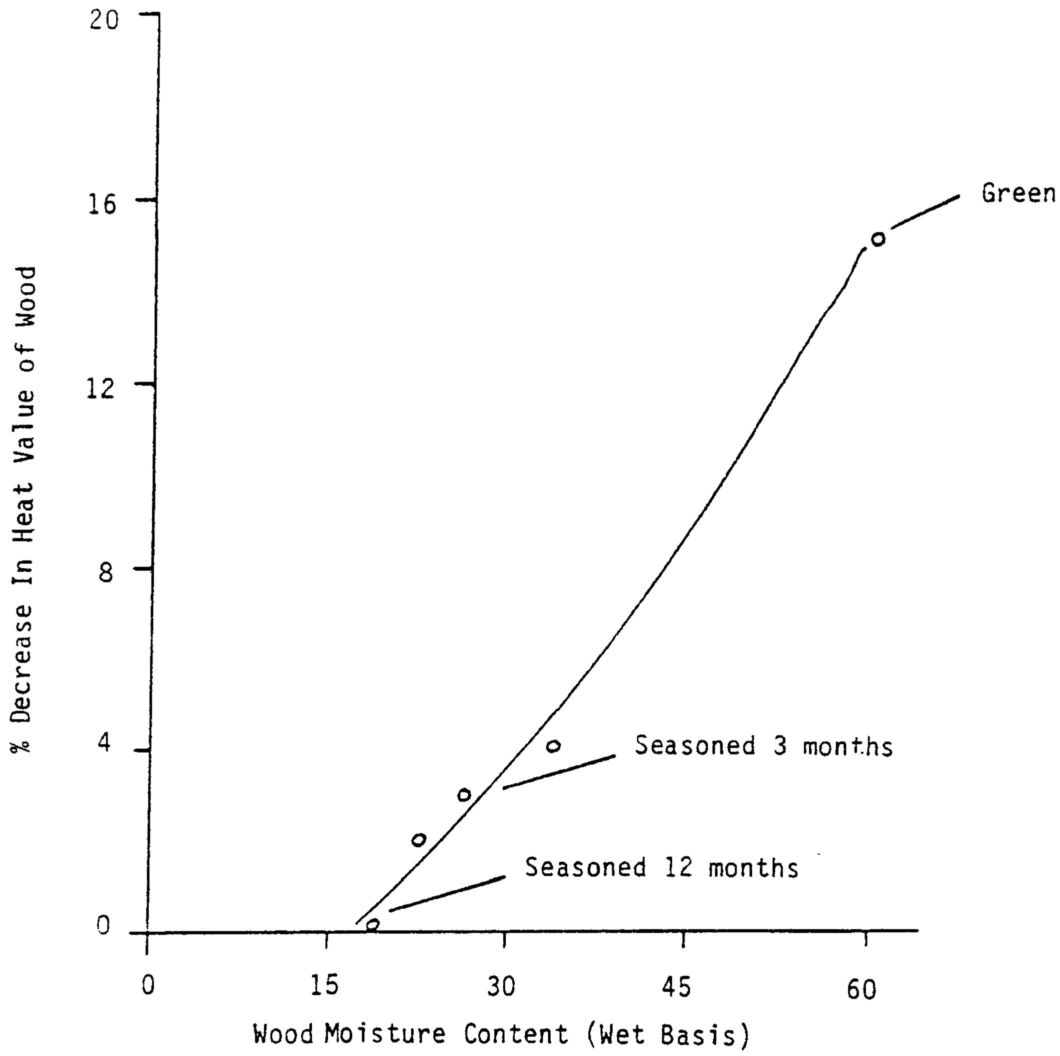
The moisture content of wood affects both the heat value of the wood and the combustion process. As the wood burns, the moisture in the wood is evaporated to form steam. This change from the liquid to gaseous state requires energy, which reduces the overall heating value of the wood. The evaporation process also lowers the temperature in the firebox, which further inhibits combustion.

Proper air drying or seasoning of firewood for three to four months can increase the heating value 10 to 12%.[29] The actual amount of moisture that can be removed through air drying depends on the relative humidity of the air around the wood and proper storage practices. Wood that is stored on the ground during wet periods with plastic completely covering the pile will rot rather than dry, for example. Depending on ambient conditions, properly air dried wood will have a moisture content of 10 to 20% (moist wood basis), which corresponds to the maximum overall efficiency range. Figure 4 illustrates the effect of moisture content on the heating value of wood.

Combustion of very dry wood also increases emissions and decreases the overall efficiency.[20, 30] Kiln dried wood (less than 10% moisture content, wet basis) tends to pyrolyze and burn very rapidly producing a very hot fire. The gases which evolve during the rapid pyrolysis are not adequately mixed with combustion air so that complete combustion does not occur. These unburned gases represent increased emissions[20] and a significant energy loss.

FIGURE 4

% Heating Loss
vs
Wood Moisture Content*



*Based on author's interpretation of data contained in Reference #29

The effect of wood moisture content on energy efficiency is shown in Figure 5. For the wood stove tested to produce this data, an overall 60% or greater energy efficiency corresponds to wood moisture content between about 10% and 25%, wet basis. Using Figure 4, this corresponds to a seasoning time of four months or more.

OPERATION

Operation is more important than either fuel species or moisture content.[19] The size, number of pieces, and loading techniques significantly influence the rate of combustion, hence, the stove efficiency.

