

THE TECHNICAL AND ECONOMICAL FEASIBILITY OF SOLAR ENERGY UTILIZATION
FOR DOMESTIC ENVIRONMENTAL CONTROL IN THE STATE OF KANSAS

by

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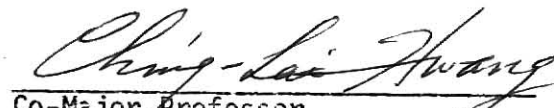
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1. Introduction

The future and well-being of any country is interrelated with its production and use of energy. With the ever increasing global demand for energy, we are going to face a conflict of energy shortages and a detriment level of pollution and land desecration from energy production. The dilemmas of energy-resource shortages and power production-environmental pollution will never be solved by arguments or neglect. All possible energy sources should be researched and investigated before they are exploited [16,68].

Fossil fuels, as they have been used so far, are very inefficient. Five-sixths of the energy used in transportation, two-thirds of the fuel burned to generate electricity, and almost one-third of all the remaining energy usage is discarded as waste heat. That is more than half of the total energy we consume. Furthermore, a good part of these fuels that is not converted into power or waste heat is emitted as polluting compounds like carbon and sulphur dioxide and nitrous oxide. Also, taking huge amounts of coal from underground and strip mines pollutes water ways and scars the land [72].

Nuclear power has been looked to as an answer to our energy problems. As of late, however, it looks as though the reserves of uranium are expected to last only until a few years into the 21st century. Nuclear power is just about limited to the generation of electricity, and as they operate now, nuclear fission plants are less efficient in conversion than conventional fossil fuel plants. In addition, twice as much water is

needed to cool nuclear plants than fossil fuel plants because of the intense heat they create during operation [70].

Hydroelectric power, and pumped storage hydroelectric plants provide an effective means for utilities to maximize the use of existing generating facilities to meet peak load demands. However, because of the limited availability of hydroelectric sites in most parts of the U.S. and the large amount of land required for reservoirs, this source of energy will be limited [9].

Nuclear fusion has received considerable attention as the ultimate power source. It combines the advantage of being free of air pollution with the ancillary benefit of an almost inexhaustible fuel supply. Difficulties in the fusion reaction arise from the fact that it involves techniques of analyses and design that require a great deal of development.

Solar energy is a clean abundant source of energy (Appendix A). Utilization of this boundless source of energy was not impossible in the past except for the fact that it simply could not compete with the well-established low cost of electrical energy. Nowadays, due to energy shortages and high cost of fossil fuel, and since nearly 18% of all energy consumed in the U.S.A. is for space heating, the possibility of domestic heating by solar energy may not only be of interest to the individual householder but of national importance [17].

Direct utilization of solar energy will be of two categories, a decentralized, small scale and immediate category, and a centralized, large scale and future oriented one. The immediate applications of solar energy

will be water and space heating and air conditioning of domestic houses, schools, and shopping centers. Future oriented applications will be large scale thermoelectric and thermoionic conversion, photo voltaic and photo chemical conversion, large sea water distillation, and solar furnaces [20,67].

Indirect utilization of solar energy such as wind, sea waves, and ocean thermal difference is of interest to researchers now, but it seems that this category belongs also to future planning [5,52].

1.1 Background

The utilization of solar energy for water and space heating is not new. There are at least several thousand solar water heaters in homes in Florida, Arizona, and California. On the whole, solar water heaters have very satisfactory performance, they are practical and they save a good amount of fuel [23].

A solar space heating program initiated in 1938 at M.I.T. resulted in a series of four experimental solar houses. During the period 1940-1950, about ten houses were built utilizing the sun for space heating. Nowadays, there are few hundred such houses in Massachusetts, Colorado, Kansas, Florida, New Mexico, Arizona, California, Washington D.C., and other parts of the states [52].

Almost all solar houses built so far utilized part of the roof as a heat collector through which hundreds of gallons of water were circulated. Heat transferred to the water is stored in a tank in the basement. Circulated hot water or warm air constitutes the medium for space heating. Since the possibility of long periods of insufficient

sunshine, most of the solar houses are equipped with a standby heating system using gas or electricity. However, in sunny climates at low latitudes solar energy may provide all the heat necessary, but this would require a huge collector and storage area. A standard design philosophy that has evolved for solar space heating calls for only a part of the total heat requirement to be met by solar energy. To carry over the space heating through long cloudy or continued very low temperature periods, supplementary conventional heating systems are provided [36].

The combination of collector and storage into a single structural part of the building on the south wall was a major feature of the experimental houses built by Trombe in France [11]. The south wall is usually double glazed, and behind the glazing at a distance of 10 cm from the glass, there is a concrete wall, 20 cm thick, painted black which serves as both a radiation absorber and a heat storage medium. Openings are provided through the concrete at top and bottom so that air circulates through the space between the glass and concrete, and through the room. The circulation is by natural convection and no pumps or controls are used [60].

The utilization of solar energy for cooling appears to be a logical application since, first, it is needed in areas where sunshine is abundant and, secondly, the greatest amount of energy is available when the need for cooling is greatest. However, cooling by solar energy still presents formidable technical and economic problems. Although a number of experimental investigations have been made, the manufacture of commercial units is still in a preliminary stage [42].

1.2 Problems in Solar Energy Utilization

There are several fundamental problems upon which further research and information must be obtained or technological breakthroughs realized in order to bring solar energy utilization to its fullest potential.

These problems are the following:

1. Accurate prediction of solar energy availability.

Solar energy is a transient and intermittent one not only seasonally and geographically, but also with such meteorological variables as cloud patterns, atmospheric contamination, and atmospheric water vapor content [27,63].

2. Collection of low intensity solar energy.

For most low temperature applications, plane collectors appear advantageous, but they require more space, capital cost and some maintenance. For high temperature collection, concentrating collectors are more suitable, but then they are expensive and require more maintenance. If collectors can be constructed and maintained cheaply by improvements in both cost and collection efficiency then a vast number of solar utilization devices will become immediately practical.

3. Storage medium and space.

Storage, either from the standpoint of initial energy storage or storage of the end effects of the use of solar energy is necessary in practically all applications. In such applications as space heating or cooling, the thermal energy itself must be stored for days and used as necessary in order to maintain predetermined temperature

levels. Storage mediums such as water or rocks are cheap, but they are bulky and require large areas and frequent maintenance. Besides, storage mediums such as salts take less space, but they are not commercially proved to release energy when needed [39,66].

4. Mature Technology.

Solar energy has not reached a stage of a mature technology. Mature technologies are characterized by products which have been manufactured for a considerable time with little change in performance, and are highly competitive in regard to cost. They achieve product improvement from cost reductions in manufacture rather than from accomplishing new functions. In a mature technology industry, it is extremely difficult to introduce a new product which typically offers only marginal improvement in performance. In order that a new product be capable of commanding an appreciable portion of the market it must have sufficient reliability and life [59].

5. Long Term Investment.

Use of solar energy is an example of the substitution of capital investment for the operating expense of fuel consumption. It also relieves a portion of the present and future energy shortages. However, substantial funds and an appreciable period of time have to be committed to the development program [42].

6. Inelasticity of Demand.

The short-term demand for fuel is highly inelastic; this means that a small shortage leads to a large price increases. The petroleum industry could then improve its position substantially by not trying

to change the mode of inelastic energy demand or by not introducing or encouraging alternatives. Besides, the industry as a whole, be it petroleum, petro-chemical or electrical is richly rewarded for selling present energy and present energy-consuming devices. Any alternative to this present energy may upset the whole industry planning for growth and profit [40,73].

1.3 Solar Centralization

Some interesting proposals for commercial exploitation of solar power have been advanced in recent years. One, advanced by Peter Glazer of Arthur D. Little, Inc., [21] suggests placing a light weight panel of solar cells in an orbit 22,300 miles above the earth, where they could be exposed to sunlight 24 hours a day. Solar cells would collect the radiant energy and convert it to electricity with an efficiency of 15 to 20 percent. The electricity would then be converted electronically in orbit to microwave energy with an efficiency of 85 percent which is possible today. The microwave radiation would be at a wave length selected to penetrate clouds with little or no loss and would be collected by a suitable antenna on the earth. Present techniques can convert microwave energy to electric power with an efficiency of about 70 percent, and 80 to 85 percent should be attainable. Glazer estimated that a 10,000 mw satellite power station, large enough to meet New York city's present power needs, would require a solar collector panel five miles square [49]. The receiving antenna on the earth would have to be only slightly larger,

six miles square. Since the microwave energy in the beam would be comparable to the intensity of sunlight, it would present no hazard. The system, according to Glazer, would cost about \$500 per KW, roughly twice the cost of a nuclear power plant, assuming that space shuttles were available for the construction of the satellite. The entire space station would weigh five million pounds, slightly less than the Saturn moon rocket at launching. To meet the total estimated U.S. electric power demand of 2,500,000 mw for the year 2000 would require 250 satellite stations of this size [48].

Another solar power concept (national solar power farm) has been advanced by the Meinels at the University of Arizona [7]. The key to their idea lies in concentrating solar energy with mirrors to heat a fluid which would in turn provide the heat to produce the steam to power a conventional turbine electric power generator. Heat collected during daylight hours would be stored in molten salts at 1000 degrees F. A heat exchanger would transfer the stored energy to steam at the same temperature. The thermal storage tank for a 1000 mw generating plant would require a capacity of about 300,000 gallons of water. The collectors for such a plan would cover an area of 316 million square meters (123 square miles) [42]. The Meinels estimate that a 1,000 mw solar power station might be built for about \$1.1 billion, or about four times the present cost of a nuclear power plant. Despite this high capital outlay, they calculate that a plant with an operating lifetime of forty years should produce power at an average of only half a cent per kilowatt hour. The Meinels propose that industry and the federal government immediately undertake design and construction of a 100 mw demonstration plant [7].

1.4 This Work

This work is an assessment of the technical and economical feasibility of solar energy utilization in the state of Kansas. At this stage, solar heating and cooling of typical single family dwellings is investigated. Technical and economical realization of solar energy at present and future energy costs is documented, together with the effects of thermal insulation and temperature design criteria on energy conservation.

This study does not promote or downgrade any sort of energy sources. It only gives the opportunity for solar energy to prove that it deserves exploitation if we are to alleviate our energy shortages and meet the total energy demand in the future.

2. Solar Energy Utilization in the State of Kansas

There are five different approaches to solar energy utilization in the State of Kansas. Three of these, solar energy for heating and cooling, wind energy conversion, and bioconversion to fuels have near-term applications. Two other approaches, solar thermal conversion, and photovoltaic conversion can provide significant amount of electric power in the future [30].

2.1 Kansas Background

Located in the geographical center of the United States, Kansas has a temperate climate generally typical of the American Great Plains Region. Its air is dry, its temperature ranges are large, and its sunshine is abundant. Due to its location between the atmospheric moisture supply of the Gulf of Mexico and the vast sources of less humid air from the north and west, Kansas rainfall is highest in late-spring and early-summer. Unlike states lying to the east, Kansas winters are drier, with less snow, and more sunshine. Snow seldom lies on the ground for more than a week or two at a time, annual precipitation averages in the eastern, middle and western sections are 34.57 inches, 25.94 inches, and 18.70 inches, respectively [51].

Topographically, Kansas is commonly thought of as flat, but actually by far the greater part of the state is made up of rolling country. Elevations vary from less than 1000 feet in the southeastern part to more than 4000 feet near the Colorado line. Due to this, there is a pronounced difference in wind velocities between the eastern and western parts of

Kansas. Over the eastern third, the winds (8 to 15 M.P.H) are not noticeably higher than those of other states between Kansas and the Atlantic Coast; but the western third is one of the windiest inland areas in the country. The prevailing winds in Kansas are from the south from April to October, inclusive, except that in the western part they are from the southeast during April, May and June and in some sections through July and August. During the winter season north or northwest winds prevail, though south winds are frequent, especially in the eastern half of the state [34].

Hail distribution in the state of Kansas increases steadily from the eastern to the western border with the greatest frequency and hazard in May and June. The mean annual number of days with hail is 2 to 4 days in the eastern section, 4 to 6 days in the western section. Table 2.1 shows hail size and loading.

Frost danger in Kansas is seldom serious except after abnormally warm weather in March or early April. The average depth of frost penetration ranges from 10 inches in the south to 15 inches in the north. Both values are moderate in comparison with the whole country. It is usually a good practice for foundations to extend 12 inches below frost penetration lines [25].

Tornadoes are not uncommon in Kansas, on the average 13 tornadoes occur in the state each year, 45 percent of these occur in the eastern third, 34 percent in the middle third, and 21 percent in the western third. Tornadoes have been known to occur in every month of the year except January and December. They are more frequent in May and June. Earthquakes in Kansas are not common [28].

Table 2.1 Hail Size and Loading in the State of Kansas [25]

Section	Hail					
	Diameter Inches	Weight Lbs	Terminal Velocity ft./sec.	Kinetic Energy ft.-lb.	Resultant Velocity ft./sec.	Kinetic Energy ft.-lbs.
Eastern	1	0.017	73	1.43	88	2.58
Western	1.5	0.058	90	7.35	112	11.38

2.1.1 Kansas Temperature

Average temperature in Kansas ranges from 58 F in the southeastern counties to 52 F in the northwestern with an average of 55 F for the state as a whole. The coldest month is January, with an average temperature of 30 F, however the lowest winter temperature often occurs during the first half of February. During the mid winter season the average minimum temperature ranges from 25 F in the southeastern counties to 14 F in the northwestern; and sub-zero weather has occurred almost every year in every part of the state, although as a rule temperatures below zero do not continue for more than two or three days. After the middle of February there is normally an irregular but general warming up until late July or early August. The warmest month is July with an average of 79 F, however, August has generally more oppressive heat owing to decreased wind movement. During mid summer, normal maximum temperature range from 90 F to 95 F over the state and readings of 100 F or higher are rather common. The highest temperature on the state's record is 121 F, which occurred at Fredonia on July 18, 1936, the lowest ever recorded was - 40 F at Lebanon on February 13, 1905 [51]. A graphical weather summary for Manhattan for 1975 is given in Fig. 2.1.

2.1.2 Solar Radiation in Kansas

There are two major solar radiation measurement stations in Kansas. Dodge City is located at 37°-46' north latitude, 99°-58' west longitude, and at an elevation of 2625 ft. above sea level, and Manhattan at

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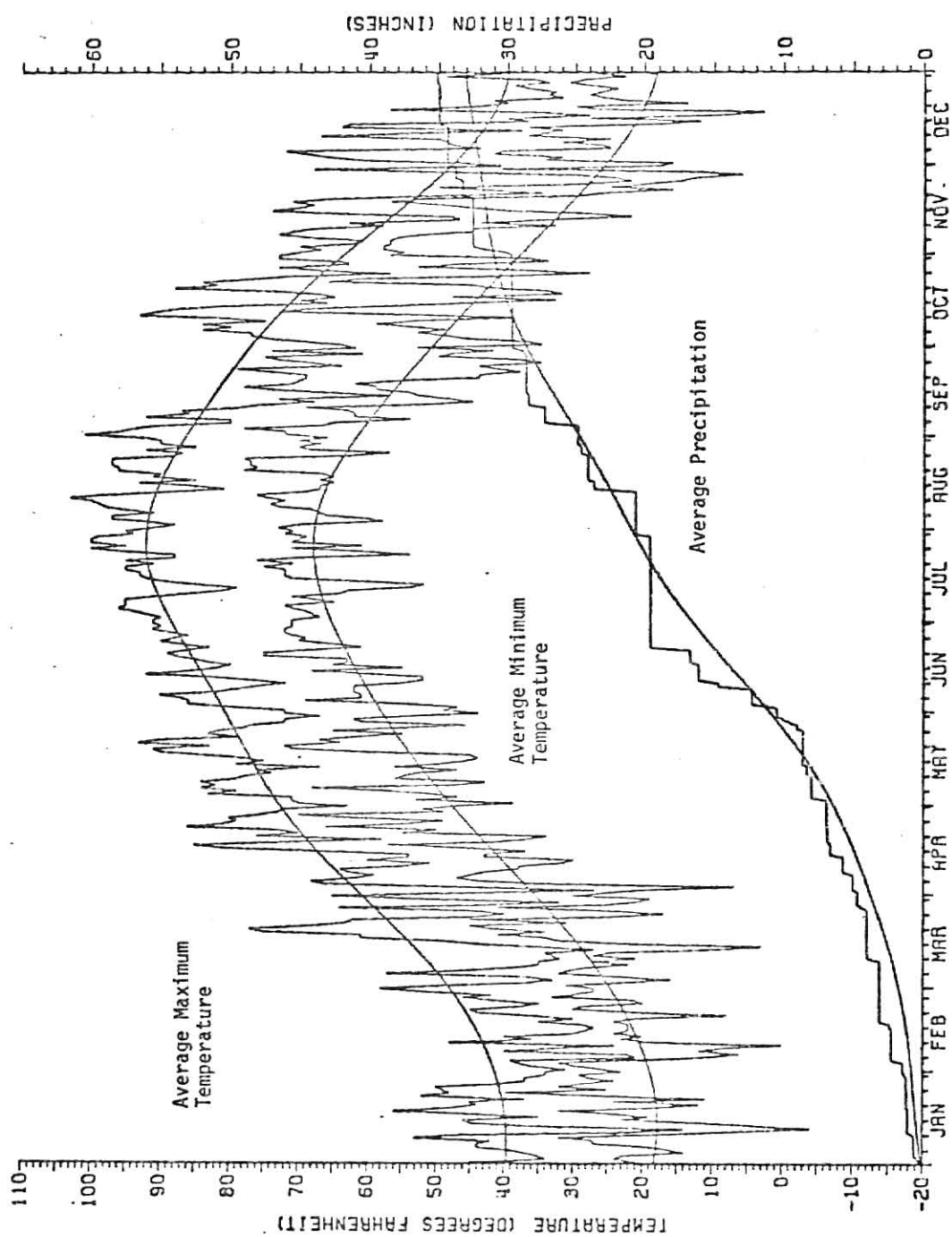


Fig. 2.1 Graphical Weather Summary for Manhattan, 1975 [56].

