Home heating using a wood-fired boiler in conjunction with a heat storage unit
by Steven Richard Hagan

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Industrial Arts Education
Montana State University

Abstract:
The purpose of the study was the design, construction and operation of a wood-fired boiler, used in conjunction with a heat storage unit,to heat a single-family dwelling.

The system consisted of a fire tube type boiler to heat water that was stored in a 1500 gallon storage tank. This hot water was used to heat the house through fin tube type radiators mounted under the floor joists of the main floor of the house. The system was installed and tested in a house located near Bozeman, Montana.

In order to evaluate the performance of the system, two variables were studied. One was the amount of potential energy available in the fuel and the second variable was the amount of heat that was actually realized in the house.

To compare the wood heating system's performance with a conventional heating system, electrical baseboard heaters were used as a control. The two systems were operated alternating weekly, with the wood heating system in operation for three weeks and the electrical heating system operating for two weeks.

Measurements of the temperature both inside and outside the house were taken every hour using two thermographs. This temperature difference was used to calculate the heat needed to keep the house at a comfortable temperature. The wood that was consumed in the boiler was weighed to determine the potential energy available and a watt hour meter was installed on the electrical heating system to record the amount of electricity used.

It was found that the wood heating system provided heat for $1.75 per million Btu1s and the electrical heating system provided heat for $5.89 per million Btu's. The wood-fired boiler operated at an efficiency of 55 percent.

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Date Aug. 4, 1978

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Approved:

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MONTANA STATE UNIVERSITY
Bozeman, Montana

June, 1978

ACKNOWLEDGMENTS

The writer wishes to express his sincere appreciation to the persons whose assistance contributed to this study:

To Dr. Doug Polette, whose technical advice and physical contribution to the project was invaluable.

To Dr. Max Amberson, for his aide and encouragement as the writer's committee chairman.

To Dr. Doug Bishop, for his advice and help as a member of the writer's committee.

To the Department of Agricultural and Industrial Education, Montana State University, for the graduate assistantship that made advanced study possible.

To Don Lee, for technical advice and his application of great expertise in welding.

To Luella Polette, for her tolerance and hospitality during the project.

To Noelle, for her constant support and the effort and enthusiasm in editing and typing.

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ABSTRACT

The purpose of the study was the design, construction and operation of a wood-fired boiler, used in conjunction with a heat storage unit, to heat a single-family dwelling. The system consisted of a fire tube type boiler to heat water that was stored in a 1500 gallon storage tank. This hot water was used to heat the house through fin tube type radiators mounted under the floor joists of the main floor of the house. The system was installed and tested in a house located near Bozeman, Montana.

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It was found that the wood heating system provided heat for $1.73 per million Btu's and the electrical heating system provided heat for $5.89 per million Btu's. The wood-fired boiler operated at an efficiency of 55 percent.

CHAPTER I

THE PROBLEM AND ITS SETTING

INTRODUCTION

People are becoming more interested in alternatives to the use of conventional heat sources to heat their homes.[1] They may be concerned with the use of finite fossil fuels or, more probably, they are concerned with the increase in the cost of heating their homes with conventional fuels. It has been forecast that between 1972 and 1985, the cost of No. 2 fuel oil will increase by 613%, electricity by 157% and that by 1981, natural gas will increase 409%.[2] As a result, people will be looking for alternate energy sources or ways of reducing conventional energy consumption.

One alternative is the use of wood. In many parts of the country, there is ample wood on a renewable basis and, if used wisely, this could supply many families with their home heating needs. However, the problems involved in using wood to heat homes have limited its use.

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[1] Alan L. Hammond, "Individual Self-Sufficiency in Energy," Science 184, (April 19, 1974), p. 278.

[2] Stewart Byrne, Report //1; The Arkansas Story (Toledo, Ohio: Owens-Corning Fiberglass Corp., 1975), p. 1.

When using wood to heat a home, a certain amount of inconvenience is involved. If a conventional wood space heater is used, it must be loaded a number of times during the day and the rate of combustion must be controlled in order than an even heat be produced. This creates an additional problem of incomplete combustion and the production of large amounts of smoke. These problems create a need for a central wood heating system that would be competitive with other alternative energy heating systems and burn wood efficiently thus producing less smoke and minimizing homeowner inconvenience.