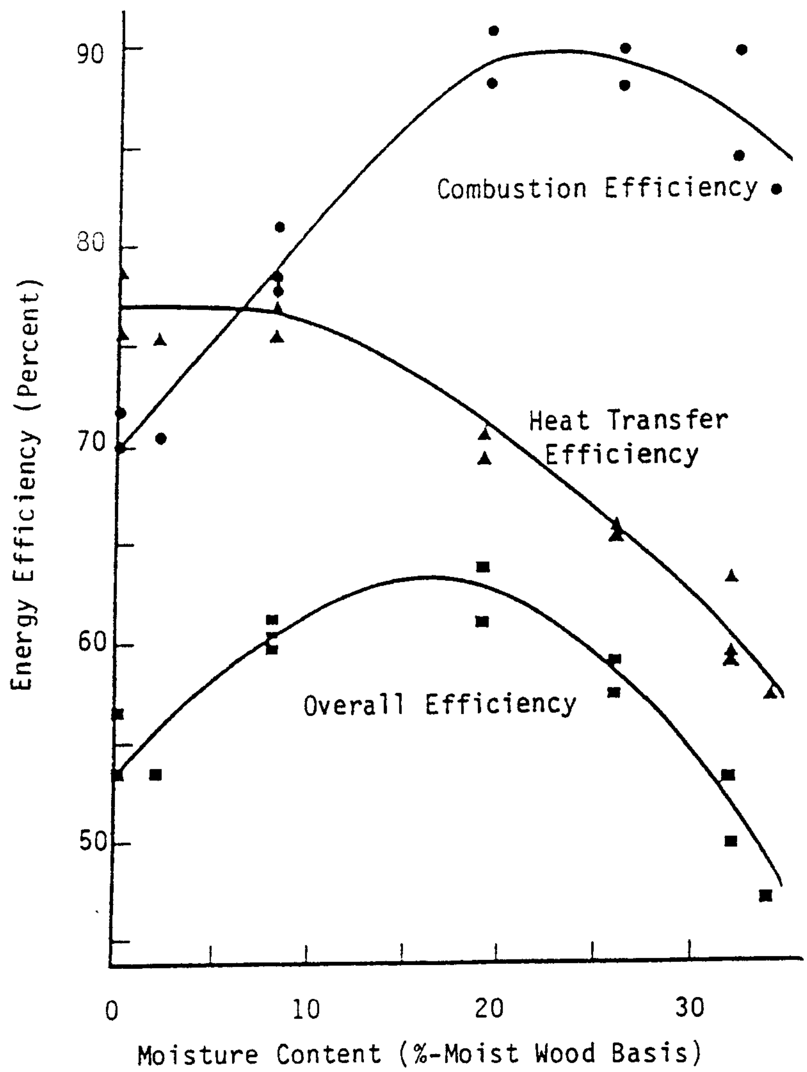
BURN RATE

As wood burns, it releases energy in the form of heat. As heating demand increases, more fuel must be consumed to satisfy this demand. The burning rate is, therefore, normally adjusted to meet the demand. Emissions for a stove also are related to the burn rate[42], although the specific relationship is not well defined with different reports indicating different relationships.

In general, however, the data indicates that total particulate emissions (g/kg fuel) decrease as burn rate increases. According to Hubble[42], both the highest thermal efficiency and highest emissions are associated with lowest burn rates. Therefore, as the burn rate increases, emissions would decrease. At least two other studies[36, 41] support the concept that emissions decrease as the burning rate increases. These findings are further supported by a study conducted by Harper[26] that indicates that optimal efficiency lies between the low and medium burn rates. Condensible organics decrease as the burn rate decreases, but condensible organics increase as the burn rate decreases.

FIGURE 5

Efficiency vs Moisture Content



The dependence of efficiencies on fuel moisture content in an airtight stove. The air inlet setting was varied to maintain an average power output of about 17,000 BTU's per hour for all moisture contents. The fuel load volume was approximately constant.[55]

The reasons for the differences in the burn rate -- emissions relationship are not known but many variables are likely to be involved. Differences may be caused by the way the burn rate was established or by other variables such as appliance design or fuel moisture. For example, emissions associated with a large charge of wood that has its burning rate restricted by oxygen starvation would be expected to be different than emissions generated in a series of small charges burning in an excess air condition even if the overall burn rate were the same (lb wood/hr). Both these operating conditions are common for wood stoves and is dependent upon the operator.

PIECE SIZE

Emissions from the stove are related to log size.[42] The shape and size of the log determines the surface area and the distance that water trapped in the fuel must travel before reaching the surface. Thus the rate of evaporation and the rate of pyrolysis[7] are affected, as well as the char burning that occurs on the surface. Excessive fuel surface area in the stove requires larger quantities of oxygen[26] to facilitate combustion. Without a proper air to fuel ratio in the combustion zone, these gases are exhausted out the stack without undergoing combustion. Basically, combustion of large wood pieces (small surface area per volume) generates less emissions than combsution of small wood pieces (large surface area per volume).[7, 42] Ideal wood piece size is 3½ to 5 inches in diameter[13] providing it can maintain the desired burning rate. Wood larger than this provides insufficient surface area to promote proper combustion, while pieces smaller have too much surface area. However, it must be noted that according to one study[25] the organic emission rate is not a function of log size, although the distribution between the different constituants (creosote, particulate, and condensible organics) is affected. At comparable burn rates, the particulate and creosote emissions are higher while the condensible organic emissions are lower for the small logs when compared to the large logs.[25]

The pile must be properly stacked to allow hot combustion gases and oxygen to come in contact to promote combustion. Stacking the fuel pile loosely promotes combustion. On the other hand, tightly packing the pile, thus eliminating air movement and combustion, can extinguish a fire. Therefore, the operator needs to load the firebox with care to maintain proper air flow around the fuel.