39°-12' north latitude, 96°-35' west longitude, and 1140 ft. elevation. Figure 2.2 shows the North-Central Region isolines of average clear day solar radiation in $\text{cal./cm}^2/\text{day}$ received during the week of September 27 to October 3. The figure shows that Kansas receives on the average at that particular week the amount of $500 \text{ cal/cm}^2.\text{day}$ or $1842.50 \text{ Btu/sq.ft/day}$.

2.1.3 Kansas Energy Background

An analysis of federal energy policy reveals that prior to 1973 a coordinated body of national energy policy did not exist [35]. National energy-related policies had been developed primarily for purposes other than providing direction for the efficient functioning of the national energy system. The fact that energy-related policies had been fragmented among 64 federal agencies leads to the observation that energy was considered only one aspect of broader considerations rather than as an inter-related system. The emergence of the energy crisis of 1973, however, led to an increasing awareness of the problematic nature of energy supplies and to the proliferation of energy policy proposals designed to cope with the energy supply problem. A number of measures designed to increase energy supply, reduce energy demand, and insure equitable distribution of available energy resources were passed in 1973. Within this body of federal action lie the greatest implications for state and local governments. Increased national concern over energy problems signals a new federal dominance in directing energy policy in both production and consumption areas. Potentially, states stand to lose some authority in the

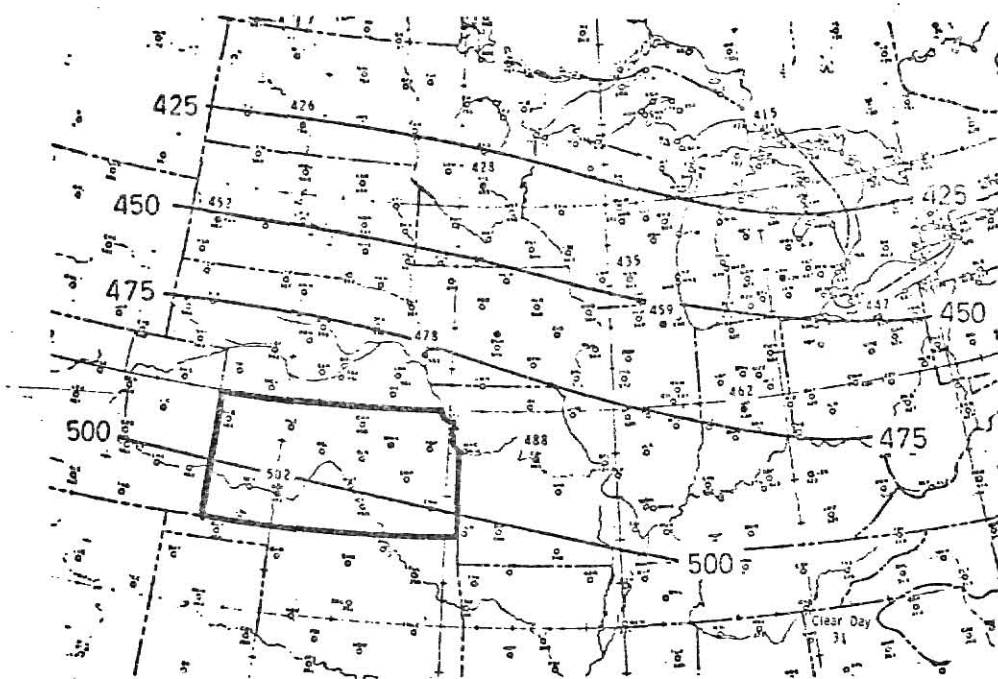


Fig. 2.2 Average Solar Radiation in Cal./cm²/day Received During the Week of September 27 to October 3. Isoline 500 Crosses the State of Kansas [56].

regulation of primary and secondary energy production. In addition they will probably receive greater administrative responsibility for federal and state initiated energy conservation programs and will likely find that agency reorganization or restructuring is necessary for effective energy policy administration.

Kansas, like most other states, found itself without a well-defined energy policy in early 1973. Kansas energy policies had been developed in a non-crisis atmosphere in response to occasional specifically important problems. On the whole, such policies were formulated in response to the traditional regulative concerns of state government.

Kansas energy policies prior to 1973 can be divided into two major groups: those directly related to energy production and consumption and those intended for other purposes which indirectly affected energy production and consumption. Policies directly related to energy included the regulation of gas, oil, electric utilities, and the development of nuclear energy potential. Revenue policy, environmental protection and transportation had indirect effects on energy policies. All in all, Kansas energy policy was so badly distributed among many agencies that no single one had the development or implementation of a comprehensive state energy policy as its sole or dominant focus or responsibility.

The energy crisis has taken different forms in various regions of the country. In some sections the supply of home heating fuels has been the dominant concern. In other sections electrical energy supply has been a pressing problem. It is estimated that if current supplies and uses of energy resources in Kansas continue at the present rate, then oil

will run out in seven years; and natural gas in 13 years [35]. Only coal supplies are sizeable, but Kansas coal is expensive to mine and is high in sulphur pollutants. When it comes to fuel minerals, once-rich Kansas faces depleting energy supplies. Tables 2.2-2.4 and Fig. 2.3 show the dwindling production of coal, oil, and natural gas. Tables 2.5 and 2.6 show the increase in electrical energy consumption and generating capacity, and Fig. 2.4 shows the decline of drilling for oil wells in Kansas.

2.2 Feasibility of Utilization

Almost all production of energy from present energy sources lead to major climatological and ecological changes, besides, they are subject to depletion in the near future. Only solar energy development can guarantee an inexhaustible source of energy, a solution to future ecological problems, and a means to maintain the radiative equilibrium of the earth.

The total energy needs in the State of Kansas can be divided into four main categories:

1. Energy needs for propulsion
2. Energy needs for industry
3. Energy needs in the form of electricity
4. Energy needs for space heating and cooling.

The most obvious application of solar energy at present is in water and space heating and cooling. Categories one, two, and three need an intermediate conversion stage and a concentrated high temperature source. This requires more research, innovative thinking and massive federal funding. Solar energy contribution for these three categories will have its greatest impact in the future [18,19].

Table 2.2 Coal Production, Kansas, 1890-1974 [29,32,33]

Year	Tons
1890	2,259,922
1900	4,467,870
1910	4,921,451
1920	5,926,408
1930	2,429,929
1940	3,578,952
1950	2,124,980
1955	739,116
1960	876,343
1965	888,274
1970	1,627,000
1971	1,151,000
1972	1,227,000
1973	1,086,000
1974	680,000

Table 2.3 Crude Oil Production, Kansas, 1890-1974 [29,32]
(in 1,000's of Barrels)

Year	Total
1890	1
1900	75
1910	1,128
1920	39,005
1930	41,638
1940	66,139
1950	107,586
1955	121,669
1960	113,453
1961	112,241
1962	112,076
1963	109,107
1964	106,252
1965	104,733
1966	103,738
1967	99,200
1968	94,505
1969	88,716
1970	84,812
1971	78,532
1972	73,744
1973	66,227
1974	60,000

Table 2.4 Natural Gas Marketed Production, Kansas, 1890-1973 (29-32]
(in Millions of Cubic Feet)

Year	Total
1890	413
1900	3,657
1910	59,380
1920	21,158
1930	37,630
1940	90,003
1950	323,261
1960	634,410
1970	899,955
1971	885,144
1972	N/A
1973	889,268

* Marketed Production = Gross Production - Repressuring losses
- losses

* Gross Production = Production from Gas Wells + Production
from Oil Wells.

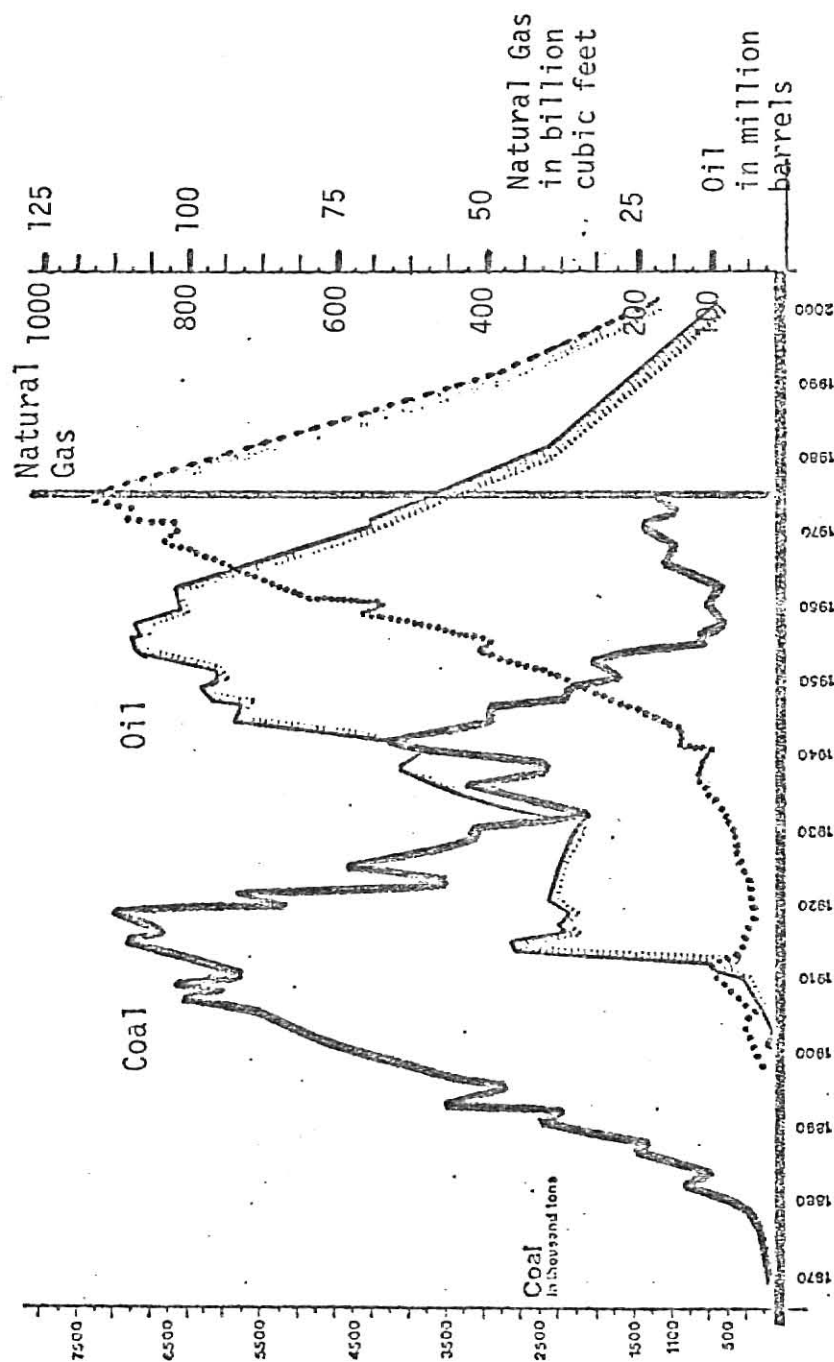


Fig. 2.3 Actual and Projected Production of Fuel-
Related Minerals [35]

Table 2.5 Electric Energy Production, Kansas, 1920-1973 [29,32]

(in Billions of Kilowatt-Hours)

Year	Total
1920	0.437
1930	1.014
1940	1.573
1950	3.707
1960	8.222
1961	8.830
1962	9.452
1963	10.559
1964	11.085
1965	11.302
1966	12.363
1967	13.303
1968	13.823
1969	15.325
1970	15.929
1971	16.425
1972	16.957
1973	17.524

Table 2.6 Electric Generating Capacity, Kansas, 1960-1973 [29]

(in Mega watts)

Year	Total
1960	2036
1961	2243
1962	2443
1963	2664
1964	2709
1965	2995
1966	3012
1967	3436
1968	3452
1969	3474
1970	3657
1971	4086
1972	4114
1973	5447

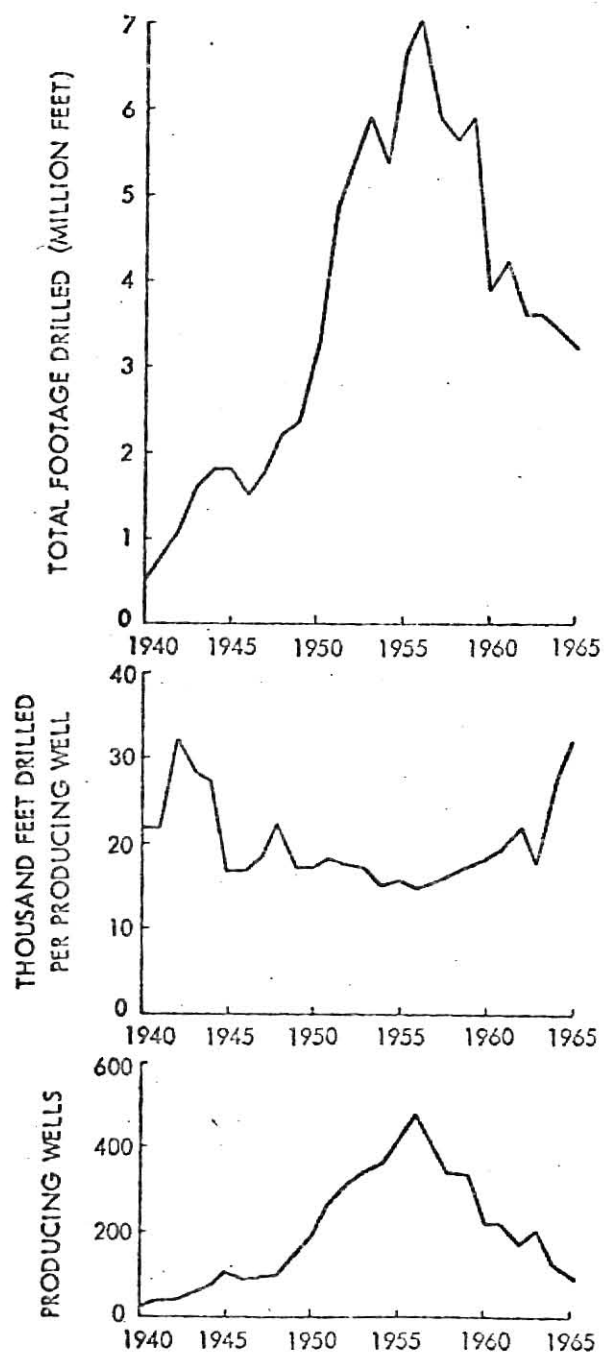


Fig. 2.4 Decline of Drilling in Kansas. Fewer Producing Wells are Being Found, and Deeper Drilling is Necessary for Successful Wells [13]

2.2.1 Technical Feasibility of Solar Space Heating

Since solar energy in the state of Kansas is available in abundant inexhaustible, distributed supply and can be utilized without causing chemical or thermal pollution or waste disposal problems, it can fill an important role in the future mix of energy sources.

