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:

Mat L. Anderson
Chairperson, Graduate Committee

Mat L. Anderson
Head, Major Department

Henry L Parsons
Graduate Dean

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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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

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[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°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

[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.

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[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 Bariether 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]

$$Q = U_d S \, \Delta t$$

[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

for a total R value of 44.85. The R value symbolizes the resistance to heat flow and is the reciprocal of the U value (heat loss coefficient). As a result, 44.85 (R value for the ceilings) is divided into one, giving the U value for the ceiling building system. The product of the area and the heat loss coefficient is then multiplied by the design temperature difference to equal the heat loss per hour through each separate building system.

TABLE 8

TOTAL HEAT LOSS IN BTU PER HOUR BY TRANSMISSION AND INFILTRATION

Structure	Area or Volume (sq.ft. or cu. ft.)	U Factor	Design Temperature Difference (°F)	Heat Loss Per Hour (Btu)
ceilings	1682 sq.ft.	.022	90	3330.36
floors	1682 "	.168	10	2825.76
walls	1768 "	.040	90	6364.8
doors	40 "	.050	90	180.0
windows	293 "	.609	90	16059.33
infiltration	3364 cu.ft.	.018	90	5449.68
	TOTAL Heat Loss in Btu/hr.			34209.93

The design temperature difference in Table 8 is calculated by subtracting the low annual average for the locality of the study (-20°F) from a comfortable home interior temperature (70°F). This gives the design temperature difference for all building systems exposed to the outside. It should be noted that the design temperature difference for the floors is much lower because the basement is to be heated. The products of the area, U factor and design temperature difference are then totaled to find the total heat loss in the house used in the study.

The amount of air infiltration is found by finding the total volume of air in the house and using one-fourth of that figure (one-fourth of the air is displaced every hour). A new home may have one-half of the air displaced every hour.[37] However, due to the fact that the house used during the study has an uninterrupted plastic film as a vapor barrier, magnetically sealed steel doors and windows that were installed and insulated with care, a value of one-fourth of the volume being displaced every hour was used.

It should be noted that even though the window area was a small fraction of the total area exposed to heat loss, the heat loss through the windows is almost equal to that of the other areas combined (windows--16059.33 Btu per hour heat loss, combined other areas--18150.60 Btu per hour heat

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[37]Burgess H. Jennings, Heating and Air Conditioning (Scranton: International Textbook Co., 1956), p. 152.

loss, data from Table 8, p. 28). The windows used were Anderson thermopane windows and their heat loss could be greatly reduced through the use of additional storm windows.

HEAT STORAGE UNIT

Having found the total heat loss in the house (34209.93 Btu per hour), it is possible to calculate the size of the heat storage unit needed. Two factors are involved when determining the size of the heat storage unit. First it was determined that the heat storage unit should hold enough heat to keep the house at $70^{\circ}F$ with an outside temperature of $-20^{\circ}F$ for at least 36 hours. Using a temperature difference of $100^{\circ}F$ in the tank ($100^{\circ}F$ minimum for effective heating to a maximum of $200^{\circ}F$), it was then possible to calculate the size of the storage tank. The following formula was developed by the researcher for this purpose.

$$V = \frac{(H_{loss})\ (H_s)}{(\Delta t)(W)(S_n)}$$

Units $\rightarrow$ $\dfrac{\left(\frac{\cancel{BTU}}{\cancel{HR}}\right)\left(\cancel{HR}\right)}{(°F)\left(\frac{lbs}{ga}\right)\left(\frac{\cancel{BTU}}{°F\cdot lb}\right)}$ = gals

check

where:

V = volume of heat storage medium

H_{loss} = heat loss per hour in house (34209.93 Btu/hr)

Δt = temperature difference in tank, maximum minus minimum ($100^{\circ}F$)

W = weight in pounds of storage medium (water = 8.3 lbs/gal)

H_s = ~~heat loss per hour in house (34209.93 Btu/hr)~~

36 Hrs

Fuck up

S_n = specific heat of storage medium (specific heat of water = 1.00)

so:

$$V = \frac{(34209.93)\ (36)}{(100)(8.3)(1)} = 1483.8 \text{ gal.}$$

Using this figure for the number of gallons in storage, a tank measuring four feet in diameter and sixteen feet in length was ordered. This tank was calculated to have a 1504.03 gallon capacity.

BOILER

The size of the fire box was of initial concern because it was thought that it should hold enough wood to heat the water in the storage unit 100°F. As a result, only one loading and firing would be necessary for a day and a half of heat for the house. The following formula was developed to find the size of the fire box.

$$V_{fb} = \frac{Btu_{load}}{(W)(H)(E)}$$

where:

V_{fb} = volume of the fire box in cubic feet
Btu_{load} = number of Btu's per load
W = weight of Lodgepole per cubic foot (24 lbs/ft^3)
H = number of Btu's of heat in a pound of dry wood (8600 Btu/lb)
E = estimated efficiency of the boiler (.50)

In order to find the number of Btu's per load needed to heat the water in the storage unit 100 degrees, a simple calculation was used. The temperature difference ($100^{\circ}F$) is multiplied by the number of pounds of water in the tank (1500 gallons at 8.3 pounds per gallon = 12,450 pounds). Therefore $100^{\circ}F$ multiplied by 12,450 will equal 1,245,000 Btu's in storage. This figure was used in the formula as the number of Btu's per load.

Using the formula for the volume of the fire box, its dimensions were calculated:

$$V_{fb} = \frac{1,245,000}{(24)\ (8600)\ (.50)} = 12.0639 \text{ cubic feet}$$

Because sheet steel is obtainable in varying lengths and widths of four feet, it could be made four feet long with less waste. The final dimensions of the fire box were then calculated to be 27 inches high by 22 inches wide by 46 inches long, giving a total volume of 15.8 cubic feet. When split wood is stacked, there is actually only 80% actual wood in the total volume due to the air spaces. Eighty percent of 15.8 is 12.64 cubic feet of actual wood in the fire box. Burning this amount of wood should produce the necessary Btu's to raise the water in the heat storage unit 100 degrees.

After the size of the firebox was calculated, it was necessary to find the amount of heat absorption area needed to transfer the heat from the burning wood to the water for heat storage and distribution. The following formula was used for this calculation:

$$A = \frac{(H_p)\ \text{Btu/hr}}{K}$$

where:

A = surface area exposed to heat transfer in squ. ft.
K = constant for heat transfer through 1/4" hot rolled steel (33,475)
Btu/hr = total number of Btu's available in one loading of the fire box divided by an estimated time for the combustion of the wood (7 hrs.)
H_p = a factor for converting the area of absorption to boiler horsepower (10)

so:

$$A = \frac{(10)\ (117,857)}{33,475} = 53.13 \text{ square feet}$$

The original design for the boiler was a simple cylinder inside a larger cylinder. However, it was found that this design did not have enough surface area for heat absorption. As a result, a design was used that incorporated fire tubes that would greatly increase the area for heat transfer. Table 9, p. 34, lists the sizes of areas of the boiler that are subject to heat transfer.