CHARGING RATE

The size of the firebox establishes the maximum charge size that can be loaded into the stove. Typically, this charging capacity is restricted to 40% of firebox volume.[10] The charge size has an effect on emissions.

Overcharging (too large a load) causes the premature volatilization of combustion gases in zones where temperatures are below the ignition temperature, causing excessive emissions and reduced efficiencies.[7, 11, 26] To heat the entire volume of the combustion chamber up to temperature may result in a much higher rate of combustion than desired and result in overheating the room, again representing a loss of efficiency. Many manufacturers claim this problem can be overcome by reducing the amount of combustion air; however, this produces a slow smoldering fire, low on energy and high in air pollution.[46] "Banking" a stove with a large charge of wood for overnight or sustained burns without frequent charging creates the same effect. The slow smoldering fire typically generates a lot of combustion gases that are never ignited, decreasing combustion efficiency and increasing air pollution. However, one study indicates that overall efficiency was not significantly different at half capacity or full capacity[39], since at full capacity thermal efficiency increased while combustion efficiency decreased. However, this is a less desirable situation since emissions are expected to increase with decreasing combustion efficiency (emissions were not measured in the just referenced study[39]). On the other hand, undercharging (too small a load) allows for excessive combustion air. Since overall efficiency decreases as excessive combustion air increases this again generates an energy loss. Maximum efficiency occurs when approximately 1/3 of a load is added (i.e., 30 to 35% of the firebox volume) at each charge. Therefore, careful attention should be given to selecting a stove that will give the desired heat output when properly charged.

CREOSOTE FORMATION

In addition to heat output and energy efficiency a stove operator needs to be aware of creosote buildup to prevent a potential fire hazard. As condensible hydrocarbons (tars) leave the combustion zone a condensation process begins. The rate of condensation depends on initial gas temperature and the amount of cooling that occurs in the stack. The quantity of condensible hydrocarbons that accumulate on the stack wall also is dependent on the amount of condensible hydrocarbons generated during the combustion process, which is dependent upon several variables already discussed, primarily combustion efficiency. A study by Harper[26] concludes that air dried (approximately 25% moisture content) hardwoods are the most desirable fuel regarding the reduced formation of creosote. In another study by Shelton[19] reference can be found regarding creosote buildup as a function of temperature with low temperature fires forming more creosote.

This appears logical in that creosote is a product of incomplete combustion and diminishing stack gas temperatures. This study is further supported by findings contained in Hubbles'[42] report. These findings indicate that as the burning rate increases, the formation of creosote decreases.

Contrary to popular belief, high wood moisture content does not automatically mean more creosote formation.[50] According to one study[19] neither moisture content nor species had a significant effect on creosote formation when operating under a restricted air smoldering condition. However, when operating under a medium to high fire condition in a closed combustion chamber there was a substantial decrease in creosote formation as moisture content of the fuel increased.[19] This may have been the result of a decreased pyrolysis rate resulting from more moist fuel. Under the same conditions (i.e., medium to high fires) more creosote was reported[19] from pinon pine (softwood) than from oak (hardwood). This same study investigated creosote formation when combustion occurred in an open door mode rather than a restricted air mode. Under these conditions, creosote formation increased as the moisture content of the fuel increased. This type of combustion would more likely occur in a fireplace rather than a wood stove.

VI. STOVE SELECTION

Selecting a wood stove that suits one's particular need can be very frustrating. There are numerous designs made by a multitude of manufacturers with an equal number of claims of superiority. Basic areas of differences include construction materials, size, internal configuration, heat output, charge size, and overnight burning capabilities. Not all of these parameters are of equal importance in the selection of a stove, however. Selecting the proper size stove to fit the use and heating needs is probably the most important aspect to be considered and often the most misunderstood.

In selecting a wood stove, the concept "the bigger the better" is incorrect. Actually, the reverse is true, and this basic premise should be kept in mind throughout the selection process.

SIZE DETERMINATION

Size determination should be based upon anticipated heating demand. If the wood stove is to be the sole source of heat in the house, the unit must be able to equal the house's total heat loss. The amount of heat loss from a house is a function of many variables including temperature, wind speed, relative humidity, and siting variables such as exposure to wind and available sunlight. In addition, the insulating properties of individual houses vary considerably with the size and shape of the dwelling and amount of insulation used in construction.

Table 4 has been developed to aid in the selection of a wood stove and to illustrate theoretical heat losses as a function of outside design temperatures.[a]

[a] Outside design temperature is the lowest temperature that is expected to occur once in 13 years.

TABLE 4 [a]

Outside Design Temperatures [b]
of
Pacific Northwest Cities

CITY	DEGREES FARENHEIT (F°)
Idaho	
Boise	-10
Lewiston	5
Pocatello	-5
Twin Falls	-10
Oregon	
Eugene	15
Pendleton	-15
Portland	10
Washington	
Seattle	15
Spokane	-15
Tacoma	15
Walla Walla	-10
Yakima	5
Alaska	
Juneau	-5

[a] ASHREA 1980

[b] Normal design conditions winter - occurs once in 13 years.