STATEMENT OF THE PROBLEM

The purpose of this study was to design and construct a wood-fired boiler to be used in conjunction with a heat storage unit to heat a single family dwelling. The feasibility of the wood heating system was then to be compared to a conventional electrical heating system.

NEED FOR THE STUDY

The need for a central heating system using wood as the fuel is threefold. First, with the projected increase in the cost of conventional energy sources such as electricity, natural gas and fuel oil, homeowners are looking for cheaper alternative sources of heat. At today's prices, $15.00 worth of wood provides as many potential Btu's of heat as $130.00 worth of electricity, $36.00 worth of natural gas and $30.00 of fuel oil. These figures are based on $30/cord wood split and delivered, $0.444/kwh electricity, $.003671/ cu. ft. natural gas and $0.42/gal. No. 2 fuel oil delivered. It must be noted that the figure for electricity cannot be directly compared to the figures for wood, natural gas and fuel oil because heat output from electricity is 100% efficient and the other fuel sources are approximately equal in efficiency and much less.[3] However, the cost of central heating systems on the market today that use wood as fuel is prohibitive to the average homeowner. Secondly, other possible alternatives to the use of conventional energy sources, such as solar heat collection or capturing the energy of the wind, are not yet sufficiently perfected to be economically feasible for use in an average home. The use of wood can be an interim energy source until these alternatives are perfected. Finally, the widespread use of wood as a fuel would lead to increased air pollution which could

[3]Interview with Lyne Martin, Montana Power Representative, May 2, 1978.

partially be alleviated with a system that burns the wood more efficiently and does not emit large particulates of carbon.

OBJECTIVES

The following objectives were developed to accomplish the purpose of the study:

1. To design a central wood heating system that would include a wood-fired boiler and a heat storage unit.

2. To test the efficiency of the central wood heating system.

3. To compare the central wood heating system to a conventional electrical heating system with respect to fuel costs.

ASSUMPTIONS

The nature of the study dictated that the following assumptions be made:

1. That the current energy shortage and increase in energy cost will continue.

2. That wood is a renewable energy source and will be available in many parts of the country.

3. That the wood used will be representative of its

species as to Btu's per pound.

4. That the data received will have implications for the feasibility of using a wood-fired boiler and heat storage unit to heat a dwelling.

5. That the moisture in the firewood used will be uniform and will not affect the data collected.

LIMITATIONS

The investigator was aware of the following limitations in this study:

1. Only lodgepole pine will be used to fuel the boiler and therefore, no inferences can be made as to the performance of other species of wood used to fuel the boiler.

2. Only standing dead trees of the species lodgepole pine will be used and there will be no account for the moisture content of the wood.

3. There will be no quantitative evaluation of the contribution of solar infiltration through windows in the house.

4. The data will only be applied directly to one house in one particular climatological location.

DEFINITION OF TERMS

Alternative energy heating system - a heating system using wood, wind or the sun as an energy source.

Boiler - wood-fired, water-jacketed, fire tube type boiler not designed to produce steam.

Btu - British Thermal Unit which equals weight in pounds times the change in temperature in degrees Farenheit times the specific heat of the substance.

Conventional energy heating system - a heating system using natural gas, electricity, fuel oil or propane as an energy source.

Heat storage unit - 1500 gallon steel tank filled with water, insulated with a minimum of 12 inches of fiberglass insulation.

R value - resistance to heat flow and equal to the reciprocal of the U value.

Radiators - 3/4" fin tubes installed just under the floor joists of the main floor of the house.

Specific heat - the number of Btu's required to raise the temperature of 1 lb. of the substance $1^{o}F$. The specific heat of water is one.[4]

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[4] Charles E. Dull, Modern Physics (New York: Henry Holt and Company, 1945), p. 230.

System - boiler, heat storage unit, radiators and related plumbing and wiring exclusive of the electrical heating system.

Temperature differential - difference between the temperature inside the house and the temperature outside the house.

U value - hourly rate of heat transfer for one square foot of surface when a temperature difference of $1^{o}F$ exists between the air on the two sides of the surface.[5]

Variable costs - costs of operation of the wood heating system including fuel and maintenance.