TABLE 9

AREA OF HEAT ABSORPTION IN THE BOILER

Part	Dimensions	Area
Top (fire box)	2' x 4'	8 sq.ft.
Sides (fire box)	(2' x 4')2	16 "
Back (fire box)	2' x 2'	4 "
Fire tubes	(3"dia.,33"long)18	38.88"
TOTAL		66.88

The fire tubes are mounted horizontally above the fire box so that the burning gases pass out the back of the fire box and enter the fire tubes (refer to figure 1, p. 35). The gases then move forward through the fire tubes and up the flue at the front of the boiler. The complete fire box (excluding the door) is jacketed with water and in addition, a water reservoir surrounds the fire tubes. Three one-inch inlets are fitted at the base of the boiler for cool water returning from the heat storage unit and one three-inch outlet at the top of the boiler near the flue for water convecting to the heat storage unit.

Access doors were provided to the ends of the fire tubes due to the fact that they are subject to sooting which reduces the efficiency of heat transfer. It is a simple

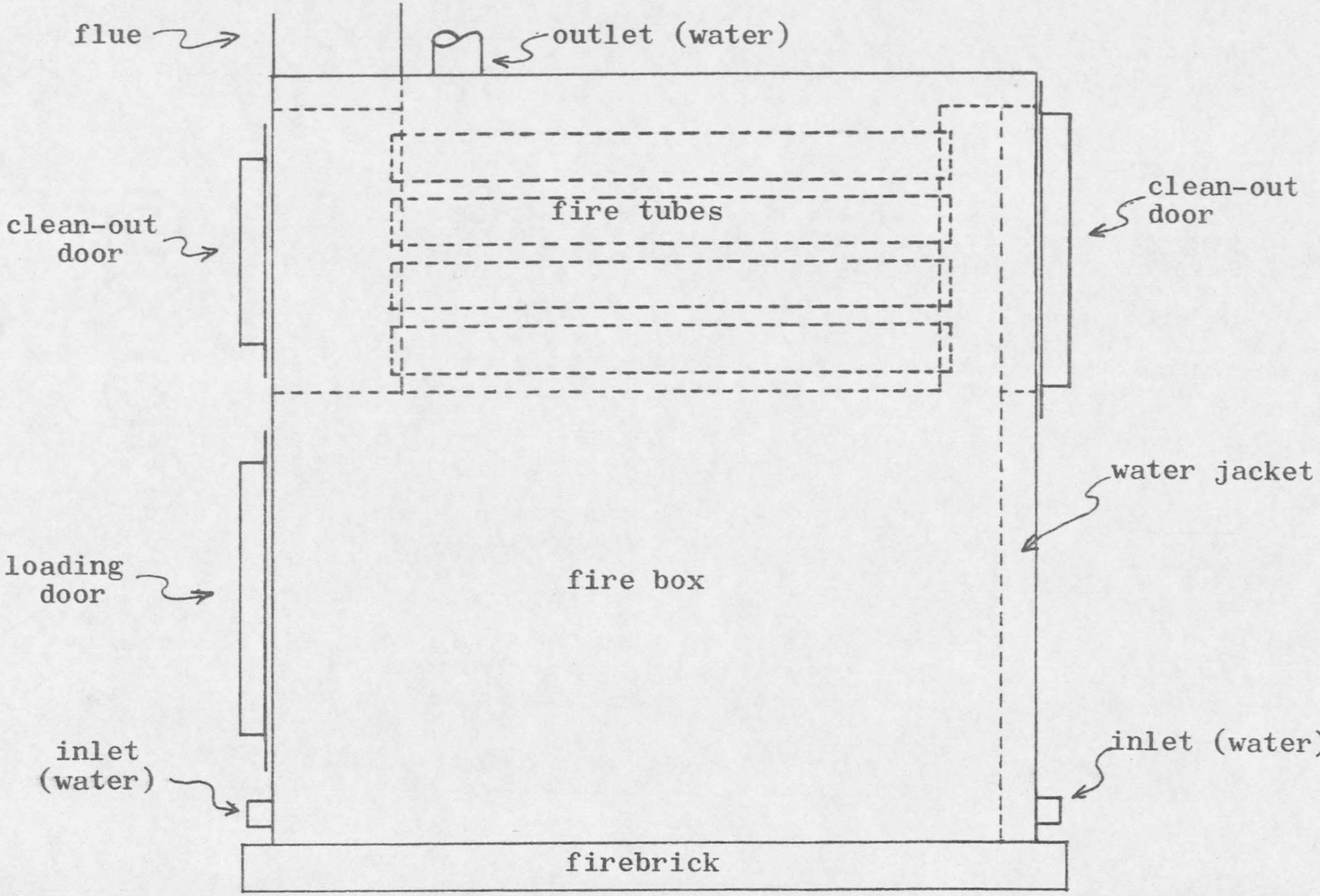

FIGURE 1. Fire tube boiler (side view).

matter to remove one of these doors and run a cleaning rod down the tubes to remove the soot.

When using hot rolled steel that will be exposed to high heat, there is a possibility of warping. To alleviate this problem in the clean-out doors, a lining of 3/8" asbestos sheet, four layers thick, was installed to insulate the sheet metal from the heat. These doors and the fire box door were also reinforced around the periphery with angle iron. This creates a heavy but very stable unit.

HEAT CIRCULATION AND DISTRIBUTION

Basically, there are two circuits in the circulating system. One circuit connects the boiler to the heat storage unit. The other circuit connects the heat storage unit to the radiators that transfer the heat from the water to the air that heats the house (refer to figure 2, p. 37).