Consider as an example, a two story model house situated in Kansas, and as shown in Chapter 4, Fig. 4.1. A brief summary of this house is as follow:

Heated floor area	= 1522 sq.ft.
Heating losses with 1" insulation	= 33787 Btu/(hr total area)
Heating losses with 4" insulation	= 19531 Btu/(hr total area)
	(From Table 4.3).
Outside design temperature	= -10F
Degree day base [61]	= 65F
Average degree days in Kansas	
in January [44]	= 1221
Average degree days per	
day in Kansas in January	= $1221/31 = 40$
Heating losses with 1" insulation	= $\frac{33787}{1522}$
	= 22.2 Btu/(hr sq ft)
Heating losses per degree day	= $\frac{22.2 \times 24}{65 - (-10)}$
	= 7.10 Btu/(sq ft degree day)
Heating losses in January	= 7.10×40
	= 284 Btu/(sq ft day)

Total heating losses of

model house

$$= 284 \times 1522$$

$$= 432,248 \text{ Btu}/(\text{total area day})$$

Insolation in January at

50% probability of at least

receiving the indicated

amount [56]

$$= 841.50 \text{ Btu}/(\text{sq ft day})$$

Solar heat collected at 40%

collector efficiency

$$= 336 \text{ Btu}/(\text{sq ft day})$$

An analysis of heating losses per sq. ft. per day of heated area together with solar energy collected per sq.ft. per day is given in Table 2.7. For example, the total space heating losses in January is 284 Btu/(sq ft day), meanwhile the total insolation or solar heat that can be collected at 40% efficiency is equal to 336 Btu/(sq ft day). Table 2.8 and Fig. 2.5 show a comparison of total solar heat collected by two collectors with areas equal to 50% and 25% of heated floor area. From Fig. 2.5, it can be seen that both collectors do not furnish all heating requirements.

Table 2.9 shows the percentage of heat collected by the two collectors to heat required for the two story model house. The same analysis is also carried for the same model house when it is equipped with 4" insulation. For example Table 2.10 and Fig. 2.6 show that a collector of area equal to 50% of heated floor area can furnish all space heat requirements during the whole heating season. A collector of area equal to 25% of heated floor area can furnish 50% of heat requirements in

Table 2.7 Two-Story Model House Heat Losses Btu/(sq ft day) Versus Solar Heat Collected Btu/(sq ft day)

Month	Average Degree Days		Space Heating Losses Btu/(sq ft day)	Solar Heat Collected at 40% Collector Efficiency Btu/(sq ft day)
	Per Month	Per Day		
Jan.	1221	40	284	336
Feb.	980	32	227	464
Mar.	747	24	170	626
Apr.	339	11	78	696
May	—	—	—	848
June	—	—	—	880
July	—	—	—	824
Aug.	—	—	—	739
Sept.	—	—	—	523
Oct.	270	9	64	515
Nov.	699	23	163	345
Dec.	1051	35	248	304

Table 2.8 Two-Story Model House Heat Losses Btu/(total area day) Versus Solar Heat Collected by Two Different Collectors

Month	Space Heating Losses Btu/(total day)	Solar Heat Collected by Two Collectors of Areas Equal to 50 % and 25 % of Floor Area Collector No. 1 (761 sq ft area)	Collector No. 2 (380 sq ft area)
Jan.	432,248	255,696	127,848
Feb.	345,494	353,104	176,552
Mar.	258,740	476,386	238,193
Apr.	118,716	529,656	264,828
May	—	645,328	322,664
June	—	669,680	334,840
July	—	627,064	313,532
Aug.	—	562,379	281,189
Sept.	—	401,808	200,904
Oct.	97,408	391,915	195,957
Nov.	248,086	262,545	131,272
Dec.	377,456	231,344	115,672

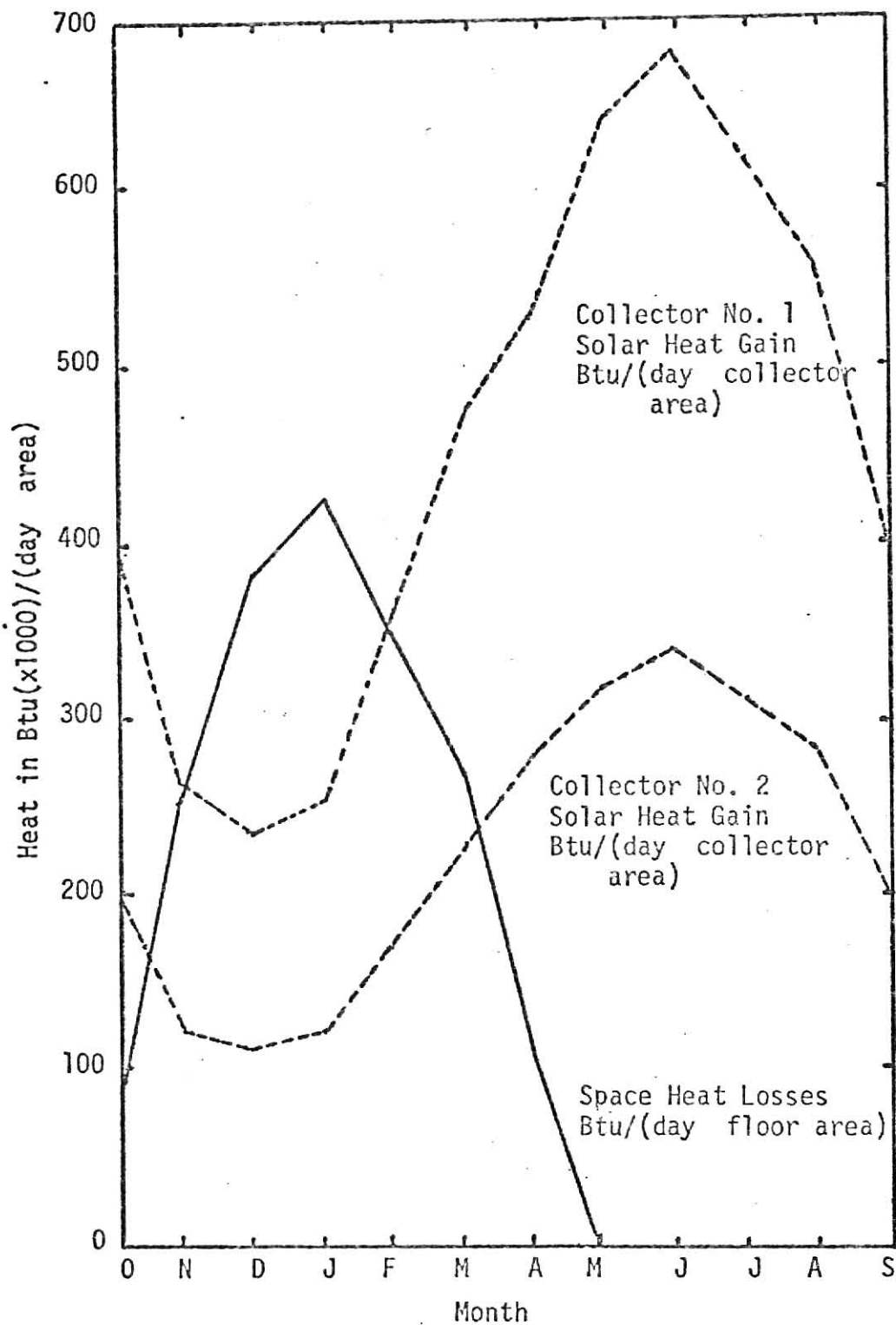


Fig. 2.5 Daily Heat Losses and Solar Heat Collected at Kansas Two-Story Model House ($T_0 = -10^\circ\text{F}$, 1" insulation).

Table 2.9 Percentage of Solar Heat Collected to Space Heat Losses for
Two-Story Model House
(1 inch insulation)

Month	Collector No. 1 (50 % Floor Area) %	Collector No. 2 (25 % Floor Area) %
Jan.	59	29
Feb.	102	51
Mar.	184	92
Ap.	448	224
May		
June		
July		
Aug.		
Sept.		
Oct.	403	201
Nov.	105	52
Dec.	61	30

Table 2.10 Two Story Model House Heat Losses Btu/(total area. day) Versus Solar Heat Collected
by Two Different Collectors (4 inch insulation)

Month	Space Heating Losses Btu/(total area. day)	Solar Heat Collected by Two Collectors of Areas Equal to 50 %, 25 % of Floor Area Collector No. 1 Collector No. 2
Jan.	249,608	255,969 127,848
Feb.	199,686	353,104 176,552
Mar.	149,764	476,386 238,193
Ap.	68,642	529,656 264,828
May	—	645,328 322,664
June	—	669,680 334,840
July	—	627,064 313,532
Aug.	—	562,379 281,189
Sept.	—	401,808 200,904
Oct.	56,161	391,915 195,957
Nov.	143,524	262,545 131,272
Dec.	218,407	231,344 115,672

Table 2.11 Percentage of Solar Heat Collected to Space Heat Losses for
Two-Story Model House

($T_0 = -10^\circ\text{F}$, 4 inch insulation)

Month	Collector No. 1	Collector No. 2
	(50 % of Floor Area) %	(25 % of Floor Area) %
Jan.	102	51
Feb.	177	88
Mar.	319	159
Ap.	778	389
May		
June		
July		
Aug.		
Sept.		
Oct.	698	349
Nov.	183	91
Dec.	106	53

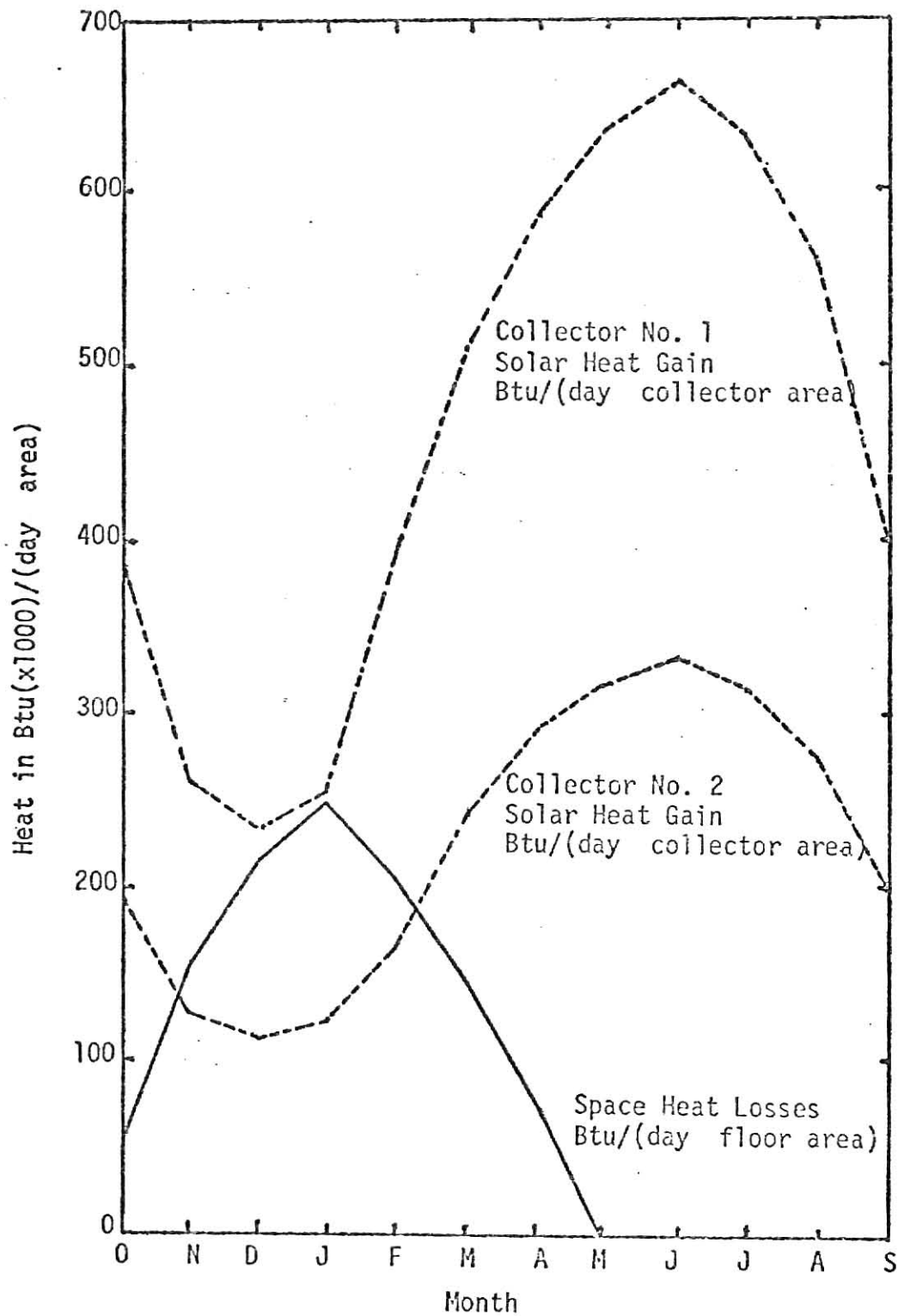


Fig. 2.6 Daily Heat Losses and Solar Heat Collected at Kansas Two-Story Model House ($T_0 = -10^\circ\text{F}$, 4" insulation)

December and January, 90% of heat requirements in November and February, and all the heat requirements in April and October as depicted by Table 2.11.

In conclusion, the collection of solar heat energy in the state of Kansas by the use of flat plate collector at 40% collection efficiency and an outside temperature of -10 F, so as to meet heating requirements is proved to be feasible.

2.2.2 Economic Feasibility

The Housing and Urban Development Act of 1968 set a 10 year goal of 26 million new and rehabilitated housing units [31]. In an effort to apply the stated goal to the state of Kansas, the Planning Division of the Kansas Department of Economic Development prepared a document in 1971 of which the following is a summary. The total number of household that will reside in the state of Kansas by 1990 is 965,000. Between 1960 and 1970 a total of 150,000 new units were added to the housing stock, over 100,000 of these units were used to replace units demolished or otherwise removed. Assuming a continuation of the replacement requirements, the total new construction requirements for the forecast period (1970-1990) would be as given in Table 2.12. A net total of 255,000 replacement households will be created during the period (1970-1990) increasing the total number of households in the state of Kansas from a 1970 level of 727,000 to 965,000 in 1990. These additional households are grouped in terms of structure type as given by Table 2.13. This shows that almost 80 percent of the total need indicated falls into the single family category.

Table 2.12 Kansas Total Housing Requirements [31]

Time Period	Required Total Construction
1970 - 1975	106,000
1975 - 1980	107,000
1980 - 1985	121,000
1985 - 1990	119,000
Total	453,000

Table 2.13 Kansas Replacement Housing Requirements by 1990 in Terms of
Structure Type [31]

Structure Type	Own	Rent	Total Number
Single family	159,000	42,000	201,000
Multi-family	6,000	40,000	46,000
Mobile Home	7,000	1,000	8,000
Total Number	172,000	83,000	255,000

Population growth in the state of Kansas is given in Tables 2.14, 2.15 and Fig. 2.7. It can be seen that in 30 years (1970-2000) the population growth in the state of Kansas will have an optimistic pattern of 40%, a pessimistic pattern of 3.3% and most likely pattern of 19%.

Number of single family dwellings required

(1970-1990) = 201,000

Average number of new dwellings per year = 10,000

Average floor area of each dwelling = 1500 sq ft.

Minimum average daily solar radiation on a tilted flat plate collector [16] = 350 Langley
= 1290 Btu/(sq ft day)

Solar heat gain per dwelling per day at collector area of 1500 sq.ft. = 1.93×10^6 Btu/(area day)

Solar heat gain per dwelling per day at 40% overall efficiency = 0.77×10^6 Btu/(area day)

Solar heat gain per dwelling per day at 40% overall efficiency and with collector area equal to 25% of dwelling

floor area = 0.19×10^6 Btu/(0.25 area.day)

Tables 2.16 and 2.17 show the total savings due to solar energy utilization in the state of Kansas. For example Table 2.16 shows daily savings of \$0.19 to \$1.69 due to solar heat utilization as a substitute to natural gas or electricity at 1973 price index. In summary, the economic feasibility of solar energy utilization in the state of Kansas is demonstrated by a minimum savings of 0.70 million dollars per year to a maximum optimistic savings of 305 million dollars per year.

Table 2.14 Population Growth, Kansas and the U.S.A. [32]

Year	Population		Kansas Population as a Percent of U.S. Population
	Kansas	U.S.A.	
1860	107,206	31,443,876	0.34
1870	364,339	38,558,371	0.94
1880	996,096	50,189,209	1.98
1890	1,428,108	62,979,766	2.27
1900	1,470,495	76,212,168	1.93
1910	1,690,949	92,228,496	1.83
1920	1,769,257	106,021,537	1.67
1930	1,880,999	123,202,624	1.53
1940	1,801,028	132,164,569	1.36
1950	1,905,299	151,325,798	1.26
1960	2,178,611	179,323,175	1.21
1970	2,249,071	203,165,699	1.10
1980	2,391,000	242,307,000	0.99 Forecast *
1985	2,475,000	263,624,000	0.94 Forecast.

* U.S. Department of Commerce, Bureau of the Census.

Table 2.15 Kansas Population Growth Forecast* [35], [31], [32].