Calculating heat losses utilizing the outside design temperature is an accepted practice that minimizes the number of variables that must be considered in determining the theoretical heat loss. Table 4 lists numerous Pacific Northwest cities and the corresponding outside design temperature. The value obtained from this table can then be utilized in conjunction with Figure 6 to estimate the hourly heat loss. Since the outside design temperature is expected to be reached only once in 13 years, it is advisable to use a slightly warmer temperature to represent the more typical situation that is anticipated unless the stove is to be used as the sole source of heat.

After the design temperature and square footage of the home has been determined, the estimated heat loss can be obtained using Figure 6. This value is for a "typical home" and needs to be adjusted for the specific design situation. The "typical home" used here is a single-story frame house with wood siding and single pane windows. Ceilings were insulated to R-30, walls to R-11, and floors to R-19, consistent with today's construction standards. Adjustments to the "typical home" heat loss value must then be made. This can readily be accomplished using Table 5. Differences in design characteristics between the "typical case" and the "specific case" should be noted on Table 5 and the total percent heat loss or heat savings computed. Figure 7 can then be used to obtain the adjusted heat requirement based on the estimated heat requirement and the computed percent heat difference.

After the "adjusted" hourly heat loss has been determined, the intended specific application must be considered. Most homes are not constructed to readily accommodate a complete conversion from conventional heat to wood heat. Homes that were constructed with individual room heat or forced air heat systems