The boiler to heat storage unit circuit is simple in design. It consists of one three-inch line that connects the bottom of the heat storage unit to the bottom of the boiler. The other three-inch line connects the top of the boiler to the top of the heat storage unit. Three-inch plumbing was used to allow a large volume to flow and there are no valves or pumps in the circuit. The principle of

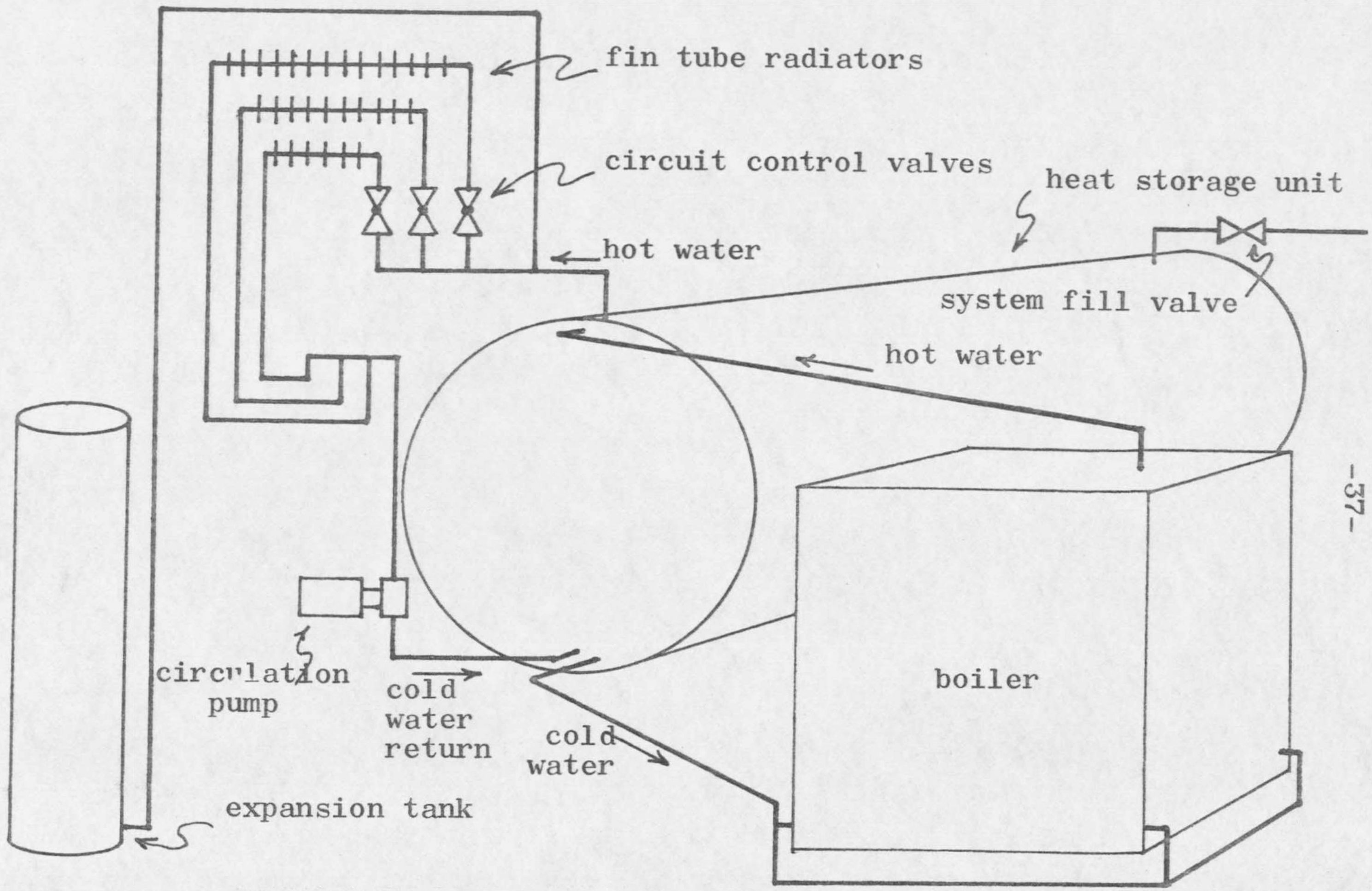

FIGURE 2. Heating system schematic.

convection (hot water, being less dense and lighter, rises) is used to transfer water from the boiler to the heat storage unit. A pump or valve installed in the circuit could cause a constriction in the line through loss of electricity to the pump or inadvertent closing of the valve. This constriction would allow steam to be produced in the boiler and create the possibility of increased pressure which the system could not handle.

The other circuit is used to transfer hot water to the radiators from the heat storage unit. It consists of a large line that is plumbed to the top of the heat storage unit to pick up hot water for the radiator system. This line is divided into separate circuits at a manifold that distributes the hot water to different areas of the house. There are three sub-circuits, one going to the family room and utility room, one going to the living room, and one heating the master bathroom. Each of these circuits is fitted with a valve that adjusts the flow to each circuit. The sub-circuit used to heat the living room also passes through a coil installed in a concrete slab in the floor of the entryway.

The radiators used in these sub-circuits are conventional fin tubes, suspended just under the floor joists.

They are designed to heat the floor of the room above.

The return line from these sub-circuits then connects to another manifold that is connected to the bottom of the heat storage unit.

A hot water circulating pump was fitted between the manifold and the heat storage unit and then wired to a thermostat in the house. As the house cools off, the pump circulates water to the radiators raising the air temperature in the house, and shuts off when the air in the house reaches the pre-set temperature on the thermostat.

The inlet and outlet of heat circulation circuit and boiler circuit are plumbed to the storage tank in such a way that the water in the heat storage tank can be somewhat isolated. This may be desirable if the water in the storage unit is cold and there is a demand for heat in the house. A fire can be built in the boiler and the hot water will pass into the tank and directly into the heat distribution system for quick heat in the house.

The water pressure in the whole system is regulated by three means. First, a pressure reducer valve was fitted which serves to fill the system with water. This valve isolates the domestic water from the water in the heating system and maintains the pressure in the heating system at about six pounds. As the pressure in the heating system drops below this pre-set pressure, the reducer valve allows water to flow from the domestic water supply to the heating system until it returns to pressure.

A second means of limiting the pressure in the heating system is the use of an expansion tank. As the water in the system gets hotter, it expands and the expansion tank provides a place for this extra volume without increasing the pressure above a safe limit. The expansion tank is basically an air cushion in the system; as the water expands, it begins filling the expansion tank thus compressing the air in the tank. The size of the expansion tank was computed by finding the expansion of the volume of water used in the system. With a temperature increase of 150°F (50°F incoming water, to a high of 200°F water temperature in the system after heating), the water was found to expand in volume by 56.96 gallons.[38] Because the system could not tolerate a substantial increase in pressure, a 160 gallon expansion tank was used. This will increase the pressure in the system 6-8 pounds which is within the pressure limits of the system.

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[38] Louis Allen Harding and Arthur Cutts Willard, Heating Ventilation and Air Conditioning (London: Chapman and Hall, 1937), p. 20.

If the pressure should increase to a point that threatens the components of the system, a pressure relief valve will open and allow the pressure to drop. This valve is plumbed into the top of the tank and is fitted with a bleed-off line to a drain.