Forecast Number								
Year	(1)		(2)		(3)		(4)	
	Population	Increase/ Decade %	Population	Increase/ Decade %	Population	Increase/ Decade %	Population	Increase/ Decade %
1980	2,391,000	6.31	2,323,705	3.0	2,706,000	20.32	2,471,675	9.87
1990	(2,541,872)	6.31	2,364,033	1.70	2,966,000	9.61	2,897,105	17.21
2000	(2,702,264)	6.31	2,331,170	-1.40	3,311,000	11.66	(3,196,955)	10.35

* 1970 Population = 2,249,071 [32]

* Figures between brackets are interpolations

(1) Forecast of U.S. Department of Commerce, Bureau of the Census

(2) Forecast of Population, Research Laboratory of Kansas State University [35]

(3) Forecast developed by Dr. M. Jarvin Emerson, Kansas State University [31]

(4) Forecast (3) adjusted by Langston, Kitch and Associates, Inc. [31]

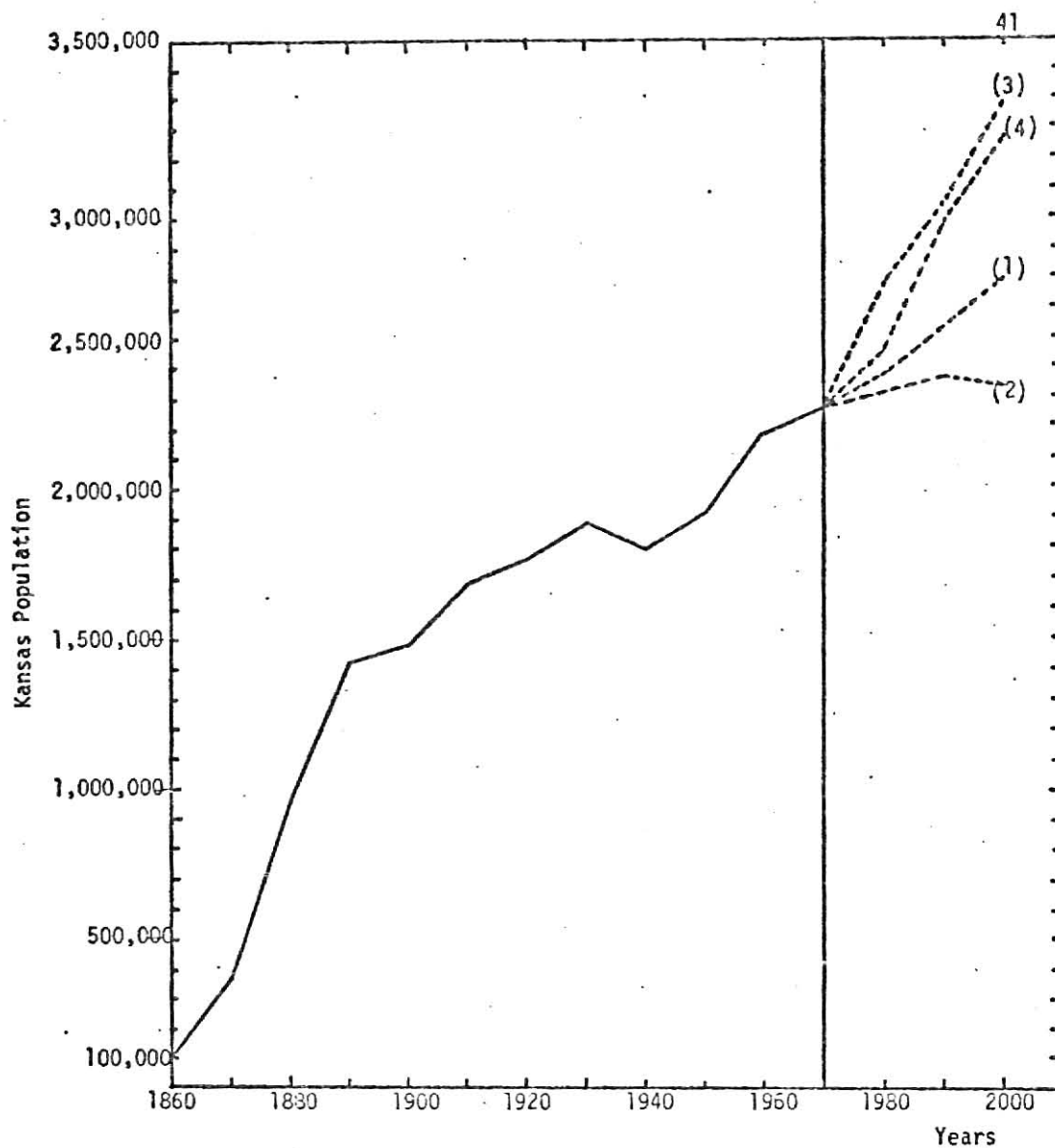


Fig. 2.7 Kansas Population Growth

- (1) Forecast of U.S. Department of Commerce, Bureau of the Census
- (2) Forecast of Population, Research Laboratory of Kansas State University [35]
- (3) Forecast Developed by Dr. M. Jarvin Emerson, Kansas State University, [31]
- (4) Forecast (3) Adjusted, by Langston Kitch and Associates Inc., [31]

Table 2.16 Daily Money Savings Due to Solar Heat Utilization for Various Energy Sources at 1973 Cost Index

Category**	Type of Collection	Heat Gain Btu/(Area. Day)	Money Savings \$/Day* for Various Energy Sources		
			Fuel Oil	Natural Gas	Electricity
Far Future	Solar Heat Gain/(Dwelling. Day) at 100% Efficiency, 1500 sq ft Collector Area	1.93×10^6	2.66	1.93	16.95
Near Future	Solar Heat Gain/(Dwelling. Day) at 40% Efficiency, 1500 sq ft Collector Area	0.77×10^6	1.06	0.77	6.78
Present	Solar Heat Gain/(Dwelling. Day) at 40% Efficiency, Collector Area = 25% of Floor Area.	0.19×10^6	0.27	0.19	1.69

* Energy Sources at 1973 Index Costs [12]

Fuel Oil at 20 cents/Gallon; 1.380×10^6 B.T.U.

Natural Gas at 1 \$/MCF; 1×10^6 B.T.U.

Electricity at 3 c/Kwh; 8.78×10^6 B.T.U.

** Far Future = When technology of solar systems is mature and mass production of equipment is available.

Near Future = When efficiency of solar heat collection is not less than 40%, and solar collector cost is \$1/sq.ft. [38].

Present = Efficiency at 40%, solar energy is utilized to assist other energy sources.

Table 2.17 Yearly Money Savings Due to Solar Heat Utilization for Various Energy Sources at Present and Future Costs.

Category*	Money Savings \$ x 10 ⁶ /Year														
	Fuel Oil c/G					Natural Gas \$/MCF					Electricity c/Kwh				
	20	40	60	80	100	1	2	3	4	5	3	6	9	12	15
Far Future	9.57	19.1	28.7	38.3	47.8	6.95	13.9	20.8	27.8	34.5	61	122	183	244	305
Near Future	3.83	7.64	11.48	15.32	19.12	2.78	5.56	8.32	11.12	13.8	24.4	48.4	73.2	97.6	122
Present	0.96	1.91	2.87	3.83	4.78	0.70	1.39	2.08	2.78	3.45	6.1	12.2	18.3	24.4	30.5

* Category

Far Future = When technology of solar systems is mature and mass production of equipment is available.

Near Future = When efficiency of solar heat collection is not less than 40%, and solar collector cost is \$1/sq.ft. [38]

Present = Efficiency at 40%, solar energy is utilized to assist other energy sources.

3. Solar Energy Systems

One way of alleviating the energy shortage is by utilization of non-conventional energy sources to satisfy a portion of the total national energy demand. The renewed interest in the utilization of solar radiation for domestic, commercial, and institutional buildings has been precipitated by pollution problems, the energy crisis, and the stated policy of the new Federal Energy Office to make the United States completely independent of outside sources of energy by the year 1980.

Since solar energy is of relatively low intensity compared to other energy sources currently employed, it seems logical to apply it to low-temperature energy demands such as space environmental control, and domestic water heating, which account for approximately 30 percent of the total energy used in the United States.

The major components of a solar space-heating system are the solar collector, the thermal energy storage device, the heat transfer loop, and the heat exchanger for transferring the solar heat to the spaces intended for heating [57,62].

Solar air conditioning involves the operation of a conditioning system by means of solar energy so that regular use of conventional energy is only for auxiliary needs such as pumps and fans [75]. Solar cooling devices are similar to already known heat operated cooling systems such as absorption systems, dehumidification systems and jet ejectors except for the fact that heat from the solar collector will be utilized instead of gas or kerosene (Appendix B).

3.1 Solar Heat Collection and Storage

An exact knowledge of available solar energy and that received on a horizontal, tilted, or south-facing vertical surface is of utmost importance in solar house heating and cooling. A solar heat collector is a device that collects the sun's radiant energy by absorption and releases it in the form of heat to adjacent surfaces or mediums such as fluids in copper tubes or circulated air. This heat can be used instantaneously for space heating, or can be transferred to a storage device for later use [23].

3.1.1 Flat Plate Solar Heat Collectors

Flat plate solar heat collectors (Fig. 3.1) are composed of three parts

1. The absorber and attachment.
2. The outward heat attenuator.
3. The frame and insulation.

The reflector, an auxiliary part, may also be incorporated in the design of the solar heat collector since it increases the efficiency of solar energy collection 10 to 15 percent. Reflectors may be of the flat-type, paraboloid, or truncated cone type [71].

(1) The absorber and attachment

The absorber is a metal plate, copper, steel, or aluminum painted black and has a rough texture so as to absorb the maximum incident solar energy. The absorber, if used as part of the roof,

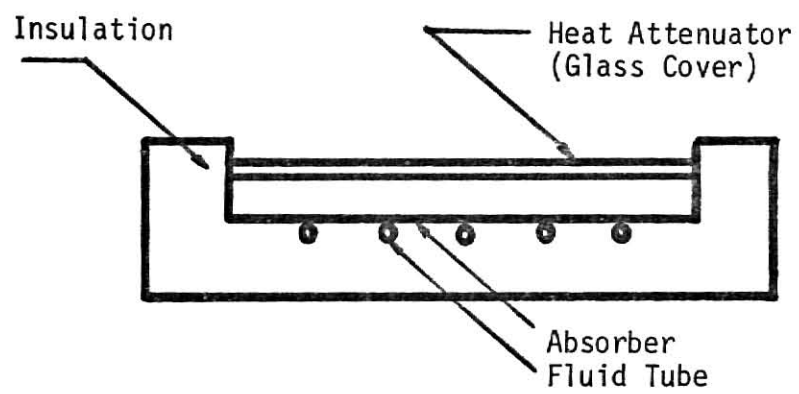


Fig. 3.1 Flat Plate Solar Heat Collector

should be light in weight, and easy in construction and maintenance. Besides it should not crack due to heat. A good absorber is one that conforms to the rules of selective radiation, and has a high retention efficiency. Such absorbers have selective surfaces with absorbtivity α of more than 0.92 and emissivity e_c of 0.1 [44].

Selective surfaces are polished metal surfaces coated with a rather special thin black layer. The surfaces appear black, and they absorb more than 90 percent of sunlight, yet the polished metal underneath radiates very little of the heat it receives from the surface coating. Selective surfaces distinguish between solar radiation (short wave length), and heat radiation (long wave length) from hot bodies [64]. An ideal absorber is one that has an absorbtivity α of unity [65].

Some investigations were made as to the applicability of porous slit-and-expanded aluminum foil-matrices as heat absorbing media for air-cooled solar collectors [6]. Porous matrices have high heat-transfer area per volume ratio, they are inexpensive, and simple in construction. Matrices in thicknesses of 0.002 to 0.006 inches can be slit into different patterns, then stretched, expanded and sprayed with Krylon 1602 flat black paint having an absorbtivity of 0.95 for the wave length range of 0.4 to 4 μm . can be used as absorbers for solar heat collectors.

(2) The Outward Heat Attenuator

Outward heat losses from the black plate absorber can be diminished by the use of one, two or three $\frac{1}{4}$ inch thick glass

panes or $\frac{1}{8}$ inch thick glass reinforced plastic panes $\frac{1}{2}$ inch apart. Glass permits passage of solar energy (short wave length of spectrum) but stops or traps the infrared radiation (long wave length) from the absorber [54].

Other types of materials such as Tedlar, Plexiglass, Mylar and Styrocel were used as attenuators either individually or combined. Tedlar, a wettable polyvinyl fluoride plastic, has an expected life time of no longer than 5 years, and its price exceeds that of glass [15]. Styrocel, which is a diffusely-transmitting foam plastic attenuates outward heat losses, but its transmittance of solar radiation is very low [53]. Besides, Styrocel is softened and distorted at high temperatures. Two other methods, the overlapped glass plate, and the rectangular honeycomb were investigated [50,4, 11] as heat attenuators. Both were found to be expensive and not practical for roof-type solar house heating.

(3) The Frame and Insulation

Proper insulation and framing of the solar collector is necessary since heat losses from the sides and back of the plate absorber are immense. Glass wool, aluminum foil, mineral wool, wood and dead air spaces are used as insulating materials. Also polyurethane foam or any other foam of high insulation index can be used as insulators. Inflammable foams if not avoided, should be coated with Pittsburg black.

3.1.2 Performance of Flat Plate Solar Heat Collectors

The useful heat (q_u) in a fluid stream which is in contact with the absorber plate is the difference between the energy absorbed by the collector (q_A) and the heat losses from the plate through glass covers (q_L) and through the insulation (q_B). The useful heat-collection rate is then given by [24,47]

$$q_u = q_A - q_L - q_B \quad (1)$$

The energy absorbed by the plate, q_A , is composed of two terms, direct radiation from the sun and diffuse heat from the entire sky

$$q_A = (H_S - H_D)R\tau\alpha + H_D\tau'\alpha' \quad (2)$$

where H_S and H_D are the solar energy flux density on a horizontal surface and the diffuse radiation flux density respectively, R is the ratio of direct radiation intercepted by a tilted surface to that intercepted by a horizontal surface, τ and τ' are the overall transmittance of glass covers for direct and diffuse solar radiation respectively, and α and α' are the absorptivity of the plate for incident and diffuse solar radiation respectively. The diffuse radiation flux density H_D , is given by

$$H_D = 0.78 + 1.07a + 6.177cc \quad (3)$$

where a is the solar altitude angle in degrees, and cc is the cloud cover. The ratio of direct radiation intercepted by a tilted surface to that intercepted by a horizontal surface is

$$R = \frac{\cos \theta_T}{\cos \theta_Z} \quad (4)$$

where θ_T and θ_Z are the angle of incidence of direct sunlight on a tilted surface and a horizontal surface respectively.

The heat losses, q_L , from the plate through glass covers may be calculated independently of the influx of solar radiation provided that the absorber is maintained at a definite temperature by circulating water.

The variables that determine these losses are:

1. Temperature of the absorbing surface, T .
2. Temperature of the outer air and sky, T_0 .
3. Number of glass covers, n , and spacing.
4. Tilt of glass covers from the horizontal, S .
5. Wind velocity over the top glass cover, V .

$$q_L = \frac{T - T_0}{\frac{n}{C \left(\frac{T - T_0}{n + f} \right)^{1/4}} + \frac{1}{h_w}} + \frac{\sigma(T^4 - T_0^4)}{\frac{1}{\epsilon_c} + \frac{2n + f - 1}{\epsilon_g} - n} \quad (5)$$

where C is a constant that depends on the collector tilt from horizontal, f is the ratio of thermal resistance of the outer glass cover to that of an average inner cover, and h_w is the wind convection coefficient. Also, the denominator of the second term of equation (5) allows for the effect on radiant interchange between parallel plates of emissivity ϵ_c of the collector and emissivity ϵ_g of the glass cover, and where σ is the Stefan-Boltzman constant, 0.1723×10^{-8} Btu/(sq ft hr $1R^4$).

$$C = 0.19 - 0.00078S \quad (6)$$

where S is the tilt angle of collector from horizontal,

$$f = 0.36 \times 10^{-0.02(V-8)} \quad (7)$$

$$h_w = 1.0 + 0.35 V \quad (8)$$

where V is the wind speed.

The heat losses, q_B , from the plate through the insulation may be calculated by conventional methods.

$$q_B = U \times (T - T_0) \quad (9)$$

where U is the overall coefficient of heat transmission of insulation and frame under the absorber plate.

3.2 Solar Heat Storage

Nearly one third of the total fuel consumed in the U.S.A. is estimated to be used for space environmental control [66]. Considerable attention is given now to the problem of energy storage in general and solar heat storage in particular.

The characteristics of an ideal heat storage system are as follows:

1. low cost of storage medium including good insulation and packaging.
2. Non-hazardous storage medium to people, and non-corrosive to construction materials.
3. High heat capacity per unit volume of storage medium.
4. High heat capacity without large temperature change of storage medium to ensure high collector efficiency.
5. Heat storage at a moderately low temperature.

Storage system design is dictated by the selection of materials in which the heat energy is to be stored. These materials can be divided into two broad types. Those that store energy in the form of sensible

heat, and those that undergo a change of state or physical-chemical change at some temperature within the range provided by solar heat collectors.