FIGURE 6

Heat Loss
vs
Design Temperature

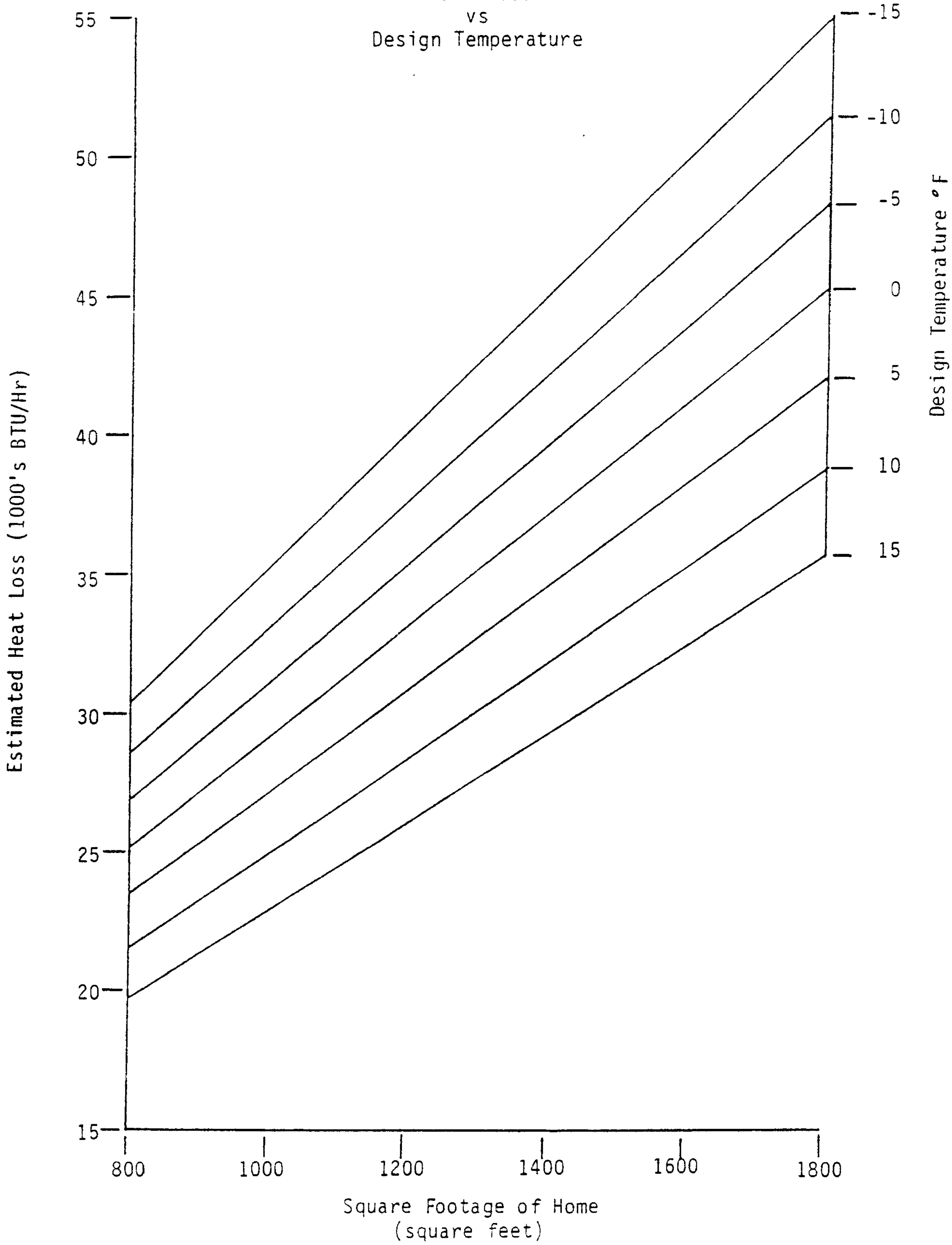


TABLE 5

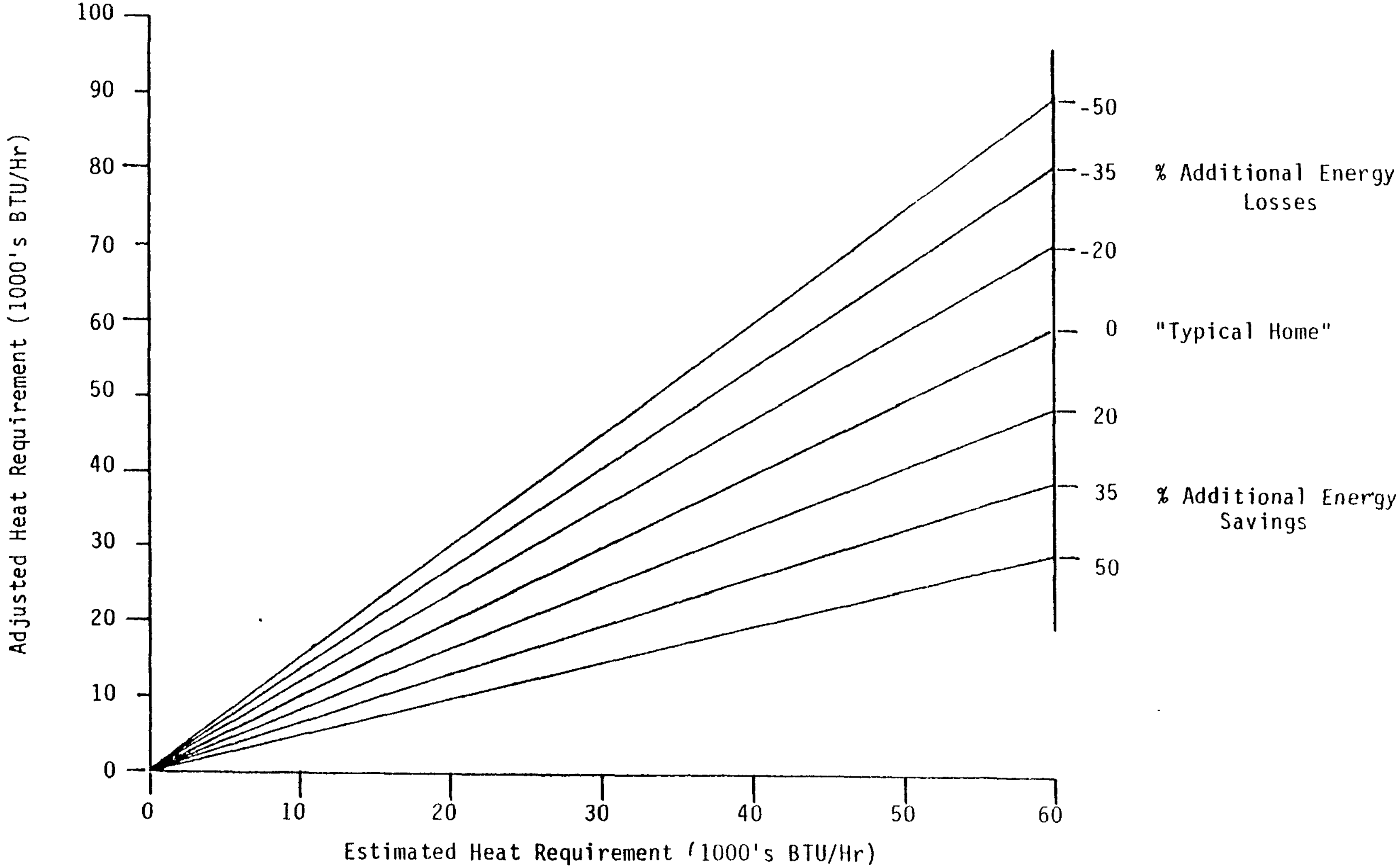
Effect of Differences
on
Total Heat Loss

Design Differences	Percent Heat Loss	Percent Heat Savings
Single story wood construction*	--	--
Two story home (wood or masonry)	--	3
Walls		
Wood R-5 (no insulation)	4	--
Wood* R-11 (2" insulation)	--	--
Wood R-15 (3" insulation)	--	6
Masonry R-5 (Brick or cinderblock, no insulation)	9	--
Masonry* R-11 (2" insulation)	--	--
Masonry R-15 (3" insulation)		
Windows		
Single pane*	--	--
Insulated	--	13
Floor		
Insulated R-5		
Insulated R-11 (2" insulation)	7	--
Insulated R-19* (3½" insulation)	--	--
Insulated R-30 (5" insulation)	--	13
Ceiling		
R-15 (3" insulation)	10	--
R-20 (4" insulation)	7	--
R-30* (5" insulation)	--	--
R-40 (6" insulation)	--	3
Infiltration**		
1/4 (tightly sealed home)	--	20
1/2	--	10
3/4*	--	--
1	10	--

R Values = Thermal resistance. The higher R value the better the insulating performance.
* Used in "typical home" example.
** Air changes per hour.