PROCEDURE

Data Collection

In order to evaluate the performance of the central wood heating system and compare it to a conventional electrical heating system, three variables were recorded: amount of wood used in the wood-fired boiler, amount of electricity used by the resistance electricial heaters, and temperature inside and outside the house. The test period extended for five weeks. Each system was in operation singly

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[5]Seichi Kouzo, J. Raymond Carroll, and Harland D. Bareither, Winter Air Conditioning (New York: The Industrial Press, 1958), p. 183.

on alternating weeks.

Wood Consumption

The conventional method of measuring the amount of wood is by volume. However, because this is very unreliable when working with split or unsplit cord wood, the wood was weighed to evaluate the amount used. All calculations were related to the weight of wood, then interpolations were made to volume.

A beam balance scale was used to weigh the wood. A reasonable amount was weighed at the beginning of each week during the time the system was being used as the heat source. Any wood left in the stack at the end of the test period was weighed and subtracted from the total for that week.

Electricity Consumption

A conventional watt-hour meter was used to record the amount of electricity consumed during the test period in which the electrical resistance heaters were used to heat the house. This meter recorded only the amount of electricity used by the heaters and was isolated from other electrical needs of the house.

Temperature Differential

One thermograph was installed inside the house to graphically record the inside temperature. Another thermograph was installed on the shaded side of the house in a protective box to graph the ambient outside air temperature. At the beginning of the five week test period, each thermograph was calibrated with an accurate mercury bulb thermometer. The thermographs were set to run for one week with a seven day graph installed and changed weekly.

CHAPTER II

REVIEW OF LITERATURE AND RELATED RESEARCH

WOOD AS FUEL

When considering the use of wood as an energy source, it must be established that wood is available on a renewable basis for use in residential heating. It has been stated that one-third of the world is experiencing a shortage of wood to be used for home heating and cooking.[6] In fact, many areas of the world were said to be treeless where extensive forests once grew. Areas of the Indian subcontinent, central Africa and parts of Latin America were reported to exhibit treeless regions which extend to a 30 mile radius around larger cities.[7] However, these shortages seem to be a problem of local areas of high population densities having a lower standard of living. In other parts of the world, there is ample wood for use as fuel. Eckholm stated:

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[6] E.P. Eckholm, Losing Ground (New York: W.W. Morton, 1976), p. 103.

[7] Jay W. Shelton, Woodburner's Encyclopedia (Waitsfield: Vermont Crossroads Press, 1976), p. 7.

> ". . . there is little point in calling this a world problem, for fuel wood scarcity, unlike oil scarcity, is always localized in its apparent dimensions."[8]

Considerable research has been done to determine the availability of timber in the United States. Shelton felt that a wood shortage in the United States was not likely to occur for three reasons. First, the United States had many sources of energy to choose from and therefore,would never be wholly dependent on one of these sources. Second, some forests existed as very stable ecosystems and thus, will be able to take the pressures man will impose on them. It has been noted that when these ecologically stable forests are cleared and then abandoned, the trees returned very quickly as if they were in fact weeds. Finally, legislation that brings about control of destructive forest practices will become stronger.[9]

Shelton went on to say that most of the wood grown in the United States is not used but decays and that "a considerable expansion of wood use is possible."[10] A study done by the State of Vermont found that the actual sustained

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[8]Eckholm, p. 104.

[9]Shelton, p. 8.

[10]Ibid., p. 7.

growth in the forests of Vermont was roughly five times the current annual harvest. It was noted that this area is a major lumber and pulpwood producer. This sustained growth rate of 1/4-3/4 of a cord per acre could be doubled with improved forest management procedures such as thinning, cutting less productive individual trees and harvesting at the most productive time.[11]

Although shortages involving quality and size in certain timber species may occur, there seems to be ample wood in the United States that is suitable for use as fuel wood. In a study conducted by the United States Forest Service, reported in Gay, on the potential fuelwood available per year in various regions of the United States, it was reported that, after timber harvest and natural mortality had been accounted for, there was a net annual growth of 61 million cords of hardwoods and 36 million cords of softwoods in the eastern forests and 1.6 million cords of hardwood and 3.4 million cords of softwoods in the forests of the northern Rocky Mountains.[12] When the amount of softwood alone for

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[11]State of Vermont, Report on the Governor's Task Force on Wood as a Source of Energy, 1975.