3.2.1 Sensible-Heat Storage Materials

Here, a change in the temperature of the material is necessary, and hence the heat capacity is proportional to the product of the specific heat and density. Table 3.1 gives specific heat, density and heat capacity for some low cost materials. These materials are usually non-hazardous, and non corrosive. Their main advantages are availability and low cost. The disadvantage of sensible-heat storage materials is that huge volumes are necessary since they have low heat capacity per unit volume. Hence, they are unsatisfactory if long term storage is required. Two of the most practical storage materials in this category are water and rock pebbles. One cubic foot of water can store 62.4 BTU per degree F rise in temperature while one cubic foot of rock can store about 36 BTU per degree F. However, pebbles are more suitable for hot-air systems in which air is heated directly by passing through the spaces between pebbles, these spaces occupy about a third of the total volume for roughly spherical pebbles of uniform size. A pebble bed, if thoroughly insulated will hold its heat for long periods because pebbles touch each other only on restricted surfaces, and the lateral heat conduction through the pebble bed is low [10].

Table 3.1 Properties of Various Specific Heat Type Storage Materials [66]

Material	Specific Heat Btu/(lb F)	Density lb/(cu ft)	Heat Capacity Btu/(cu ft F)
Water	1.00	62.4	62.40
Iron	0.11	490.0	43.90
Concrete	0.27	140.0	37.80
Brick	0.20	140.0	28.00

3.2.2. Heat of Fusion Storage Materials

Materials that undergo physical-chemical change can be used for heat storage with an additional advantage of reducing storage space. Low cost salt hydrates such as sodium sulphate deca-hydrate which was examined by Dr. M. Telkes, [41] melts in its water of crystallization when heated to its transition temperature at 90 F. The stored heat is then recovered as the material re-crystallizes. It has been found however that unless the melted salt is stirred, variations in concentration develop and recrystallization of the whole is prevented [3]; however, the use of thickening agents is now being investigated to avoid the above mentioned problem. Table 3.2 gives properties of various heat of fusion type storage materials.

Both types of heat storage materials require storage packaging, containers or space. Water for example requires a water tank with its insulation which in turn needs space and foundations. Rocks also require storage space and insulation. Containers for heat of fusion type storage materials should be resistant to corrosion, and leak-proof due to inefficient capping. Plastic containers have proved in this case to be superior to metal containers [66]. For large-scale heat storage the water tanks or pebble beds are conveniently placed underground where the heat conductivity through the earth is low, and where the heat taken up by the surrounding earth can be recovered in part when colder air or water is passed through the heat-storage unit.

For some special cases the heat capacity of metals may be used for storing heat. The heat conductance of metals is very good. The heat

Table 3.2 Properties of Various Heat of Fusion Type Storage Materials [41]

Material	Chemical Formula	Melting Temp. F	Heat of Fusion Btu/lb	Density lb/(cu ft)	Latent Heat Btu/(cu ft)
Calcium Chloride	$\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$	84.20	73.3	104.7	7670
Calcium Nitrate	$\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$	107.80	61.2	113.3	6950
Sodium Phosphate Dibasic	$\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$	97.00	120.0	94.8	11400
Sodium Sulphate	$\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$	87.80	92.4	91.0	8400

capacity at constant pressure in calories per degree of a gram of a chemical element is approximately equal to the atomic weight divided by a constant 6.4. Thus copper will absorb $6.4/63.6$ or 0.1 cal., iron will absorb $6.4/55.8$ or 0.11 cal., and aluminum will absorb $6.4/27$ or 0.24 cal./g. when heated 1°C . So, on the basis of weight, the heat storage of these metals is only one tenth and one fourth as much as that of water. On the basis of value, however, the difference is much less because the densities are greater. Thus 1 liter of water stores 1 Kcal. of heat per degree C, copper 0.89, iron 0.87, and aluminum 0.63. The cost of heat storage by metals is much greater than by water or rocks.

Other storage systems, the two-vessel systems can store much larger quantities of heat by using two parts or sections, one hot and the other cold. For example, if a concentrated solution of sulphuric acid and water is heated sufficiently the water will be distilled out and can be condensed as liquid water in another section of the closed system, which is cooled either by circulation water or air. At a later time, the residue of sulphuric acid with a small amount of remaining water may be cooled, and the liquid water then evaporates and returns to the very concentrated sulfuric acid solution which now has a lower vapor pressure. In re-entering the sulfuric acid, the water vapor gives up its heat of condensation 580 cal./g. at room temperature plus the considerable heat of mixing with the sulfuric acid. A valve may be introduced between the two vessels to prevent premature mixing, thus permitting the potential chemical heat to be stored indefinitely without thermal loss. However,

there are several problems connected with these separated storage compartments. For example, it is necessary to exclude air or other gases because they decrease the rate of diffusion of the vapor. If the material that reabsorbs the vapor is a liquid, stirring is necessary to prevent accumulation of the condensing vapor at the surface; if it is a solid, channels must be supplied to assure access of the vapor to the interior of the solid. Trays of screens holding the absorbing solid material are effective, but then the heat transfer to the outside of the heat storage unit is slow.

3.3 Heat Storage Media

The optimum capacity of an energy storage system depends on the expected time-dependence of solar radiation availability, the nature of loads to be expected on the process, the degree of reliability needed for the process, the manner in which auxiliary energy is supplied, and an economic analysis that determines how much of the total loads should be carried by solar energy. In practice, it is usually not realistic to meet all of the loads on a process from solar energy over long periods of time, so an auxiliary energy source must be used [11].

The choice of media for solar energy storage depends on the nature of the process. For water heating, energy storage as sensible heat of stored water is logical. If air heating collectors are used, storage in sensible or latent heat effects in particular storage units are indicated, such as sensible heat in a pebble bed heat exchanger. If photovoltaic or photochemical processes are used, storage is probably most logically in the form of chemical energy.

3.3.1 Water as Storage Medium

Water, as a medium of sensible heat storage, provides a practical, inexpensive and readily available solution.

The energy storage capacity of a water storage unit operating over a finite temperature difference is given by [11]

$$q_u = mC(T_0 - T_i) \quad (10)$$

where m is the mass of water through the collector, C is the specific heat of water, and T_0 and T_i are the collector outlet and inlet temperatures respectively.

3.3.2 Rock Pebbles as Storage Medium

Rock pebbles used as a storage medium in a well-designed packed bed have several characteristics that are desirable for solar energy applications: the heat transfer coefficient between the air and solid is high, the cost of storage material is low, and the conductivity of the bed is low when air flow is not present. Normally, heat is not added to this type of storage and removed from it at the same time; this is in contrast to water storage systems where simultaneous addition to and removal from storage is possible. For a pebble rock packed bed of length L that is divided into N divisions of equal length ΔX , and with air as the transfer medium, the energy balance equation at the i th bed section is [37]

$$(\rho CA \Delta X) \frac{dT_i}{dt} = mC_a(T_{i-1} - T_i) - Q_{\text{loss},i} \quad (11)$$

where ρ is the bed density, C is the bed material specific heat, A is the bed cross-sectional area, T_i , T_{i-1} are the temperatures of pebble

bed at (i-th) and (i-1) section, m is the rate of flow of air, C_a is the air specific heat and Q_{loss} is the overall heat losses to surroundings.

3.4 Location of Storage System

The storage system should be located in such a manner that it does not constitute extra load on the building structure, danger to inhabitants, or incur excessive space costs. The following are guidelines for storage location.

1. The storage system should be located in the space where the opportunity risk is the least. The basement and the attic are two candidates where space may be available. The basement if not rented will be the suitable place. Heavy storage in the attic constitute new structural design and additional costs.
2. Storage should be as close to heat collector and living space as possible. Long ducts and connecting pipes not only increase initial capital cost, but they also have a direct effect on heat losses, insulation, and pumping costs.
3. Water storage if located in the basement will give the extra advantage where loss of heat through storage insulation will contribute to the total house heating requirement. Storage in the attic or outside the building will waste this fraction of heat.
4. Storage should be located in such a manner that it does not hinder drainage of the collector during periods of non-collection so as to prevent freezing, and reduce the collector heat capacity loss.

5. Storage in the basement permits a significant transfer of heat as a result of natural convection if the flow passages to the living space are left opened during periods of low heat requirements when the circulating pump is switched off.

3.5 Conclusion

Heat capacity, reliability, and cost constitute the main basis for selection of storage media. Sensible-heat type storage materials such as water, iron, aluminum, concrete, brick and rock pebbles are reliable and not costly. While water needs a storage tank, other materials can be housed in a relatively cheap enclosure, however the superiority of water over all other materials due to its high heat capacity ($62.4 \text{ Btu}/(\text{cu ft } ^\circ\text{F})$) makes it most favorable. Heat of fusion type storage materials have not yet proved their relative merits practically or commercially. The reversible phase change which involves interchange of energy is not reliable due to the fact that many salts do not give uniform composition or complete crystallization. Constant stirring or seeding is required to solve this problem of stratification.

All in all, water and rock pebbles may be the two practical candidates for heat storage in the present due to their heat capacity, reliability and availability.

4. Design Problem

The feasibility of solar house heating and cooling in the state of Kansas will be investigated. A typical two-story house will be considered, heating and cooling loads will be calculated and analyzed with respect to incremental insulation effects, optimum economic insulation thicknesses, realistic fuel costs, and predicted future fuel costs. Sizing of the flat plate solar collector, and storage volume together with cost analysis and rate of return on investment will be given.

The two-story model house, Figs 4.1 through 4.6 will be analyzed. The details of construction are given in Table 4.1. The environmental conditions are assumed to be [43,46,47].

Heating season = 7 months, October to April inclusive

Wind velocity = 15 miles per hour

Outside temperature = -10 F

Inside temperature = 70 F

Ground temperature = 45 F

Basement temperature = 32 F

Cooling season = 5 months, May to September inclusive

Outside temperature = 95 F

Inside temperature = 78 F

The house will also be analyzed with various insulation thicknesses and with various winter outside temperatures (0,10,20,30,40 F).

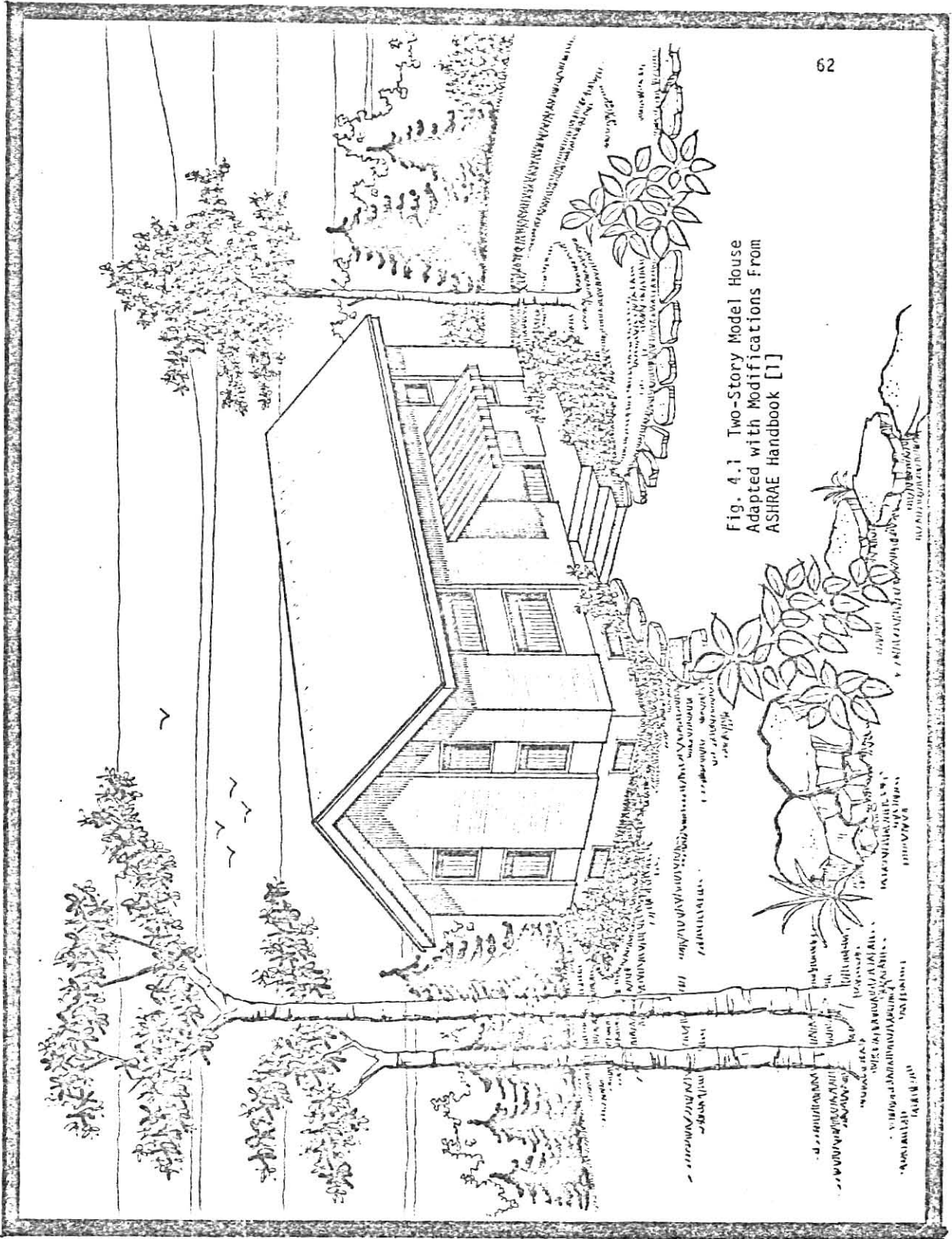


Fig. 4.1 Two-Story Model House
Adapted with Modifications From
ASHRAE Handbook [1]