CHAPTER IV

PRESENTATION OF DATA

INTRODUCTION

The purpose of evaluating the wood heating system was to determine its efficiency with respect to wood consumption and to compare it to a conventional electrical heating system. In order to perform this evaluation, a number of variables were studied.

First, the amount of heat loss through the building materials for each week was calculated. Then the amount of energy that was used during each week was totaled. From this, the efficiency of the wood heating system could be calculated and a comparison to electrical heating made.

Primary interest was focused on how much heat was realized by the amount of wood or electricity that was used.

BUILDING HEAT LOSS CALCULATION

The process developed by the researcher to find the amount of energy consumed each week was as follows:

Average temperature difference (inside to outside) per day X building heat loss coefficient per hour X 24 hours X 5 days = Total Heat Loss Per Test Period

The average temperature difference for each day was found by averaging the temperatures recorded by thermographs at each hour and then subtracting the outside readings from the inside readings. The temperatures were recorded in degrees Celsius and converted to degrees Farenheit, as current methods use the latter for calculation. Table 10, page 44, is a listing of the temperature difference for each day of the week during the study period. This average temperature difference for each hour of the day was then multiplied by the heat loss coefficients for the building systems in the house and then multiplied by 24 to find the heat loss for that day. These heat losses were totaled to find the heat loss for the five days under study. The five day period was used to allow two days between runs for time to switch from one heat source to the other.

It is revealed in Table 10, page 44, that the weather was reasonably uniform throughout the five week test period. During the weeks in which wood was used as a heat source, the temperatures were slightly lower thus creating a higher heat loss in the house.

These figures show the heat loss from the house only and do not account for heat loss in the basement or through the floor. These additional heat loss figures were added

TABLE 10

DAILY AVERAGE TEMPERATURE DIFFERENCE AND HEAT LOSS IN GROUND FLOOR OF HOUSE.

	Date	Ave. Temp. Diff.(F°)	24 Hr. Heat Loss Btu	Date	Ave. Temp. Diff.(F°)	24 Hr. Heat Loss Btu	Date	Ave. Temp. Diff.(F°)	24 Hr. Heat Loss Btu
Wood	3/20	31.17	260,864.4	4/3	35.55	297.519.36	4/16	29.34	245,549.76
Heat	21	31.52	263,793.6	4	26.45	221,361.12	17	35.05	293,337.36
	22	33.82	283,042.56	5	31.09	260,193.36	18	29.63	247,976.88
	23	34.97	292,667.04	6	35.40	296,263.92	19	24.33	203,620.56
	24	32.96	275,845.2	7	37.70	315,512.88	20	26.03	217,826.4
		TOTAL	1,376,212.8		TOTAL	1,390,850.5		TOTAL	1,208,310.9
Electrical	3/27	28.49	238,434.0	3/10	26.32	220,273.2			
Heat	28	28.06	234,835.2	11	30.67	256,678.56			
	29	25.07	209,811.84	12	35.17	294,339.12			
	30	21.24	177,758.4	13	32.71	273,751.2			
	31	23.59	197,425.44	14	29.47	246,635.52			
		TOTAL	1,058,264.8		TOTAL	1,291,677.6			

to the total for each week as the conditions in the house changed with each shift in the heat source. During the weeks in which electricity was used to heat the house, the basement was not heated and the heat loss through the floor was added to the total loss through the rest of the house. The basement was considered to have a temperature equal to that of the surrounding ground ($45^{o}F$) and the temperature differential was determined using the heat loss coefficient of the flooring system and a temperature difference of $25^{o}F$ ($70^{o}F$ - $45^{o}F$).

During the weeks in which wood was used as a heat source, the basement was heated along with the house. This was due to the fact that radiators for the hot water system were suspended from the floor joists and there was no insulation under them to isolate the heat and force it to conduct through the floor. As a result, the heat loss through the uninsulated concrete walls was added to the heat loss in the house. This heat loss is considerable in comparison to the total loss from the house, as noted in Table 11, p. 46.

TABLE 11

TOTAL HEAT LOSS PER WEEK, HOUSE AND FLOOR OR BASEMENT

Week	Heat Loss House Btu/wk	Heat Loss Floor or Basement Btu/wk	Total
Mar. 20-24	1,376,212.8	4,821,336.0	6,197,548.8
Mar. 27-31	1,058,264.8	22,412.65	1,080,677.4
Apr. 3-7	1,390,850.6	4,821,336.0	6,212,186.6
Apr. 10-14	1,291,677.6	22,412.65	1,314,090.2
Apr. 16-20	1,208,308.8	4,821,336.0	6,029,644.8

The total heat loss for each week can then be compared with the amount of energy used that week to show the efficiency of the heating system.

ENERGY USE CALCULATION

The amount of electricity used during each week that the electric baseboard heaters were used to heat the house is a simple calculation. The kilowatt hour meter isolating the electric baseboard heaters was read at the beginning and end of each week. The difference in readings from beginning to end was then multiplied by 3,413[39] to give the number of Btu's in electrical energy used that week. These totals are shown in Table 12, page 47.

[39] Conklin, p. 167.

The amount of energy used during the weeks that the wood-fired boiler was used to heat the house was found by weighing all the wood used that week. Because all wood has 8,600 Btu's per pound (with the exception of highly resinous wood), the total weight of wood consumed could be converted into Btu's used that week. These totals are also presented in Table 12.

TABLE 12

TOTAL HEAT LOSS VERSUS ENERGY USED

Week	Total Heat Loss (Btu/wk)	Wood Amt. Used (lbs)	Wood Energy Used (Btu)	Electricity Amt. Used (kwh)	Electricity Energy Used (Btu)
Mar. 20-24	6,197,548.8	894	7,688,400		
Mar. 27-31	1,080,677.4			228	778,164
Apr. 3-7	6,212,186.6	902	7,757,200		
Apr. 10-14	1,314,090.2			275	938,575
Apr. 16-20	6,029,644.8	976	8,393,600		

During the weeks of March 27-31 and April 10-14 when the electrical system was in use, the amount of electricity needed in Btu's was less than what was actually lost in the house. The electric resistance type heaters used are 100% efficient and no account was made for other sources of heat such as sun infiltration and cooking. The sun infiltration on an uncurtained window can be a significant contributor.[40]

It should also be noted that the energy-used calculations do include the two days between the testing period while the total heat loss is only calculated on the five day testing period. This occurred because there was considerable overlap on the heating sources due to the fact that it was difficult to start and stop each system abruptly. There was also considerable residual heat left in the house at the end of a test period that would be included in the next test period. However, these figures are used in a comparative sense and should not affect the results because the same method was used for each energy source period.