[12]Larry Gay, The Complete Book of Heating With Wood, (Charlotte, Vermont: Garden Way Publishing, 1974), p. 15.

the northern Rocky Mountains was divided by 5 cords per year for an average American home, enough cord wood was obtained for 680,000 households.[13] It should be noted that some of this annual growth was in areas that are inaccessible; however, these figures were reported after deducting logging wastes, old age and disease losses, and blow downs. Much of this type of wood could be suitable for fuel wood.

It must also be established whether an increase in the use of timber for fuel wood would hinder the lumber industry. Gay explained:

> ". . . taking wood for fuel from the forests should not compete with the lumber industry at all. On the contrary, it should lead to much greater production of quality timber."[14]

FUELWOOD COSTS VS. CONVENTIONAL ENERGY SOURCES

In 1978, firewood in Montana varied in cost from $15.00 per cord for mill scrap that is not delivered to $40.00 per cord for cut, split, delivered and stacked wood that is purchased near the end of the heating season. A common price was $30.00 per cord for cord wood that is cut

[13] Ibid., p. 16.

[14] Ibid.,

and delivered.[15] The datum in Table 3, p. 16 was based on this average price.

Natural gas in May of 1978 was priced according to the following schedule:

TABLE 1[16]

NATURAL GAS PRICE SCHEDULE

Increment (M=thousand)	Price per thousand cu.ft.
first 1000 cu. ft.	$5.1619
next 99 M cu. ft.	2.2284
next 200 M cu. ft.	1.8928
next 700 M cu. ft.	1.6934

It has been found that there are 950 Btu's per cubic foot of natural gas.[17]

Electricity was sold in May of 1978 according to the following schedule:

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[15] Bozeman Daily Chronicle, March 1, 1978, p. 29.

[16] Interview with Lyne Martin, Montana Power Representative, May 2, 1978.

[17] Ibid.

TABLE 2[18]

ELECTRICITY PRICE SCHEDULE

Increment	Price per kilowatt hour
first 20 kwh	$0.0169
next 80 kwh	0.0538
next 100 kwh	0.0376
additional kwh	0.0188

One kilowatt hour was reported to contain 3413 Btu's.[19]

Both No. 2 fuel oil and propane were priced at $0.42 per gallon in May, 1978. Fuel oil contains 140,000 Btu's per gallon and propane contains 98,600 Btu's per gallon.[20] The costs of these purchased fuels are reported in Table 3.

[18] Ibid.

[19] Groff Conklin, The Weather Conditioned House (New York: Reinhold Publishing Corp., 1958), p. 167.

[20] Martin.

TABLE 3

COMPARATIVE PRICES OF SELECTED FUELS

Fuel	Price of one million Btu's
Wood (lodgepole pine)	$1.71
Natural gas	5.42
Electricity	10.15
Fuel Oil (No. 2)	3.00
Propane	4.59

It should be noted that the efficiency of electric heaters is 100% and the efficiency of the furnaces that use the other fuels in the table ranged from 50% to 80%.

FUELWOOD PROPERTIES

Different species of fuelwood have different Btu ratings per cord. This is primarily due to the fact that different species of wood have different densities. It has been found that most woods have the same number of Btu's per pound of ovendried wood.[21] As a result, the most accurate method of determining the number of Btu's in a quantity of wood is by weight.

[21]David Lyle, The Lange Stove Catalog and Wood Heat Guide (Alstead, N.H.: Scandinavian Stoves, Inc., 1976) p. 15.

It has been reported by a number of authors that the energy given off during combustion of one-pound of dry wood was about 8600 Btu's.[22] This held true for all woods except those with high resin content. Table 4 was prepared from research data developed by Shelton and Lyle which lists densities and Btu's per pound for different woods found in the West.[23]

TABLE 4
POTENTIAL ENERGY OF VARIOUS WOOD SPECIES

Species	Specific Gravity	lbs/cu.ft.	million Btu/cord
Alder, red	.41	25.5	17.5
Ash, Oregon	.55	34.27	23.6
Aspen, Quaking	.38	23.67	16.3
Cottonwood, black	.35	21.81	15.0
Oak, white	.68	42.36	29.2
Cedar, western red	.32	19.94	13.6
Douglas fir, Interior West	.50	31.15	21.4
Pine, Jack	.43	26.79	20.6
Lodgepole	.41	25.5	17.5
Ponderosa	.40	24.92	17.1
Redwood	.40	24.92	17.1
Spruce, Engelman	.35	21.81	15.0
Sitka	.40	24.92	17.1

[22] Lyle, p. 15; Gay, p. 39; Shelton, p. 18.