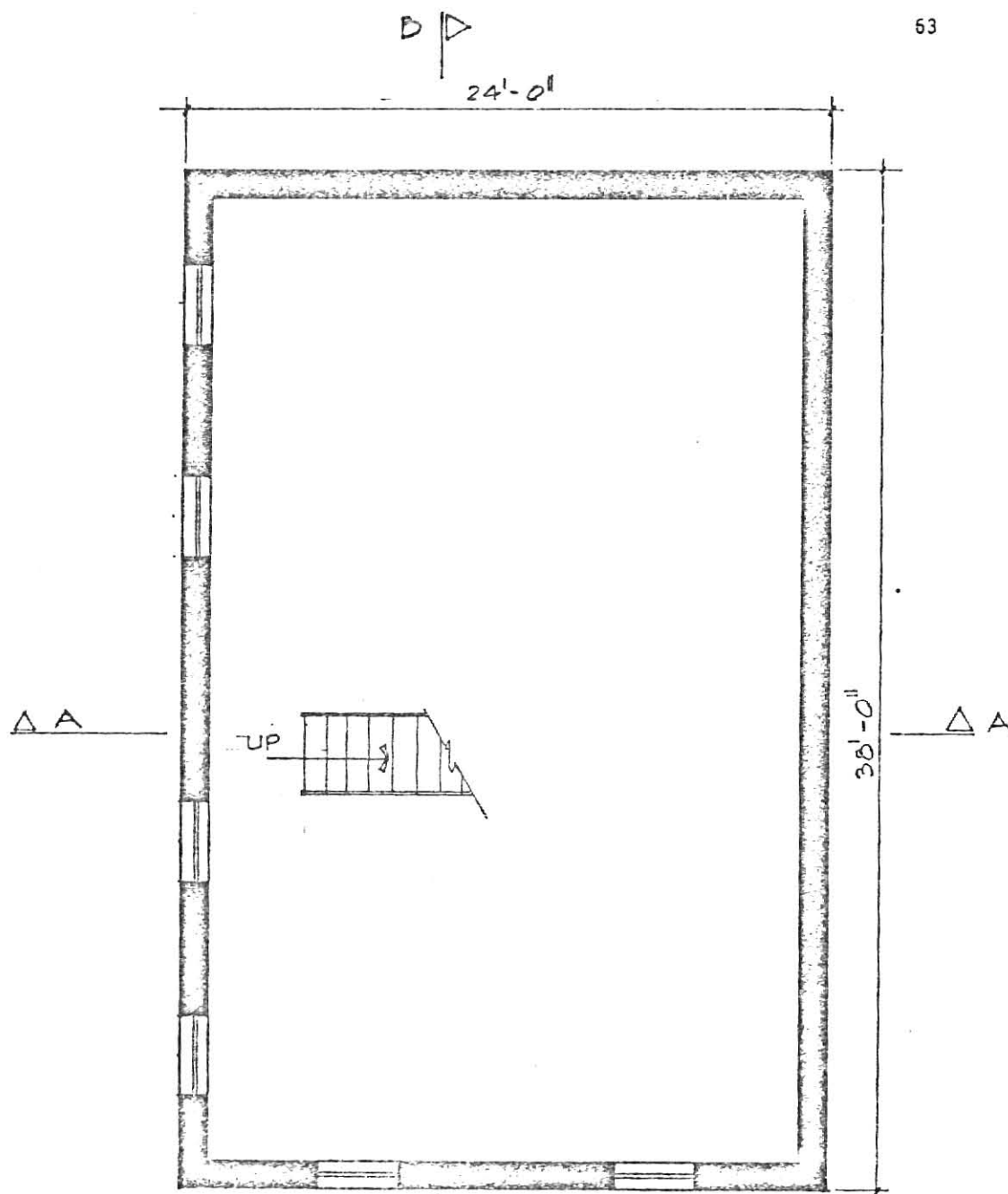
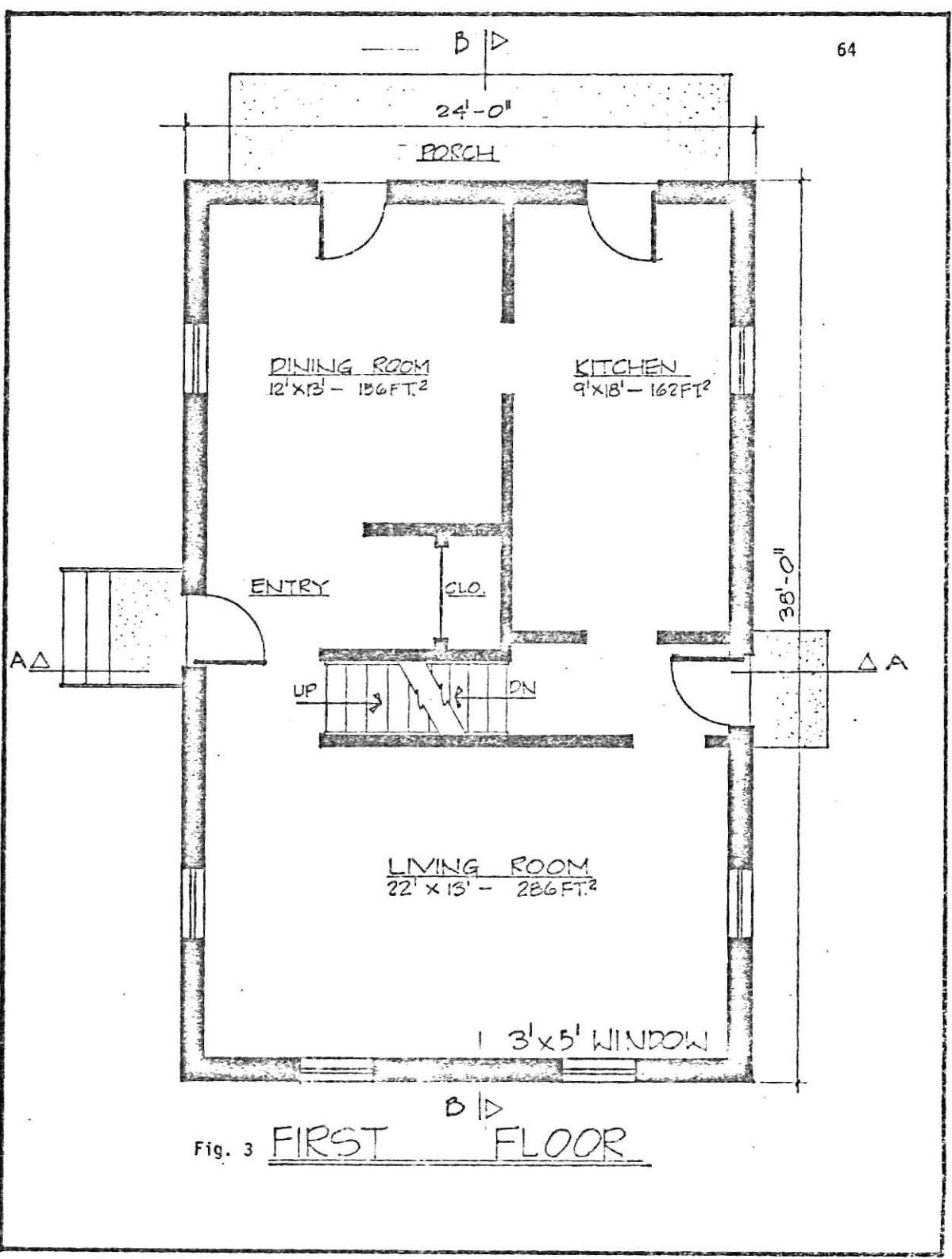


Fig. 2 ^B BASEMENT



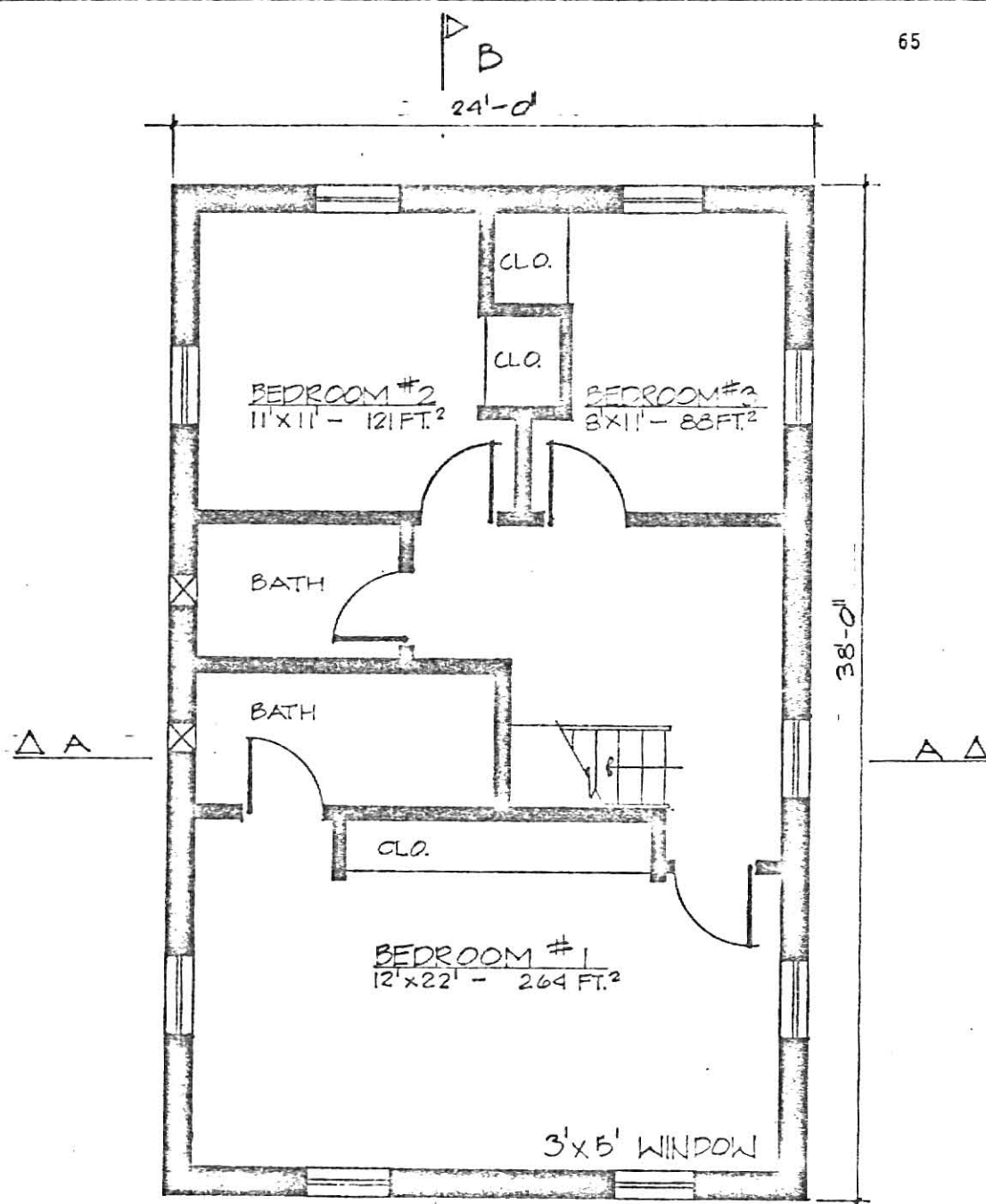
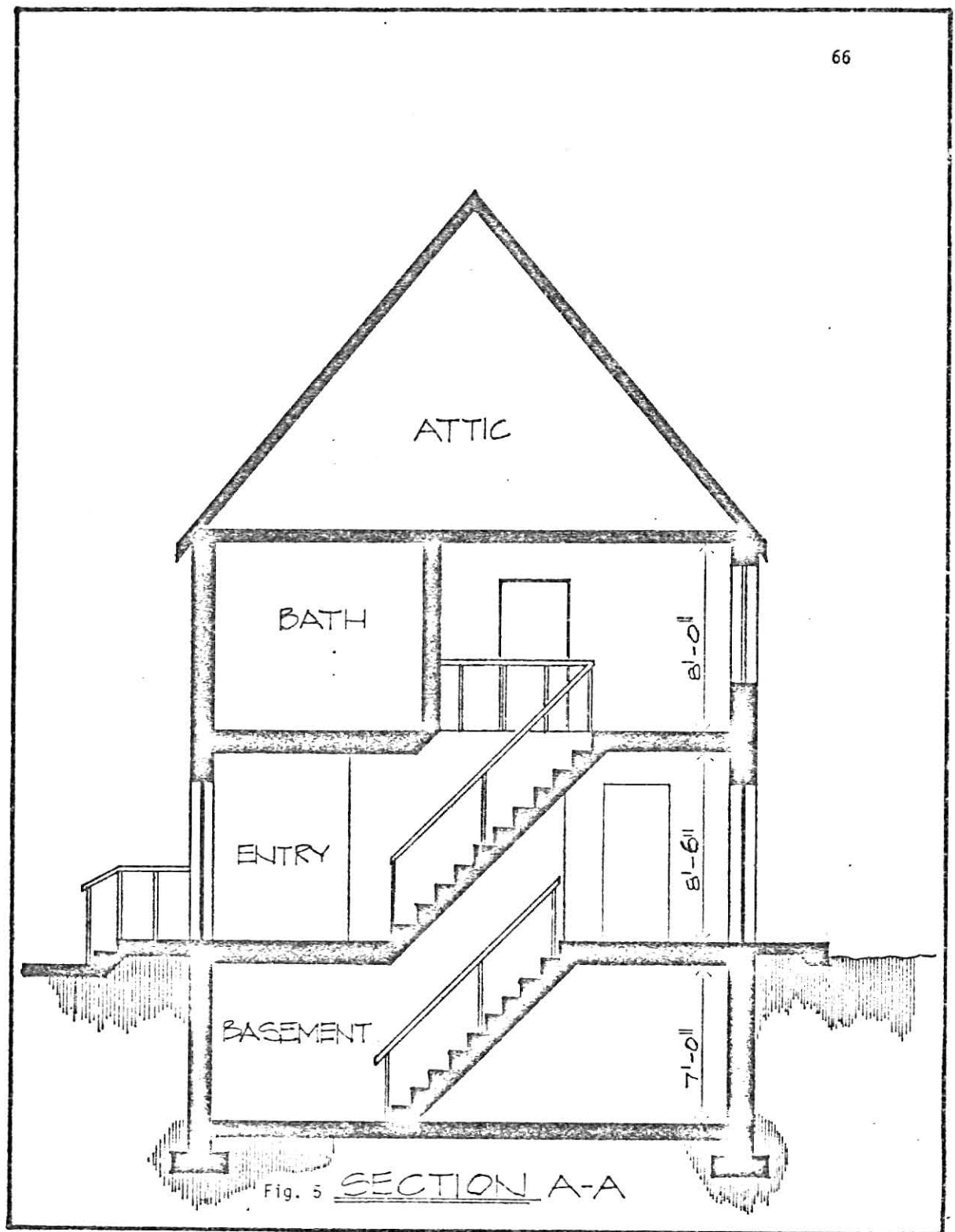


Fig. 4 SECOND FLOOR



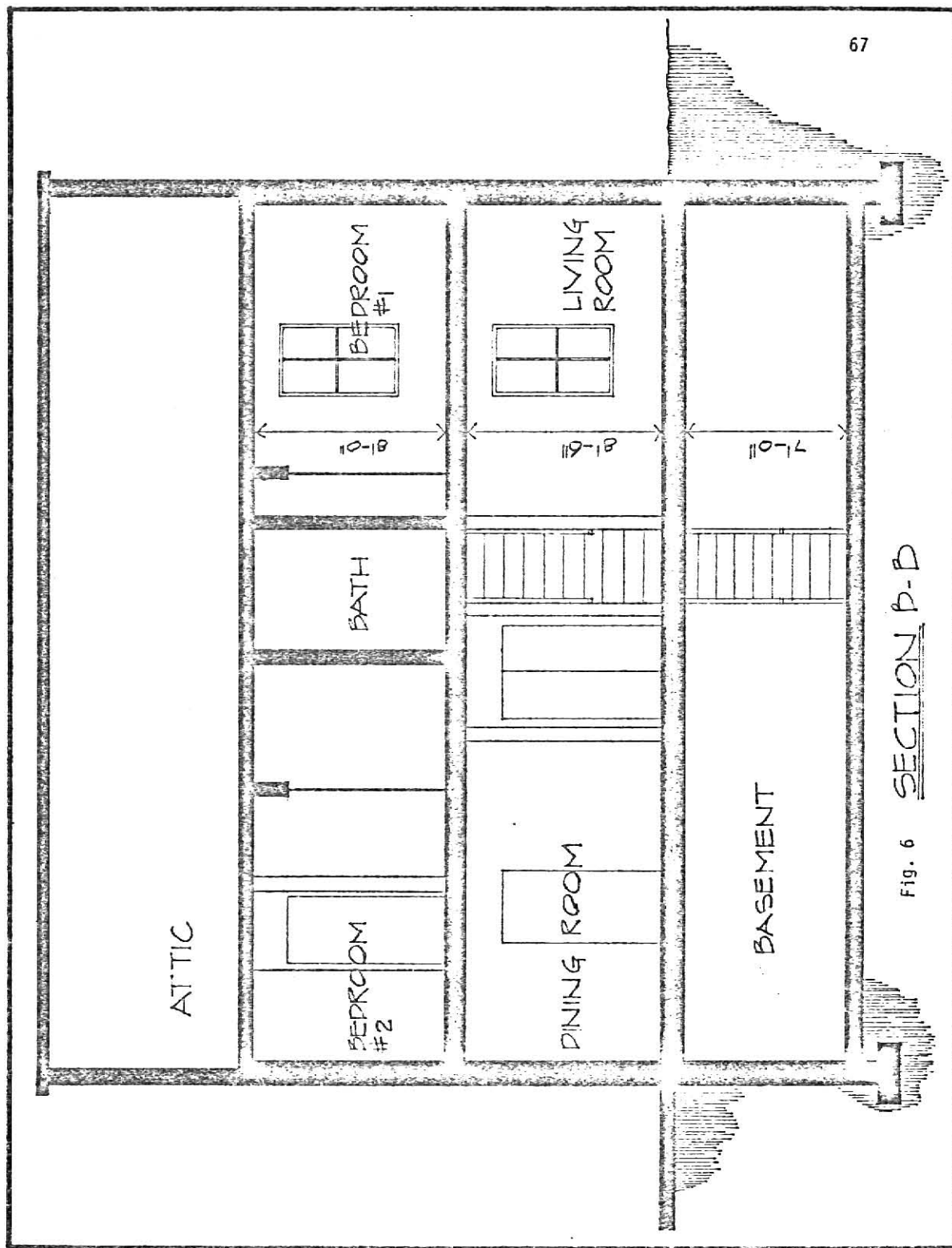


Fig. 6 SECTION B-B

Table 4.1 Two-Story Model House [1]

Item	Details of Construction [*]
Walls	4 inches brick veneer, with building paper, wood sheathing, studding metal lath and plaster,
Floor	Maple finish flooring on yellow pine subflooring, metal lath and plaster false ceiling below
Ceiling	Metal lath and plaster with no flooring above joists,
Roof	Asbestos shingles on wood sheathing on rafters,
Basement Walls	10 inch concrete
Basement Floor	4 inch stone concrete on 3 inch cinder concrete
Windows	Double hung wood windows (first and second floors) and steel casement sash (basement).

^{*}This construction is taken from ASHRAE Handbook [1], current construction may however be different.

4.1 Heating and Cooling Load Calculations

Heat in the winter is lost by transmission through outside walls, partitions next to unheated spaces, ceilings, floors, glass windows, and doors. Besides, heat is lost due to air leakage or infiltration. Prescribed amounts of air ventilation to remove odors contribute also to the total heat losses. Besides, some heat is gained in the winter due to electric lighting, electric equipments, number of occupants and their activities, and from solar radiation through windows.