FIGURE 7

Adjusted Heat Requirement
vs
Estimated Heat Requirement



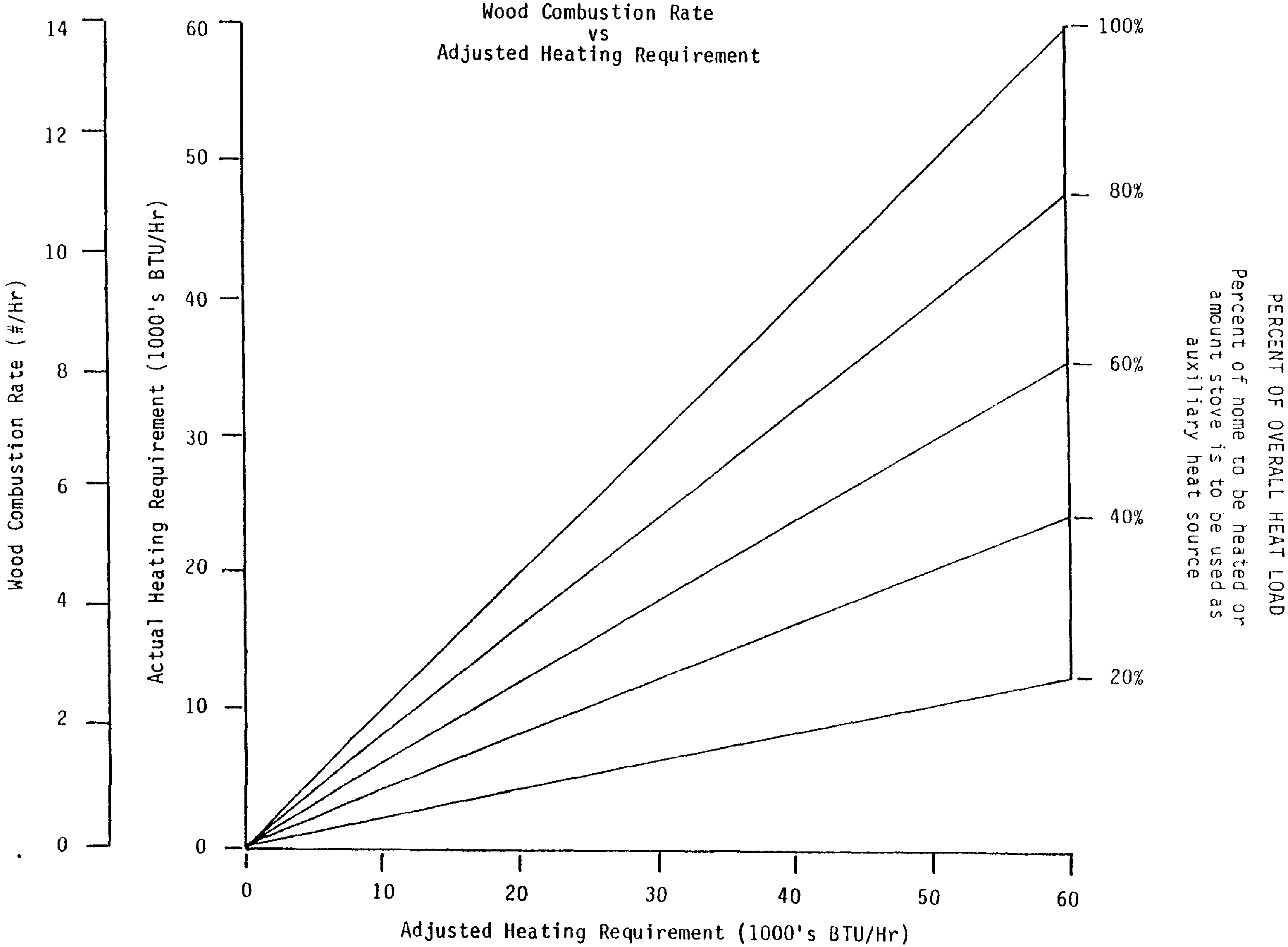
may prove very difficult to heat with a wood stove. For example, trying to heat a large ranch style home formerly equipped with electric ceiling heat to a uniform temperature would prove extremely difficult. To heat the distant rooms to the desired temperature may cause areas nearer the stove to be uncomfortably warm due to the high output which would be required of the stove. Without an adequate air movement system the exclusive use of a wood stove would create significant cold and hot spots. This type of heating leads to user discomfort and to additional fuel expenses resulting from overheating part of the house to accommodate other areas. Rather than trying to heat the entire home with a wood stove designed for localized heating, careful consideration should be given to heating just a portion of the home with wood.

Using the wood stove as an auxiliary heat source may prove to be more cost effective and provide better user comfort. By reducing the size of the stove and burning less wood, the cost of the stove and the firewood would be reduced. Also, labor associated with wood heat can be reduced, which will enhance user comfort.