[23] Shelton, pp. 18-21; Lyle, p. 17.

BOILER AND HEAT STORAGE UNIT DESIGN

The design of a boiler and heat storage unit for a residential building is dependent on a number of factors. The first consideration is the amount of heat loss through the building materials used in the building. A heating system must be able to provide this amount of heat to make up for the heat loss. Using this value of heat loss and a specified period of time, a determination can be made as to the amount of heat that is needed in storage. The size of the fire box can then be computed on the basis of the number of Btu's needed to be transferred to storage and the number of Btu's that are available in the species of wood being used. The boiler must have the necessary heat absorption area to transfer the available energy in the wood to the heat storage unit.

BUILDING HEAT LOSS

Numerous methods have been developed to calculate the heat loss in a dwelling. The generally accepted method was one reported by Konzo, Carroll and Barietber using this formula:[24]

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[24]Seichi Konzo, J. Raymond Carroll, and Harland D. Bareither, Winter Air Conditioning (New York: The Industrial Press, 1958), p. 183.

$$H = A(U)(t.d.)$$

where:

H = the design heat loss in Btu/hr
A = the area through which heat loss takes place, in square feet
U = the coefficient of heat transfer
t.d. = the temperature difference assumed between indoor-air and outdoor-air temperatures, under design conditions

Heat Loss Area

The area of all surfaces where heat loss occurs such as ceilings, walls, windows and doors is itemized and recorded on a work sheet. For each of these areas there was a reported heat loss coefficient.[25]

Heat Loss Coefficient

Different materials are reported to have different heat loss coefficients. Table 5, p. 20, was developed from information by Conklin and the Rural Electrification Administration and lists all the materials that are used in the house reported in this study.[26]

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[25]Ibid.

[26]Conklin, pp. 19-22; U.S. Department of Agriculture, Rural Electrification Administration, Electric House Heating, REA Bulletin 142-1 (1960), pp. 15-16.

TABLE 5

HEAT LOSS COEFFICIENTS OF VARIOUS BUILDING MATERIALS

Material	Thickness (in.)	Resistance (R)
Sheetrock	1/2	.45
Plywood	1/2	.63
Plywood	1	1.25
Wood fiber board	1	2.38
Building paper:		
vapor-permeable felt		.06
vapor seal, plastic film		0.00
Concrete: sand and gravel or stone aggregate (not dried)	1	.08
Roofing: wood shingles, double		1.19
Insulation: Blanket or batt, glass fiber	1	3.70
Windows: double glass, 1/4" air space	1/4	1.64
Doors: steel sheet, foam core		19.0

The number of square feet of each surface in the building that will lose heat was multiplied by its particular heat loss factor (R) and the design temperature difference in order to establish the total heat loss per hour in the building.[27]

[27] Konzo, Carroll, and Bareither, p. 183.

Design Temperature Difference

Different areas of the United States have a different low annual average temperature, and the particular design temperature for the locality under study needed to be identified. Table 6, developed from information by Jennings, lists some design temperatures of areas applicable to this study and others to be used as a comparison.

TABLE 6[28]

OUTDOOR DESIGN TEMPERATURE

State and City	Design Temp. (F)
Montana	
Billings	-25
Butte	-20
Havre	-30
Helena	-20
Maine	
Eastport	-10
Lewiston	-15
Minnesota	
Duluth	-25
Minneapolis	-20
St. Paul	-20
Arizona	
Flagstaff	-10
Phoenix	25
Tucson	25

[28]Burgess H. Jennings, Heating and Air Conditioning (Scranton: International Textbook Company, 1956), pp. 148-50.

With the design temperature of the locality known, it was then possible to calculate the design temperature difference (t.d. in the formula on page 19). The accepted comfortable inside temperature was reported to be 70°F.[29] The difference in the design temperature for inside the dwelling and the design temperature for the particular locality equalled the design temperature difference.

Heat Loss to Infiltration

Heat loss through air infiltration was reported to be another significant contributor to heat loss in a building. Infiltration was described to be the inflow of cold air through cracks around windows and doors and through spaces between building materials.