Heat transmission losses are calculated by using the following formula:

$$H = AU(t_i - t_o) \quad (1)$$

where A is the surface area, and U is its over-all coefficient of heat transmission (Appendix C), t_i is the inside temperature, and t_o is the outside temperature. Table 4.2 shows the total heat losses of the two-story model house, with basement unheated, and without considering any insulation of whole house. Table 4.3 shows the summary of heat losses at various outside design temperatures and various insulation thicknesses. For example, the heat losses at an outside design temperature of -10F and where the house is equipped with 4 inches of insulation in walls, floors and ceiling are equal to 19531 (Btu/hr).

4.1.1 Other Heat Losses and Gains

Heat is lost in winter due to cracks and infiltration and due to a prescribed ventilation index (number of air changes per hour).

Table 4.2 Heat Losses of Two-Story Model House

Space	Type	Area in (Sq ft)	U Btu/(hr sq ft F)	Temp. dif. ($t_i - t_o$) F	Heat losses (Btu/hr)
Living Room	Walls	348	0.27	80	7516.80
	Glass	60	1.13	80	5424
	Floor	286	0.28	38	3043.04
Entrance	Walls	52	0.27	80	1123.20
	Doors	42	0.38	80	1276.80
	Floor	126	0.28	38	1340.64
Dining Room	Walls	197	0.27	80	4255.20
	Glass	15	1.13	80	1356
	Door	21	0.38	80	638.40
	Floor	156	0.28	38	1659.84
Kitchen	Walls	193	0.27	80	4168.80
	Glass	15	1.13	80	1356
	Door	21	0.38	80	638.40
	Floor	162	0.28	38	1723.68
Bedroom (1)	Walls	324	0.27	80	6998.40
	Glass	60	1.13	80	5424
	Ceiling	286	0.358	43	4402.68
Bedroom (2)	Walls	146	0.27	80	3153.60
	Glass	30	1.13	80	2712
	Ceiling	117	0.358	43	1801.10
Bedroom (3)	Walls	146	0.27	80	3153.60
	Glass	30	1.13	80	2712
	Ceiling	117	0.358	43	1801.10
Stairs	Walls	152	0.27	80	3283.20
	Ceilings	272	0.358	43	4187.10
Total					75149.00

Table 4.3 Heat Losses of Two-Story Model House at Various Outside Design Temperatures and Insulation Thicknesses

Insulation Thickness in Inches	Heat Losses in (Btu/hr)					
	t_0	t_0	t_0	t_0	t_0	t_0
	-10 F	0 F	10 F	20 F	30 F	40 F
0	75149	66831	58515	49915	41599	31647
1	33787	30073	26360	22562	18849	14330
2	25913	23009	20105	17154	14250	10811
3	22300	18744	17226	14653	12116	9180
4	19531	17287	15043	12771	10527	7968
5	17956	15876	13796	11693	9613	7270
6	16779	14823	12868	10893	8938	6756

1. Heat losses due to cracks and infiltration

$$H = B(t_i - t_o)L \quad (2)$$

$$B = W.S.D \quad (3)$$

where H = Heat losses due to cracks and infiltration in Btu/hr .

B = Air leakage in cubic feet per foot of crack for a specified wind velocity (K), and type of door or window times $S.D$.

K = Average wind velocity in Dec., Jan., Feb. (15 M.P.H.).

W = 39.3 cubic feet per ft. of crack per hour at $K = 15$ m.p.h.

S = Specific heat of air (0.24) Btu/lb F

D = Density of air at 70 F (0.075 lbs per cubic foot).

t_i = Inside temperature (70 F)

t_o = Outside temperature

L = Length of window or door crack

Now the heat losses in 14 windows due to cracks and infiltration is given by

$$\begin{aligned} H &= (14)(39.3 \times 0.24 \times 0.075)(80)[(2 \times 5) + (3 \times 3)] \\ &= 15053 \text{ Btu/hr .} \end{aligned}$$

Also the heat losses in 4 doors due to cracks and infiltration is

$$H = (4)(39.3 \times 0.24 \times 0.075)(80)[(2 \times 7) + (2 \times 3)] = 4527 \text{ Btu/hr .}$$

So, the total infiltration losses is equal to 19580 (Btu/hr).

2. Heat losses due to ventilation (one air change per hour)

$$H = S \times D \times Q (t_i - t_o) \quad (4)$$

where Q = cubic feet of air entering per hour or

= Volume of space x number of air changes.

$$H = 0.24 \times 0.075 [(22 \times 36 \times 8.5) + (22 \times 36 \times 8)] \times 1 \times 80 \\ = 18817 \text{ (Btu/hr)}.$$

3. Heat gains due to persons, electric lighting, and other equipment

Heat gains from persons vary with individual and activity. An adult man seated or doing little work loses about 240 (Btu/hr) sensible heat and 160 (Btu/hr) latent heat, based on 70 F dry bulb temperature [1]. Women and children lose heat at a rate of 85 % and 75 % of an adult man respectively.

So heat gains due to 4 persons is about 1600 (Btu/hr). Heat gain from electric lighting is calculated from the following relation:

$$H_L = \text{light wattage} \times \text{use factor} \times \text{special allowance factor} \\ \times 3.41 \text{ (Btu/hr)} \quad (5)$$

Heat gain from equipment is calculated from the following relation.

$$H_E = \left(\frac{\text{Horse power rating}}{\text{Motor efficiency}} \right) \times (\text{load factor}) \times 2544 \text{ (Btu/hr)} \quad (6)$$

All in all, it is a reasonable assumption to consider the total heat gain from electrical lighting, television, radios, dish washer, washing machines, stoves, refrigerators, vacuum machines ... etc as equivalent to a 5 K W power source or $5 \times 3413 = 17065$ (Btu/hr)

So the total heat gain will be $17065 + 1600 = 18665$ (Btu/hr)

4.1.2 Insulation Optimization

Whenever the temperature inside an enclosure is different from that of the surrounding air, a transfer of heat takes place through the confining walls, floor, and ceiling of the enclosure. The more conductive the walls, the more rapid the flow of heat for the same temperature difference and the more energy that must be supplied to maintain the desired inside temperature. If heat resistance in the form of insulation is interposed in the path of the heat flow, the loss of energy is retarded and a saving is thereby made. The calculations for determining the coefficient of heat transmission in Btu/(hr sq ft F) for walls, floors, ceiling, and roof of our model house are given in Appendix C.

The question now naturally arises as to the proper thickness of insulation to use in any given case. If no insulation is used, a great amount of heat will be lost through the structure. Besides, if successive layers of insulation are added, the loss of heat during any given period diminishes but the cost of insulation increases. At some point, the sum of these quantities will be a minimum, which gives the optimum thickness of insulation. The total cost (C) is the sum of the annual heat cost (H) and the annual insulation cost (I), such as

$$C = H + I \quad (7)$$

$$H = \frac{A J N (t_i - t_o) U_i}{1,000,000} \quad (8)$$

$$I = A P X Z \quad (9)$$

where

A = area in sq ft

J = cost of heat in dollars per 1,000,000 Btu

N = number of hours during the heating season (5088)

t_i = inside temperature

t_o = average outside temperature during heating season (40°F)

U_i = coefficient of heat transmission of insulated wall.

P = annual fixed charges in percent

X = thickness of insulation

Z = installed cost of insulation $\$/(\text{sq ft inch thickness})$

The coefficient of heat transmission of the insulated wall, U_i , is given by [8]

$$U_i = \frac{1}{\frac{1}{U_w} + \frac{X}{K}} \quad (10)$$

where

U_w = coefficient of heat transmission of wall without insulation

K = conductivity of insulation Btu/(hr sq ft inch thickness F)

The total cost C becomes

$$C = \frac{ANJ(t_i - t_o)}{1,000,000} \cdot \frac{1}{\frac{1}{U_w} + \frac{X}{K}} + APXZ \quad (11)$$

For minimum cost, $\frac{dC}{dX} = 0$, that is,

$$\frac{dC}{dX} = \frac{AJN(t_i - t_o)}{1,000,000} \cdot \frac{(-U_w K) \cdot U_w}{(K + U_w X)^2} + APZ = 0 \quad (12)$$

The solution of the equation gives

$$X = \sqrt{\frac{AJN(t_i - t_o)}{1,000,000} \cdot \frac{K}{APZ} - \frac{K}{U_w}} \quad (13)$$

Since the second derivative of the cost function, C, with respect to the thickness, X, is

$$\begin{aligned} \frac{d^2C}{dX^2} &= \frac{AJN(t_i - t_o)}{1,000,000} \cdot \left(2(U_w^2 K)(K + U_w \cdot X)U_w \right) \\ &= \left(\frac{AJN(t_i - t_o)}{1,000,000} \right) \left((2U_w^3 K)(K + U_w \cdot X) \right) \end{aligned} \quad (14)$$

which is positive, so equation (13) gives the optimum thickness of insulation at the minimum total cost.

Whether or not building insulation pays depends on many factors such as cost of fuel, type of fuel, cost of insulation, inside and outside temperature, type of building construction, and duration of heating and cooling season. Table 4.4, and Fig. 4.2 show the percentage of fuel savings for various insulation (mineral wool) thicknesses for walls, floor, and roof of the two-story model house. Table 4.5 and Fig. 4.3 show the summary of fuel savings in percent for the whole house at various insulation thicknesses.

4.1.3 Return On Insulation Investment Per Heating Season

The thermal insulation for buildings has to be justified from an economic standpoint of the return on investment. The seasonal return on investment (r) is expressed in percentage as follows:

Table 4.4 Percentage of Fuel Savings Per Various Insulation Thicknesses
at $(t_0=-10)$, $(t_i=70)$ for Walls, Floor, and Roof

Insulation Thickness (inches)	Heat Losses (Btu/hr)			% of Fuel Savings (Btu/hr)		
	Walls	Floors	Roof	Walls	Floor	Roof
0	33652.8	7767.20	12192.05	0	0	0
1	16203	3828	3643	52	42	70.1
2	11217	2540	2043	67	67	83.2
3	8724	1897	1566	74	75	87.1
4	6730	1497	1191	80	80	90.2
5	5608	1248	987	83	83	91.9
6	4736	1079	851	86	86	93.0

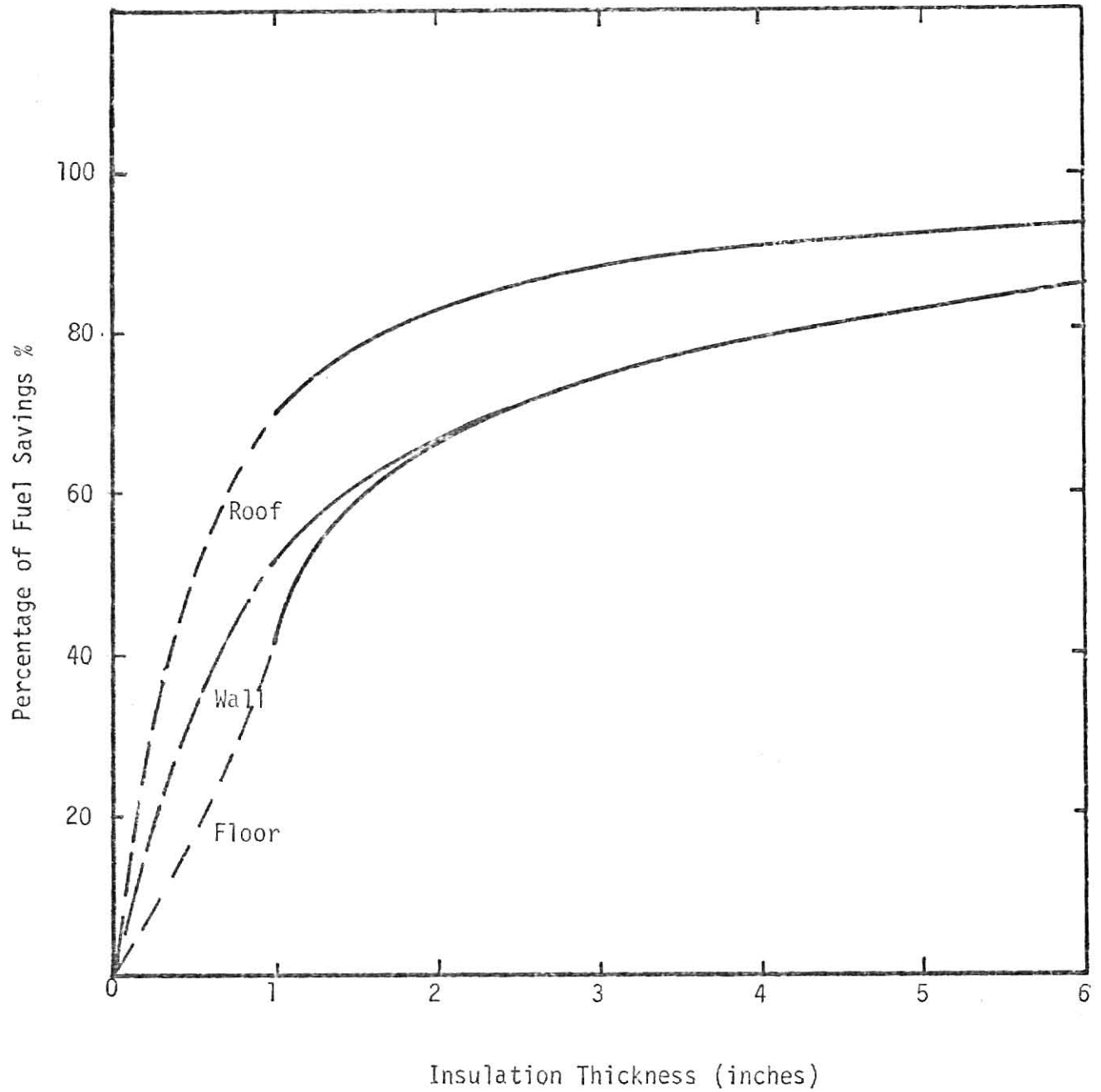


Fig. 4.2 Percentage of Fuel Savings Versus Insulation Thickness for Walls, Floor, and Roof, at $t_o = -10F$ and $T_i = 70F$.

Table 4.5 Summary of Percentage of Fuel Savings Per Various Insulation Thickness for Whole House ($t_o = -10$), ($t_i = 70$ F)

Insulation Thickness inches	Heat Losses (Btu/hr)	Fuel Savings (%)
0	75149	0
1	33787	55.00
2	25913	65.50
3	22300	70.33
4	19531	74.01
5	17956	76.11
6	16779	77.67

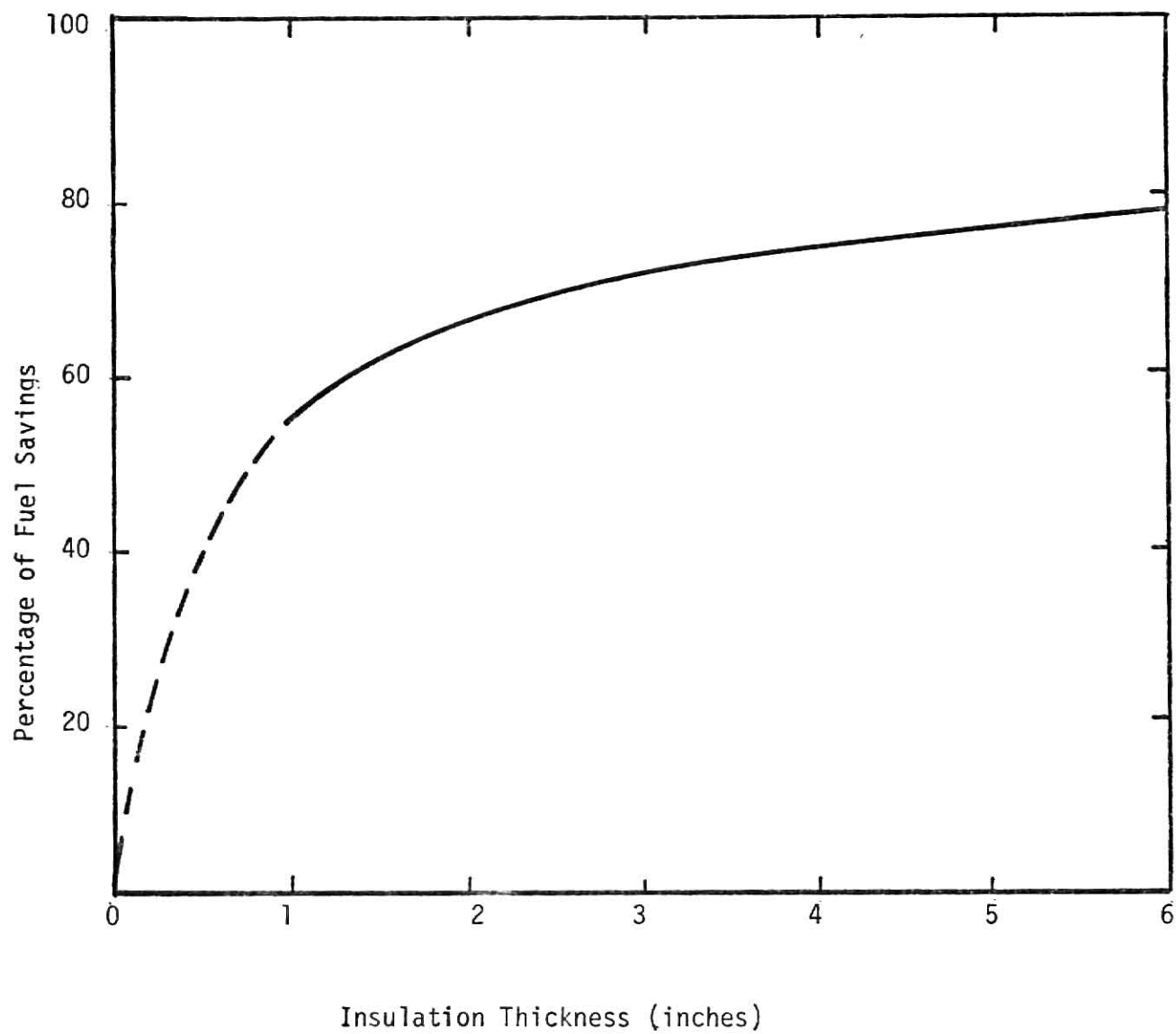


Fig. 4.3 Overall Percentage of Fuel Savings Versus Insulation Thickness for the Whole House.