Once the percent of overall heat load to be carried by the stove and the adjusted heat requirement have been determined, Figure 8 can be used to determine the approximate required wood combustion rate to supply the necessary heat. This will be used in selecting the proper size of wood stove. Although the wood combustion rate required to provide proper heat to the home has been determined, the stove selection process is not complete yet. The charge size and volume (firebox size) of the stove must still be selected. These parameters will, in effect, establish the required frequency of charging. As previously discussed in this report, a well controlled hot fire minimizes emissions and improves

FIGURE 8

Wood Combustion Rate vs Adjusted Heating Requirement



overall efficiency. Consequently, using a charge size of about 1/3 the firebox volume and allowing it to burn rapidly minimizes emissions and improves overall efficiency. Therefore, one of the prime considerations in selecting a stove should be its ability to operate under these above conditions, i.e., operate with a charge of 1/3 to 1/2 firebox capacity, at a moderate to high burn rate without producing more heat than is needed. Trying to maintain a high temperature fire in a large stove may produce far more heat than is needed. This results in either reducing the size of the charge or dampering down the stove (and sacrificing efficiency of operation) or letting the excess heat out the windows, requiring excessive fuel usage and again promoting inefficiency. As already mentioned, there is greater combustion efficiency and reduced air pollution from a hot fire than from a slow smoldering fire. Adding wood to the stove every two or three hours generally has proved to be the most effective charging rate regarding efficiency and pollution considerations. More frequent charging requires excessive operator attention. Less frequent charging of large loads causes operator inattention, resulting in reduced efficiency and increased emissions; this process is similar to fire banking.

Consequently, the choice of burn rate, charge size, and charge frequency is the key to the stove sizing process. Using the required combustion rate previously established and a theoretical time between charges, allows the use of Figure 9 to establish the desired firebox volume and thus completes the selection process. Table 6 summarizes the sizing process and provides an example illustration to assist in the size selection process.

FIGURE 9

Firebox Volume
vs
Charging Rate

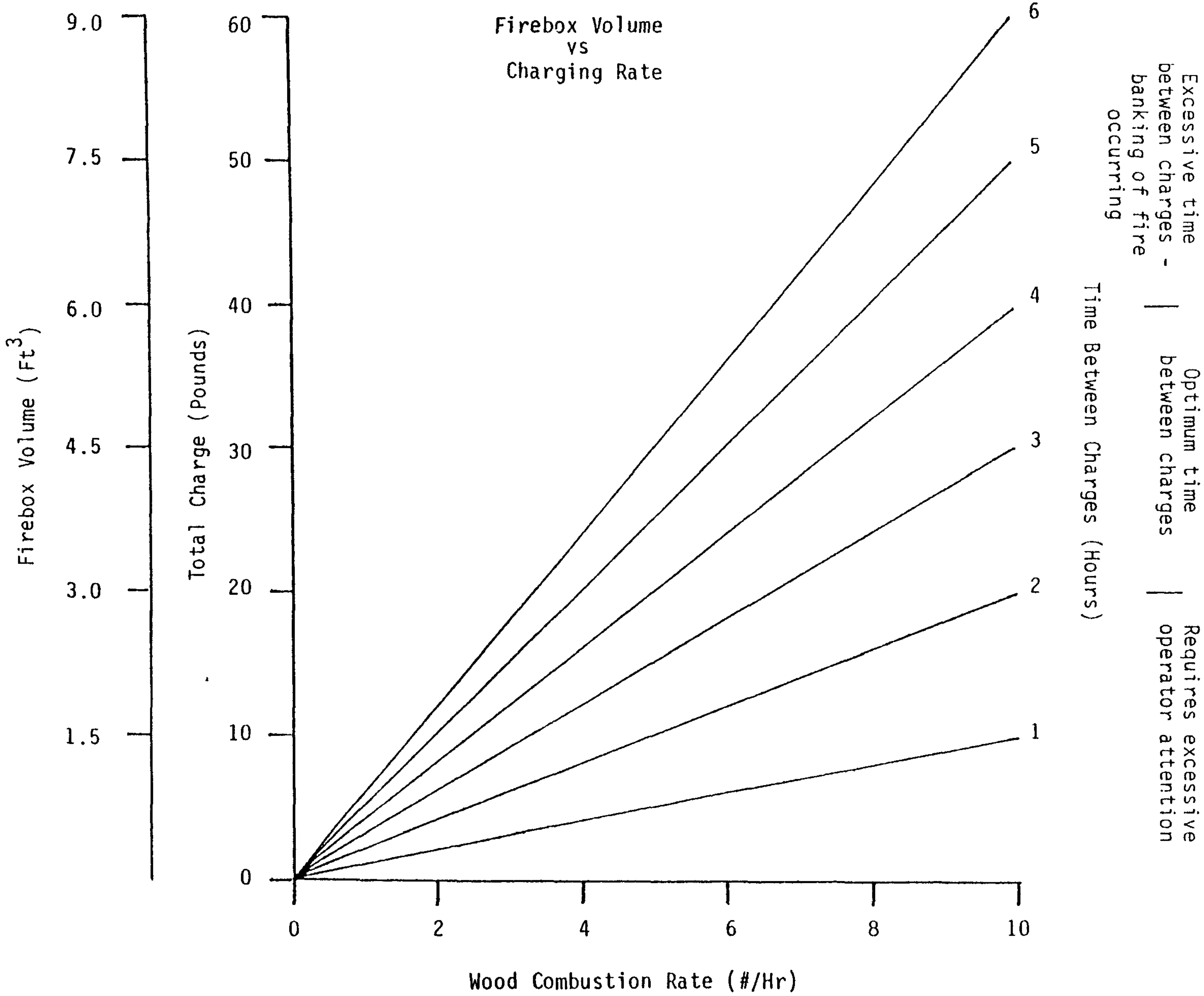


TABLE 6

Stove Sizing Process Summary
and
Illustration

1. Determine outside design temperature - Table 4.

2. Estimate square footage of home.

3. Determine estimated hourly heat loss - Figure 6.

4. Estimate effect of design difference from "typical home" Table 5.

5. Determine adjusted heat requirement - Figure 7.

6. Establish percent of home to be heated by wood heat or amount stove is going to be used as auxiliary heat.

7. Determine actual BTU requirement and required wood combustion rate - Figure 8.

8. Establish desired charging frequency.

9. Select firebox volume - Figure 9.

Illustration:

Home located in Boise, Idaho. From Table 4 Outside Design Temperature determined to be -10° F.