The coefficient of heat loss (U) is found by multiplying the specific heat of air (0.24) times the density of air (0.075) to equal 0.018. The U value of the air is then multiplied by the volume of air that entered the house each hour. This method was reported by Conklin.[30] One complete air change per hour by volume inside the house was reported to be a rough estimate.[31]

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[29]F.W. Hutchinson, Design of Heating and Ventilating Systems (New York: The Industrial Press, 1955), p. 25.

[30]Conklin, p. 38.

[31]Konzo, Carrol, and Bareither, p. 210.

In summary, it should be noted that, even with careful consideration of each detail, calculation of heat loss in a building can only be considered an estimate.

> "No heat loss calculation, no matter how carefully made, can be more than an approximation. Even under the best conditions . . . it is doubtful whether any design heat loss value is within 10 percent of the true heat loss figure.[32]

HEAT STORAGE UNIT

The heat storage unit must be able to store enough heat to heat the house at the design temperature for a specified period of time. For this study water was used as a heat storage medium due to the fact that it was cheap and that there was equipment available to be used with water for heat transfer in the system. In addition, water has a high specific heat and therefore can store a high amount of heat by volume.[33]

BOILER HEAT ABSORPTION AREA

The literature that related to boiler design was limited to steam production and in most cases was written around the

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[32] Ibid., p. 184.

[33] Charles E. Dull, Modern Physics (New York: Henry Holt and Company, 1945), p. 230.

turn of the century. However, the reported data were applicable to this study because the principles of heat transfer have not changed.

The older method of determining the number of Btu's that were absorbed through steel walls of a boiler used a concept of horsepower. The method of determining the number of horsepower in a particular boiler involved dividing the inside surface area of the boiler by 10.[34] This figure was then multiplied by a constant for a particular thickness of carbon steel to find the number of Btu's per hour that the boiler would extract from the burning fuel.[35]

A later method of calculating the heat absorbed in a boiler used a formula developed by the Babcock and Wilcox Company:[36]

$$Q = U_d S \Delta t$$

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[34]Theodore H. Taft, Elementary Engineering Thermodynamics (New York: The Industrial Press, 1955), p. 25.

[35]Otto de Lorenzi, Combustion Engineering (New York: Combustion Engineering Company, Inc., 1933), p. 158.

[36]The Babcock and Wilcox Company, Steam, Its Generation and Use (New York: The Babcock and Wilcox Company, 1963), p. 3-7.

where:

Q = conductive heat transfer in Btu's per hour
U_d = conductance of the material used in Btu's per square foot per hour
S = surface area
Δt = temperature difference causing heat flow

A close approximation can then be made as to the surface area inside the boiler exposed to heat transfer.

CHAPTER III

SYSTEM DESIGN

When consideration is given to the design of a heating system for a domestic building, the first unknown that must be found is the total heat loss in the building. Using this figure, the size of the heat storage unit and the size of the boiler can then be found.

BUILDING HEAT LOSS

The location and types of building materials that are subject to heat loss in the house under study appear in Table 7, p. 27. The data in this table summarize the numbers of square feet of each building system (walls, ceiling, etc.) that have a similar coefficient of heat loss. These figures were then used in Table 8 to find the total heat loss through each building system. The total number of square feet was multiplied by the coefficient of heat loss for that system. The U factor for each building system was found by adding the U factors for all the components used in each building system. For example, the U factor for the ceiling is an addition of the sheetrock used (R=.45) and the fiberglass insulation (R=3.70 per inch or 44.4 for 12 inches)

TABLE 7

SQUARE FOOTAGE OF BUILDING SYSTEMS IN THE HOUSE

	Ceiling (sq. ft.)	Floor (sq. ft.)	Walls(ext.) (sq. ft.)	Doors(ext.) (sq. ft.)	Windows (sq.ft.)
Family Room	204	204	144	0	42
Kitchen	120	120	96	0	17
Study	108	108	200	0	16
Utility Room	150	150	208	20	17
Living Room	325	325	480	0	90
Master Bedroom	180	180	256	0	46
Bedroom #2	115	115	96	0	20
Bedroom #3	130	130	48	0	20
Hall	39	39	0	0	0
Master Bathroom	120	120	144	0	8
Bathroom	62	62	48	0	8
Entry	129	129	48	20	9
TOTAL	1682	1682	221	40	293