BOILER EFFICIENCY

The efficiency of the boiler in the number of Btu's that it can extract from the burning wood versus the potential number of Btu's that are available in the wood can be calculated from the data in Table 12, page 47. Table 13, p. 49, presents the appropriate data describing the efficiency of the wood fired boiler.

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[40]Conklin, p. 34.

TABLE 13

EFFICIENCY IN PERCENT OF THE WOOD-FIRED BOILER

Total Heat Recorded in House (Btu)	Potential Heat of Wood Used (Btu)	% Heat Contributed by Other Sources (Btu)	Total Heat Extracted by Boiler(Btu)	Efficiency of Boiler (%)
18,439,379	23,839,200	28.31	13,219,191.0	55%

Data in Table 13 reveal the total heat recorded in the house is an addition of the heat losses in the house for the three weeks that wood was used as the heat source. The potential number of Btu's available in the wood was found by adding the pounds of wood used for the three weeks and then multiplying by the number of Btu's in a pound of wood.

Because there were other contributors of heat during the test period such as sun infiltration, cooking, and heat from people in the house, only part of the total heat loss recorded in the house was contributed by the wood heating system. Due to the fact that the electrical resistance heater is 100% efficient, the additional amount of Btu's recorded in the house during the test periods which used electricity can be used to find the percentage of heat contributed by other sources of heat. It was found that the electrical heaters accounted for 71.69% of the total heat recorded in the house during the electrical heating test period (1,716,739 divided by 2,394,767.6 multiplied by 100; data from Table 12, p. 47); therefore 28.31% was contributed by unrecorded heat sources.

When 28.31% of the heat recorded in the house is subtracted from the total heat recorded, the total heat recorded in the house that was contributed by the wood heating system is found. The efficiency can then be calculated using this adjusted heat recorded datum (13,219,191.0 divided by 23,839,200 multiplied by 100, or 55% boiler efficiency).

WOOD VS. ELECTRICITY: COST ANALYSIS

Using current rates for both electricity and wood, a direct comparison can be made of the energy sources used in this study. This information is summarized in Table 14, page 51.

The amount of wood or electricity used and the corresponding number of Btu's that were actually realized in the heating of the house are taken from Table 12, p. 47. In the case of wood, the three weeks during which wood was used as the heat source were added together. Likewise, the two weeks during which electricity was used as the heat source were added.

TABLE 14

ENERGY SOURCE USE AND WOOD VS. ELECTRIC COST COMPARISON

Energy Source/ Amount Used		Cost of Energy Source		Cost Comparison	
Wood (lbs/Btu)	Electricity (kwh/Btu)	Wood ($/lb.)	Electricity ($/kwh)	Wood ($/mil.Btu)	Electricity ($/1 mil.Btu)
$\frac{2772}{18,439,379}$	$\frac{503}{2,394,767.6}$	.0114889	.02803*	1.727	5.89

*On 503 kwh pro-rated

The cost of wood as an energy source in Table 14, p. 51 was calculated by first finding the volume in cubic feet in a cord of wood. Because part of that volume is due to air spaces in the stack, 80% of the total volume was used. Therefore a cord of 128 cubic feet (4' x 4' x 8') is multiplied by 80% to find the actual amount of wood in the cord. This figure (102.4 cubic feet) is then multiplied by 25.5 pounds per cubic foot to give the number of pounds in a cord of lodgepole (2611.2 pounds). At $30.00 per cord of firewood, the cost of a pound of firewood can be found by dividing $30.00 by 2611.2 pounds, resulting in $0.0114889 per pound of lodgepole.

The cost of electricity recorded in Table 14, p. 51, was found by using the total kilowatt hours used during the two week test period and applying this total to the current rate schedule:

TABLE 15

SCHEDULE FOR CALCULATING COST OF ELECTRICITY USED

Kwh	Rate(¢/kwh)	Cost($)
first 20 kwh	.0169	.338
next 80 kwh	.0538	4.304
next 100 kwh	.0376	3.760
any add. 303 kwh	.0188	5.6964
TOTAL 503 kwh		$14.0984

Therefore, for 503 kilowatt hours, 2,394,767.6 Btu's were realized in the house and they cost $14.10. The cost of $0.02803 per kwh reported in the table is a division of 503 kwh by $14.0984 to find the cost per kilowatt hour for this study and is only true if 503 kilowatt hours are used.

The cost of each energy source is found by multiplying the cost of each per pound or kilowatt hour by the number of pounds or kilowatt hours used. The result is then divided by the number of million Btu's realized in the house in each case. Thus the cost per million Btu's of wood was found to be $1.73 and the cost per million Btu's of electricity was found to be $5.89.

CONCLUSION

The major purpose of this chapter was to evaluate the performance of the wood-fired boiler in terms of efficiency and to compare it to an electrical heating system. To accomplish this, the amount of heat that was realized in the house was compared to the actual energy input to each heating system. These figures were then translated into cost of each energy source to find whether a wood heating system was competitive with an electrical heating system. The efficiency of the wood-fired boiler was determined by measuring the potential energy input and comparing it to the energy that was transferred to the water for heating the house.

In summary of the data presented in this chapter, the wood heating system provided heat at \$1.73 per million Btu's, the electrical heating system provided heat at \$5.89 per million Btu's and the boiler operated at an efficiency of 55%. Therefore, a dollar's worth of wood is equal to \$3.40's worth of electricity.

CHAPTER V

CONCLUSIONS, IMPLICATIONS, AND RECOMMENDATIONS FOR FURTHER STUDY

CONCLUSIONS

1. The wood heating system provides heat for the house at a cost of $1.73 per million Btu's.

2. The electrical heating system provides heat for the house at a cost of $5.89 per million Btu's.

3. The efficiency of the boiler has been found to be 55%.

IMPLICATIONS

As a result of the reported data, the researcher presents the following implications:

1. Central wood heating system variable costs are competitive with conventional heating systems.

2. Central wood heating systems can be built that minimize homeowner inconvenience and provide a comfortable heat.

3. Central wood heating systems can be designed such that they can be built by local welding shops and equipped through local supply houses.

4. Central wood heating system installation costs are competitive with other alternative energy systems.

5. Wood heating systems can be designed to minimize the amount of air pollution produced.

RECOMMENDATIONS FOR FURTHER STUDY

Through the development and testing of the heating system in this study, the researcher makes the following recommendations for further study:

1. The efficiency of a wood-fired boiler be studied utilizing a closely controlled environment to minimize extraneous variables and to evaluate the effects of temperature of incoming air, temperature of the water in the boiler, and the effect of forced draft.

2. Studies be made regarding the effects of conductive heating through a wood flooring system in terms of actual heat transmission and detrimental effects to the floor coverings (tile, carpet, adhesives, etc.).