Home size estimated at 1600 square feet. Using Figure 6, the estimated heat loss is 47,000 BTUs/Hr. Using Table 5 an additional heat savings of 13% is expected since the home is equipped with insulated windows. Therefore, from Figure 7, the adjusted heat requirement is estimated to be 41,000 BTUs/Hr.

Stove is only going to be used to heat 40% of the living area of the home. Using Figure 8, it can be determined that the actual heating requirement is only 16,500 BTUs/Hr and the wood combustion rate should be approximately 3.8 pounds per hour. Since the stove will be charged every 3 hours, it is evident from Figure 9 that a stove with a firebox volume just over 1.5ft^3 will be adequate in size. Therefore, a small stove should be used.

VII. STOVE & FIREPLACE OPERATION

Air contaminant emissions and overall efficiency of operation of a stove and fireplace are influenced by many variables. These include design, fuel characteristics, and operator technique. The following is a list of comments and suggestions provided to minimize air contaminant emissions and improve the heating characteristics of the stove or fireplace.

FUEL:

1. Select a good quality fuel. This provides more BTU's per dollar and less creosote, maintenance, and air pollution. Do not burn trash or plastics -- these can produce hazardous pollutants and affect the life of your stove and chimney. Air dried hardwoods reduce creosote formation. Hardwoods provide more BTU's per cord than softwoods, although about the same BTU's per pound as softwoods.
2. Properly season the fuel. By providing air circulation for your fuel pile and time to let it season, you will get more BTU's of heat with less air pollution. Provide a full year for optimum seasoning. Proper preparation of the fuel is essential for clean, efficient burning. The wood should be stacked properly to allow air to circulate within the pile to dry the wood. Sheltering the wood pile against rain and snow is extremely desirable. However, if covering the wood pile with plastic, one must arrange the plastic so as to prevent trapping the ground moisture within the pile.

WOOD STOVES:

3. Select a properly sized stove. Remember, bigger is not better. Determine the heating demand for your particular installation and select a stove that meets that specific heating requirement.

4. Combustion air dampers properly operated or regulated in reference to the optimum air to fuel ratio can improve efficiency and reduce emissions. Stove efficiency increases when controlled by an automatic thermostat.[16] There is a tendency to purchase a large stove with an automatic damper to allow overnight and all day operation without additional charging. These stoves are generally grossly oversized. Used in this manner this feature significantly reduces efficiency and increases air pollution, since the ideal burning rate is not maintained.

5. Burn hot fires. Stoves should be batch fed every two to three hours to produce the required heat. Overnight banking of the fire at a low combustion rate should be eliminated to improve emissions and overall efficiency. This also reduces creosote formation. Leave air dampers open to promote combustion. This improves efficiency and heat output while reducing emissions.

6. Use a stack or surface thermometer to monitor the operation of the stove to assure it is operating at maximum efficiency. Typically a stack temperature in the range of 300°F - 350°F where it connects to the stove assures a hot fire to promote combustion without excessive heat loss out the stack.

7. Don't overcharge or undercharge the firebox. Maximum efficiency and minimum air pollution depends on a proper charge. Typically this is approximately 1/3 the firebox volume. Stack the charge in the firebox loosely to allow air movement throughout the pile.

8. Use properly sized wood -- 3½ to 5 inches in diameter. Wood too large tends to smolder, while wood too small undergoes pyrolysis too fast -- both of these promote incomplete combustion.

9. Heat exchangers could be used more effectively. A run of non-insulated stove pipe is an example of a heat exchanger. These units increase thermal efficiency. However, precautions need to be taken to prevent excessive creosote accumulation and the creation of a possible fire hazard.

10. Heat sinks such as water reservoirs, could be utilized to allow the more effective operation of the stove while providing a storage area for heat for a later use. This would allow the stove to be operated continuously at its maximum efficiency with the heat being stored for later use.

<u>FIREPLACES</u>:

11. Fireplaces should be used for recreational/aesthetic reasons rather than for space heating, because of their very low energy efficiency.

12. Use of a fireplace in cold weather should be avoided. The low net overall energy efficiency may even be negative (more heat loss than gained) when the outside temperature approaches 10°F.

13. Hot full fires should be burned in the fireplace to reduce emissions.[8, 31]

14. Fireplaces equipped with glass doors should be operated with the doors open for maximum overall efficiency. When closed, glass doors severely retard the flow of heat from the fireplace into the room.

15. When not in operation and during the burn down period, glass doors should be closed to prevent the loss of heated room air up the fireplace stack.

16. Heat exchangers with blowers and tube grates help to improve overall efficiency of the fireplace. However, this increase in efficiency is typically very minor.

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