3. Studies be made of water treatment chemicals that would minimize corrosion of system parts.

4. The use of the wood heating system to preheat the domestic hot water be studied.

5. The amount and type of emitted chemicals and particulates be studied in relation to the temperature and amount of the incoming draft air.

APPENDIX

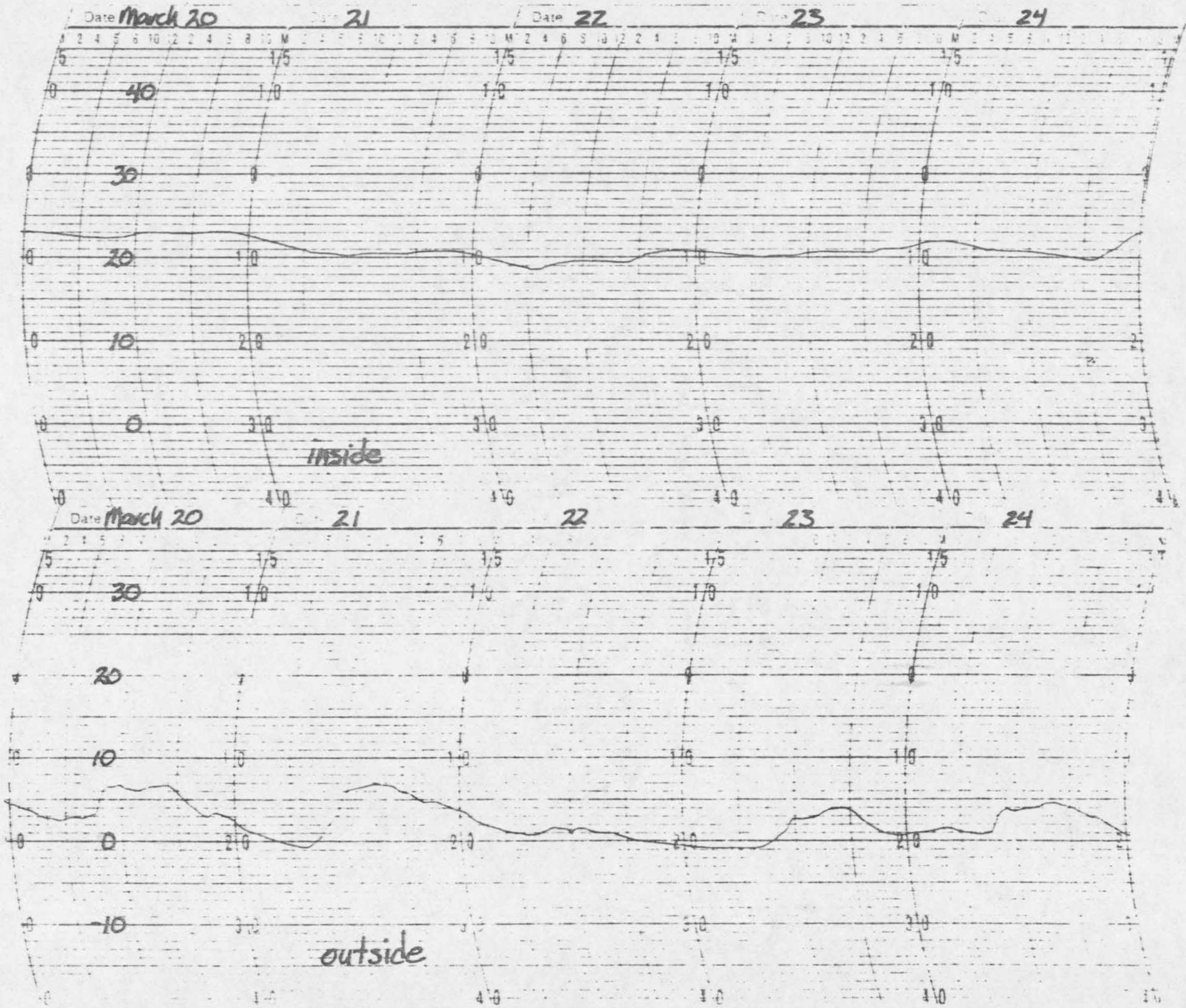

Fig. 3. Temperature Graph for March 20-24

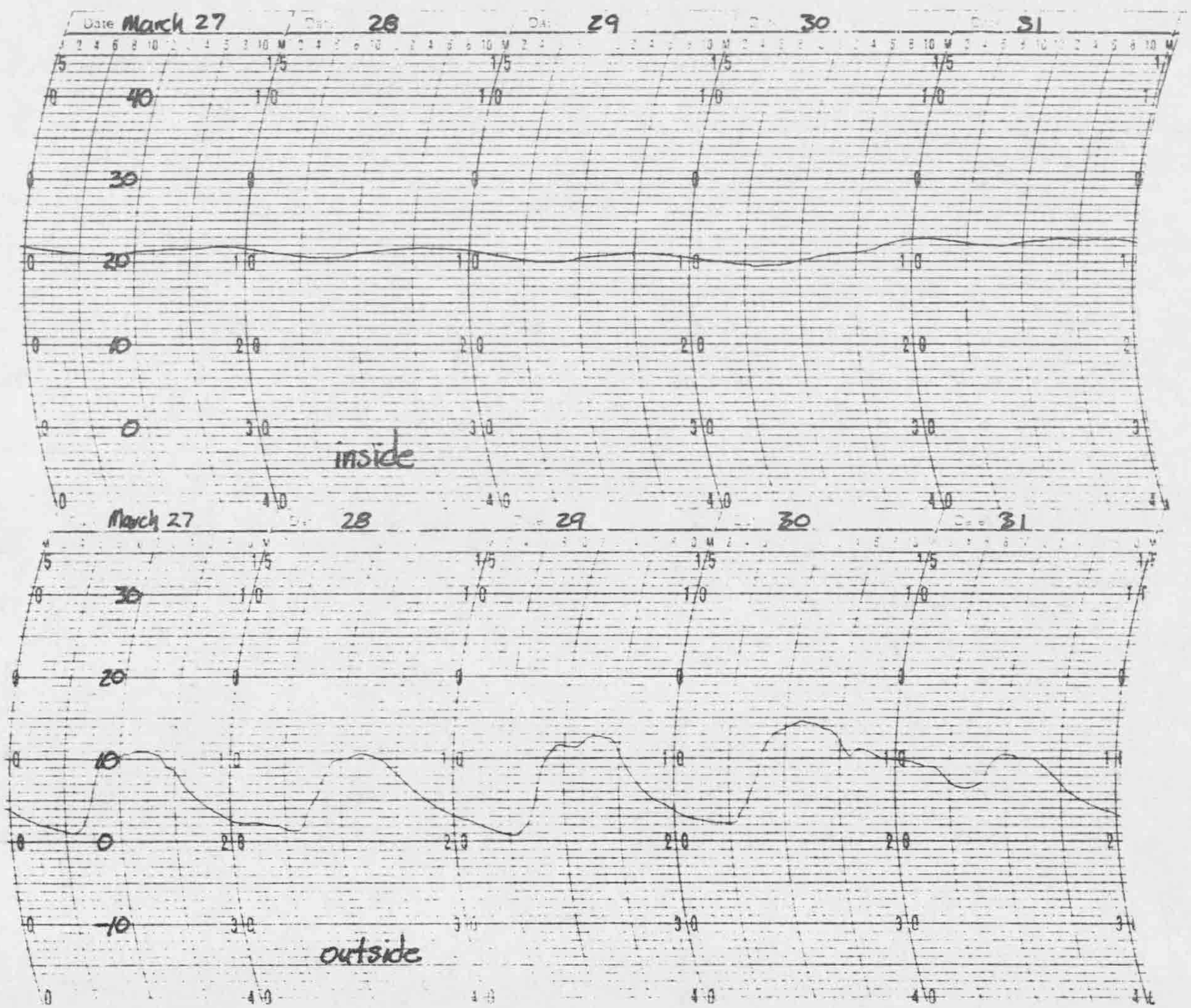

Fig. 4. Temperature Graph for March 27-31

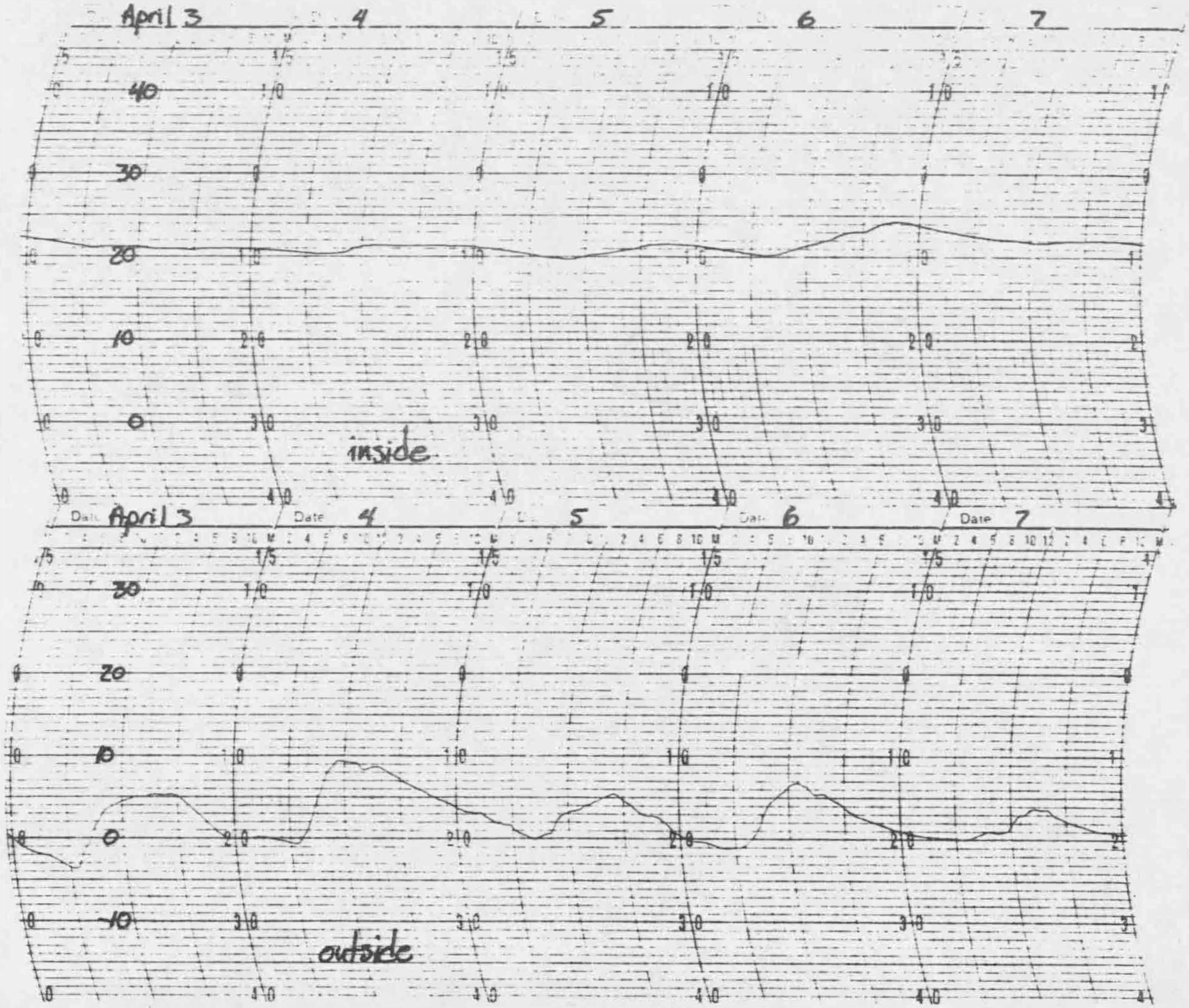

Fig. 5. Temperature Graph for April 3-7

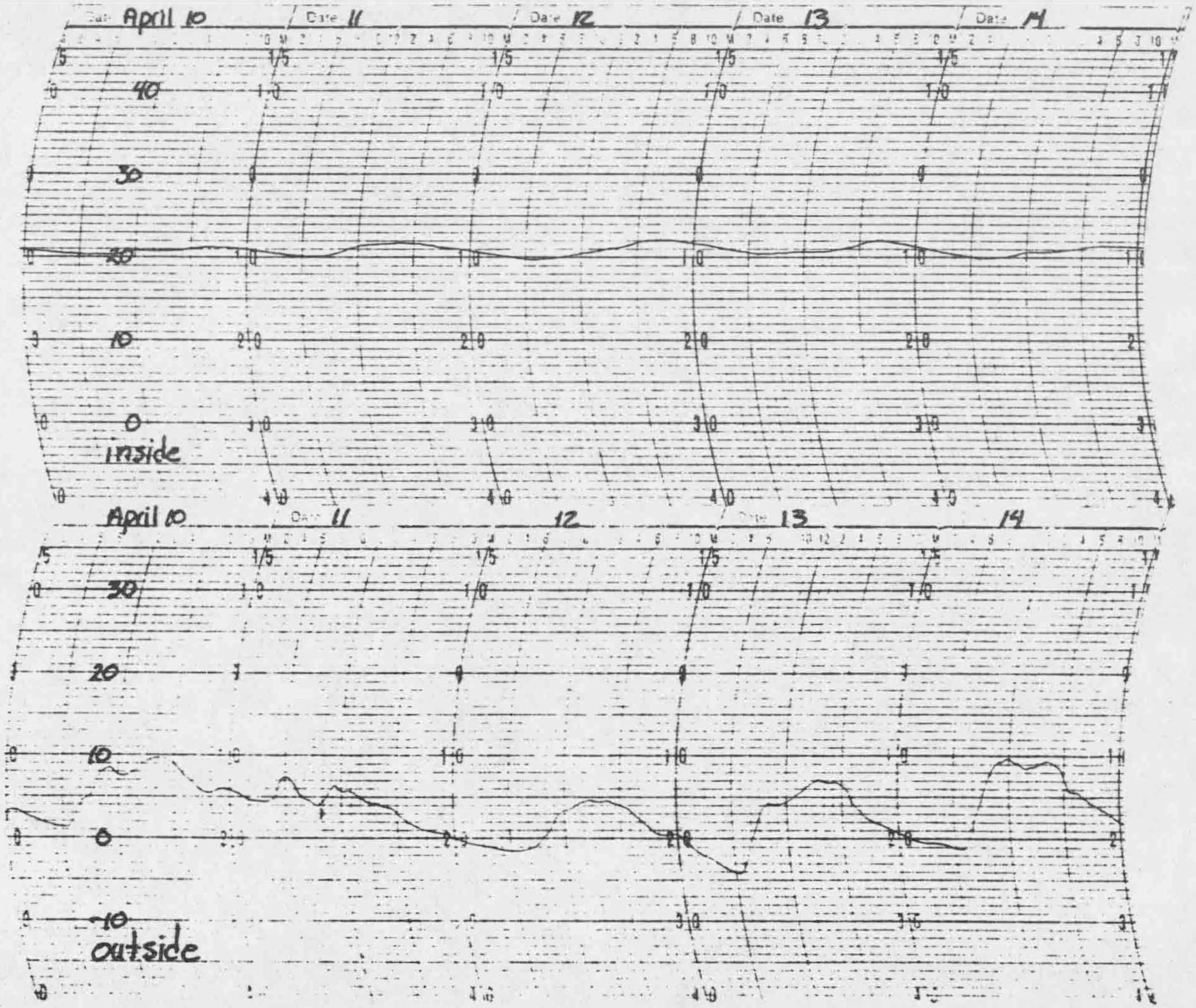

Fig. 6. Temperature Graph for April 10-14

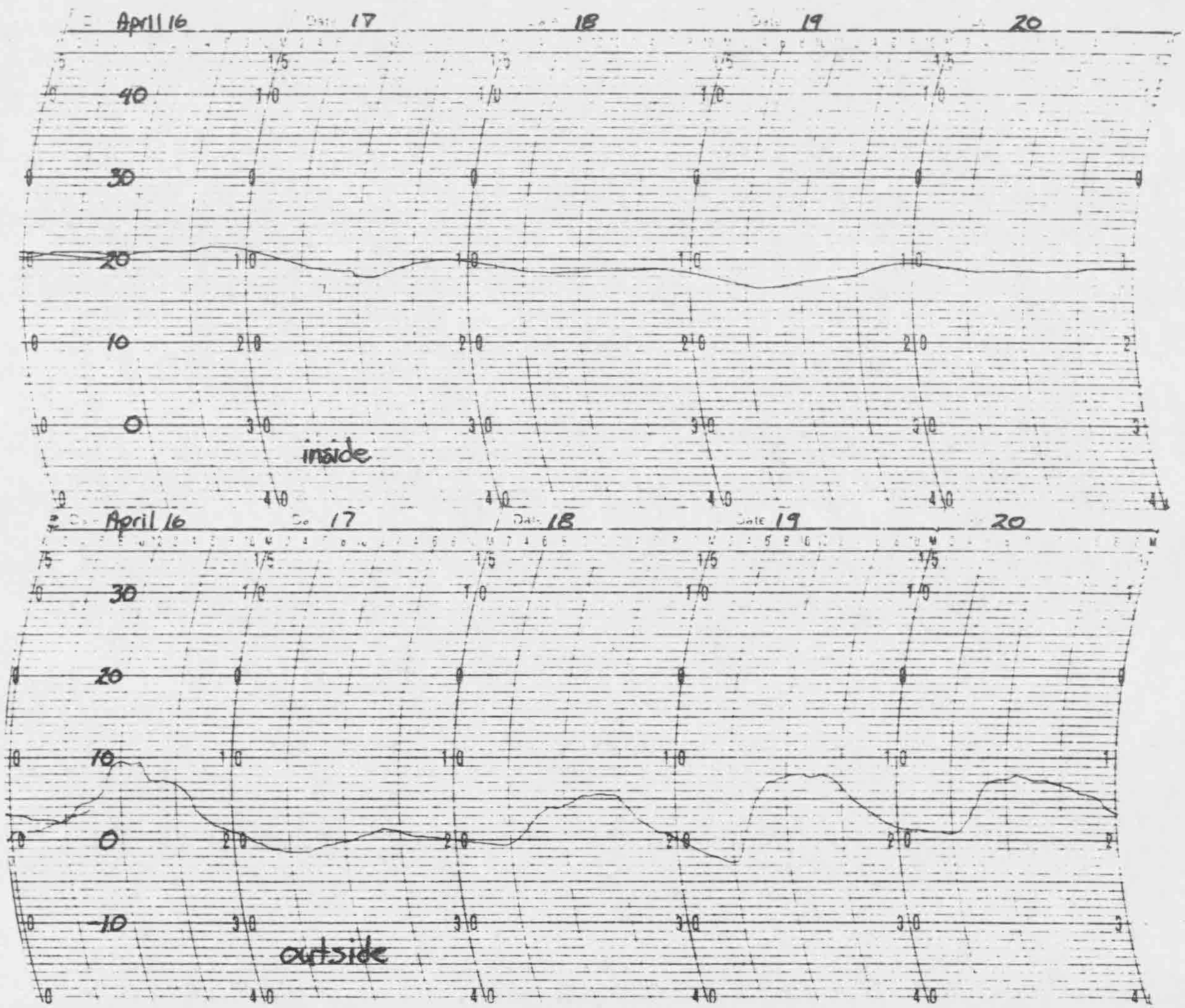

Fig. 7. Temperature Graph for April 16-20

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