$$r = 100 \times \frac{\text{Value of annual fuel or energy savings}}{\text{Net cost of insulation}} \quad (15)$$

or

$$r = \frac{(U-U_i)JN(t_i-t_{o,av})}{100(Z_i-Z_u)} \quad (16)$$

where r = return on investment in percent

U = coefficient of heat transmission of uninsulated area in
Btu/(hr sq ft F)

U_i = coefficient of heat transmission of insulated area

J = cost of heat, \$/1,000,000 Btu

N = number of hours during the heating season

$(t_i-t_{o,av})$ = average temperature difference (70-40=30 F)

Z_i = cost of insulated area in cents/(sq ft)

Z_u = cost of uninsulated area in cents/(sq ft)

(Z_i-Z_u) = cost of insulation installed in cents/(sq ft)

As an example, if we have a total wall area of 1558 sq ft with U , U_i , $(t_i-t_{o,av})$, N equal to 0.27, 0.13, 30 and 5088, respectively, and let fuel oil with heat value of 145,000 Btu/gallon be used as the heating medium at 20 cents/gallon, also let insulation costs be 20 cents/(sq ft) per inch thickness. Then, the savings due to 1" of insulation is equal to

$$(0.27 - 0.13) \times 30 \times 5088 \times 1558 = 33,293,836 \text{ Btu/Heating season}$$

or

$$\text{savings} = \frac{33,293,836}{145,000} \times 20 = \$45.92$$

The insulation cost = $20 \times 1558 = 311.6$ \$/total area

$$\text{Return on investment} = \frac{45.92}{311.6} = 14.73 \%$$

Table 4.6 shows three types of energy sources together with their respective costs with 1973 as an index, and with 100% to 500% cost increase in the future.

The optimum insulation thickness for walls, floor, and ceiling of the two-story model house in Kansas, together with the optimum annual cost of heating and insulation, for the various sources of energy at present and projected future prices are given in Table 4.7. For example, if the energy source is fuel oil at present cost of 20 cents/gallon, then the optimum insulation thickness is about 2 inches. However, if the price of fuel oil is increased five folds then the optimum thickness of insulation will be 5 inches. If electrical energy is used at present cost of 3 cents/Kwh, then the optimum insulation thickness is about 5 inches.

Table 4.8 and Fig. 4.4 show the direct relationships between insulation thickness for walls, rate of return on insulation investment, and energy source costs.

Table 4.9 and Fig. 4.5 show the annual total costs of heating and insulation at various insulation thicknesses and at the optimum thickness for fuel oil at 20 cents/gallon. Table 4.10 and Figs. 4.6, 4.7 show the optimum thickness of insulation and minimum total annual heating costs at present and projected fuel oil prices. Roofs and floors are analyzed in appendix D. Insulation requirements analysis for electrical energy and natural gas at present and future projected prices is also given in appendix D.

Table 4.6 Various Energy Sources and Their Respective Costs [12],
Together with Future Price Predictions

Fuel Oil		Natural Gas		Electricity		Index
	(J)		(J)		(J)	
cents/gallon	\$/10 ⁶ Btu	\$/MCF	\$/10 ⁶ Btu	cents/Kwh	\$/10 ⁶ Btu	
20	1.38	1	1	3	8.78	1973
40	2.76	2	2	6	17.56	Future
60	4.14	3	3	9	26.34	"
80	5.52	4	4	12	35.12	"
100	6.90	5	5	15	43.9	"

Table 4.7 Summary of Optimum Insulation Thickness and Optimum Annual Heating Costs for Various Energy Sources at Various Prices

Energy Source Type	Energy Source Cost	Optimal Insulation Thickness (Inches)			Optimal Annual Heating Costs (\$)			Total Costs (\$)	Index
		Floor	Wall	Ceiling	Floor	Wall	Ceiling		
Fuel oil	20 ¢/g.	1.42	1.38	1.63	27.74	57.60	31.76	117.10	1973
	40	2.41	2.37	2.62	42.20	89.49	47.44	179.13	Future
	60	3.17	3.13	3.38	53.26	113.15	59.45	225.86	"
	80	3.92	3.77	4.13	62.61	133.03	69.61	265.25	"
	100	4.50	4.33	4.71	70.84	150.65	78.51	300.00	"
Electricity	3 ¢/Kwh	5.16	5.01	5.26	80.75	171.65	89.31	341.71	1973
	6	7.70	7.50	7.75	116.88	250.24	128.66	495.78	Future
	9	9.65	9.40	9.67	143.82	309.02	159.04	611.88	"
	12	11.29	11.03	11.28	168.51	355.26	184.42	708.19	"
	15	12.73	12.45	12.70	190.81	402.39	207.23	800.43	"
Nat. gas	\$1/MCF	1.11	1.02	1.28	22.58	46.50	26.21	95.29	1973
	2	1.96	1.87	2.12	34.81	73.84	39.51	148.16	Future
	3	2.62	2.51	2.77	44.19	93.97	49.86	188.02	"
	4	3.17	3.06	3.31	52.11	110.93	58.12	221.16	"
	5	3.66	3.53	3.79	59.03	125.86	65.67	250.56	Future

Table 4.8 Return on Investment (r) Per Heating Season at Various Energy Costs and Insulation Thicknesses

Energy Source: Fuel Oil

Construction: Walls

Insulation Thickness (inches)	Fuel Oil Cost				
	20 cents/gallon	40 ¢/g	60 ¢/g	80 ¢/g	100 ¢/g
	(r)	(r)	(r)	(r)	(r)
0	0	0	0	0	0
1	14.75	29.5	44.25	59	73.75
2	18.96	37.92	56.88	75.84	94.80
3	21.06	42.12	63.18	84.24	105.30
4	22.75	45.50	68.25	91.00	113.75
5	23.70	47.40	71.10	94.80	118.50
6	24.43	48.86	73.29	97.72	122.15

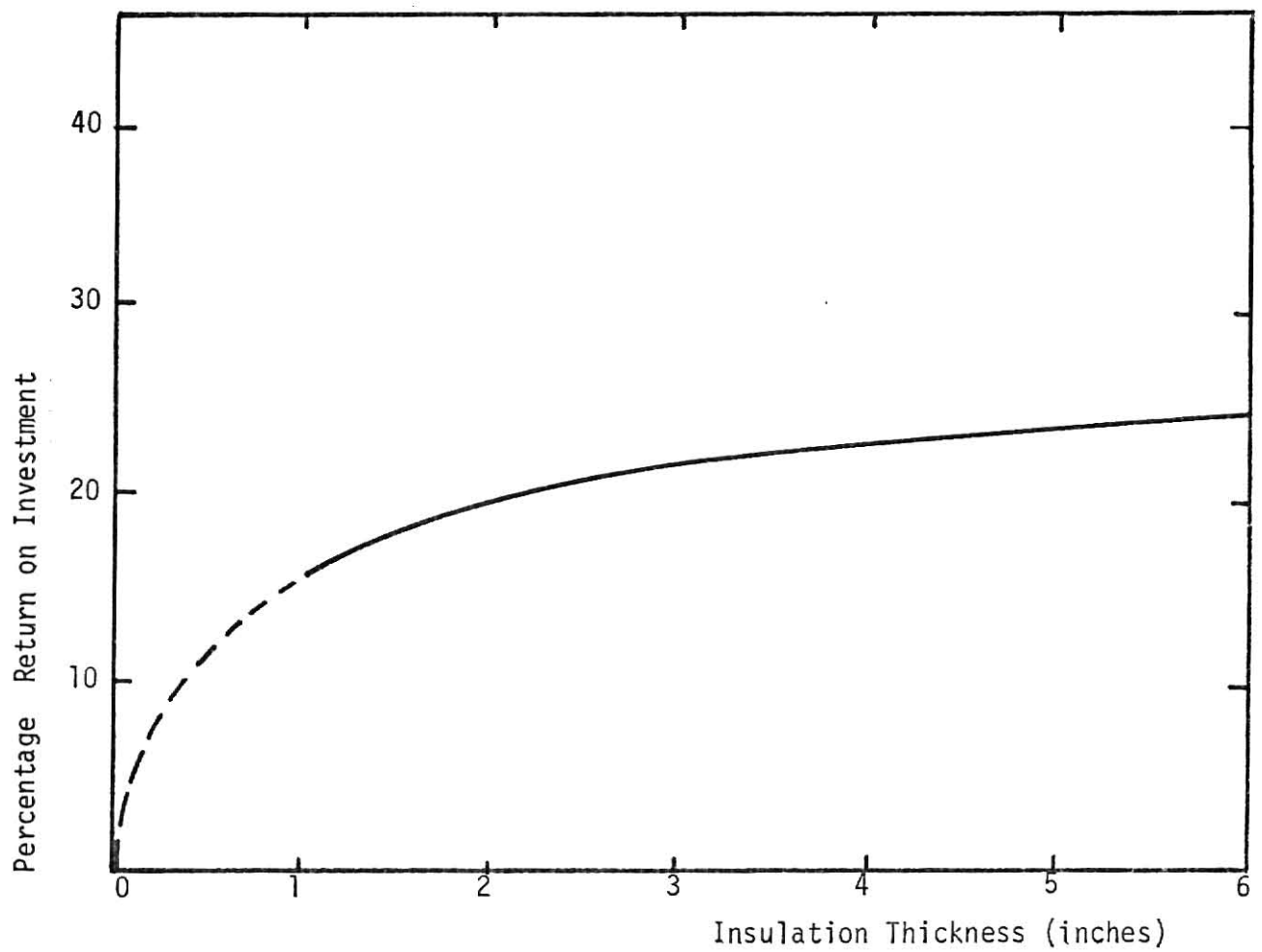


Fig. 4.4 Return on Investment Per Season at Various Insulation
Thicknesses

Energy Source: Fuel Oil at 20 cents/gallon

Construction: Walls

Table 4.9 Seasonal Heating and Insulation Costs at Various Insulation Thicknesses

Energy Source: Fuel Oil at 20 cents/gallon

Construction: Walls

Insulation Thickness (inches)	"U" Btu/(hr sq ft F)	Heating* costs (\$)	Annual** Insulation costs (\$)	Annual total costs (\$)
0	0.27	88.60	0	88.60
1	0.13	42.66	15.58	58.24
2	0.09	29.53	31.16	60.69
3	0.07	22.97	46.74	69.71
4	0.054	17.72	62.32	80.04
5	0.045	14.77	77.90	92.67
6	0.038	12.47	93.48	105.95

$$\begin{aligned}
 \text{* Annual Heating Costs} &= \frac{A J N (t_i - t_{o,av.}) U_i}{1,000,000} \\
 &= \frac{1558 \times 1.38 \times 5088 \times 30 \times 0.27}{1,000,000} \\
 &= 88.60 \text{ Dollars}
 \end{aligned}$$

$$\begin{aligned}
 \text{** Annual Insulation cost} &= A \times P \times i \\
 &= 1558 \times \frac{20}{100} \times \frac{5}{100} \\
 &= 15.58 \text{ Dollars}
 \end{aligned}$$

where P = Insulation cost = 20 cents/(sq ft inch thickness).

i = Annual fixed charges.

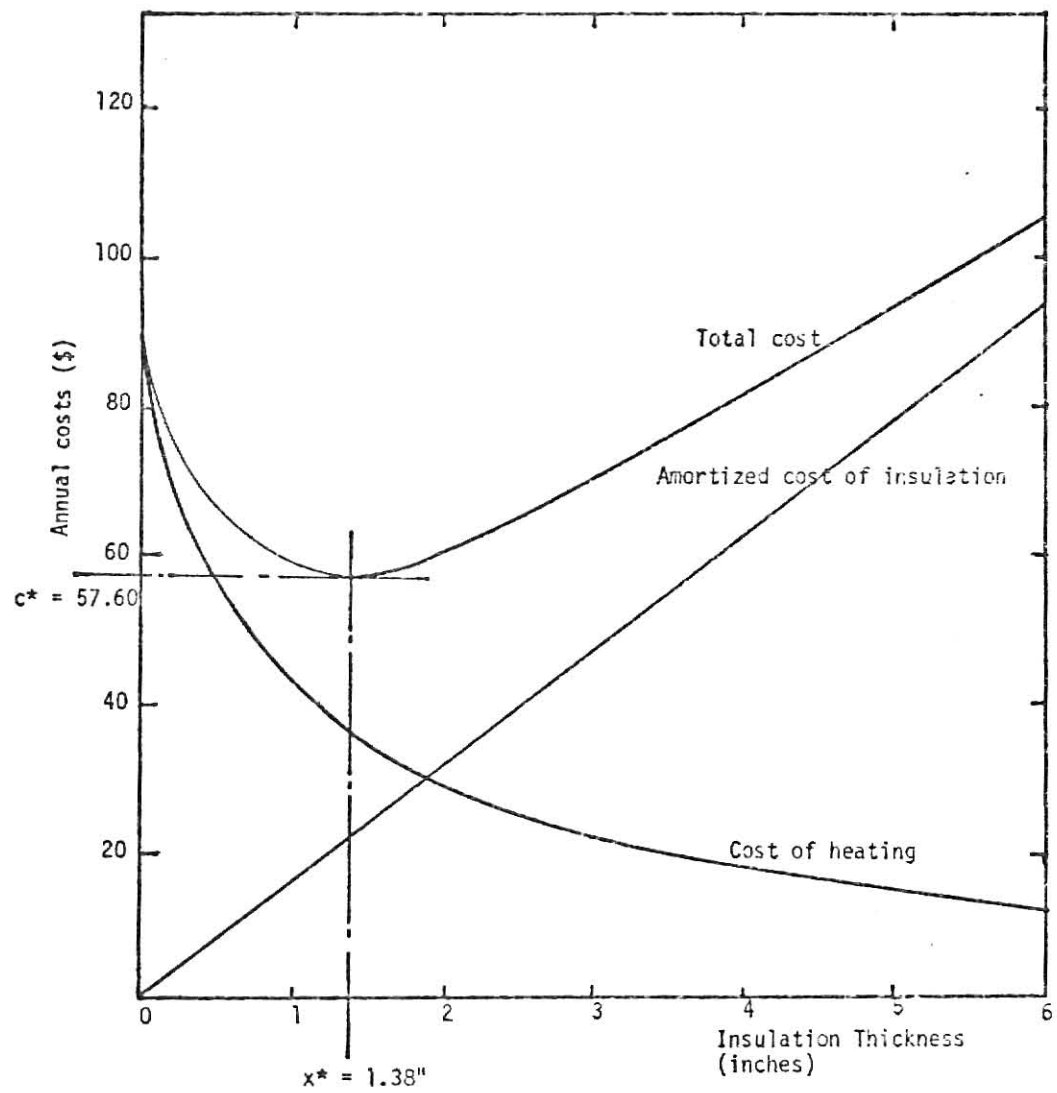


Fig. 4.5 Optimum Thickness of Insulation
Energy Source: Fuel Oil at 20 cents/gallon
Construction: Walls.

Table 4.10 Optimum Thickness of Insulation, and Optimum Annual Costs of Heating and Insulation at Various Energy Costs

Energy Source: Fuel Oil

Construction: Walls

Fuel oil price cents/gallon	Optimum Insulation Thickness (inches)	Optimum Heating Costs (\$)	Optimum 'U' Btu/(hr sq ft F)
20	1.38	57.60	0.110
40	2.37	89.59	0.0801
60	3.13	113.15	0.0654
80	3.77	133.03	0.0566
100	4.33	150.65	0.0507

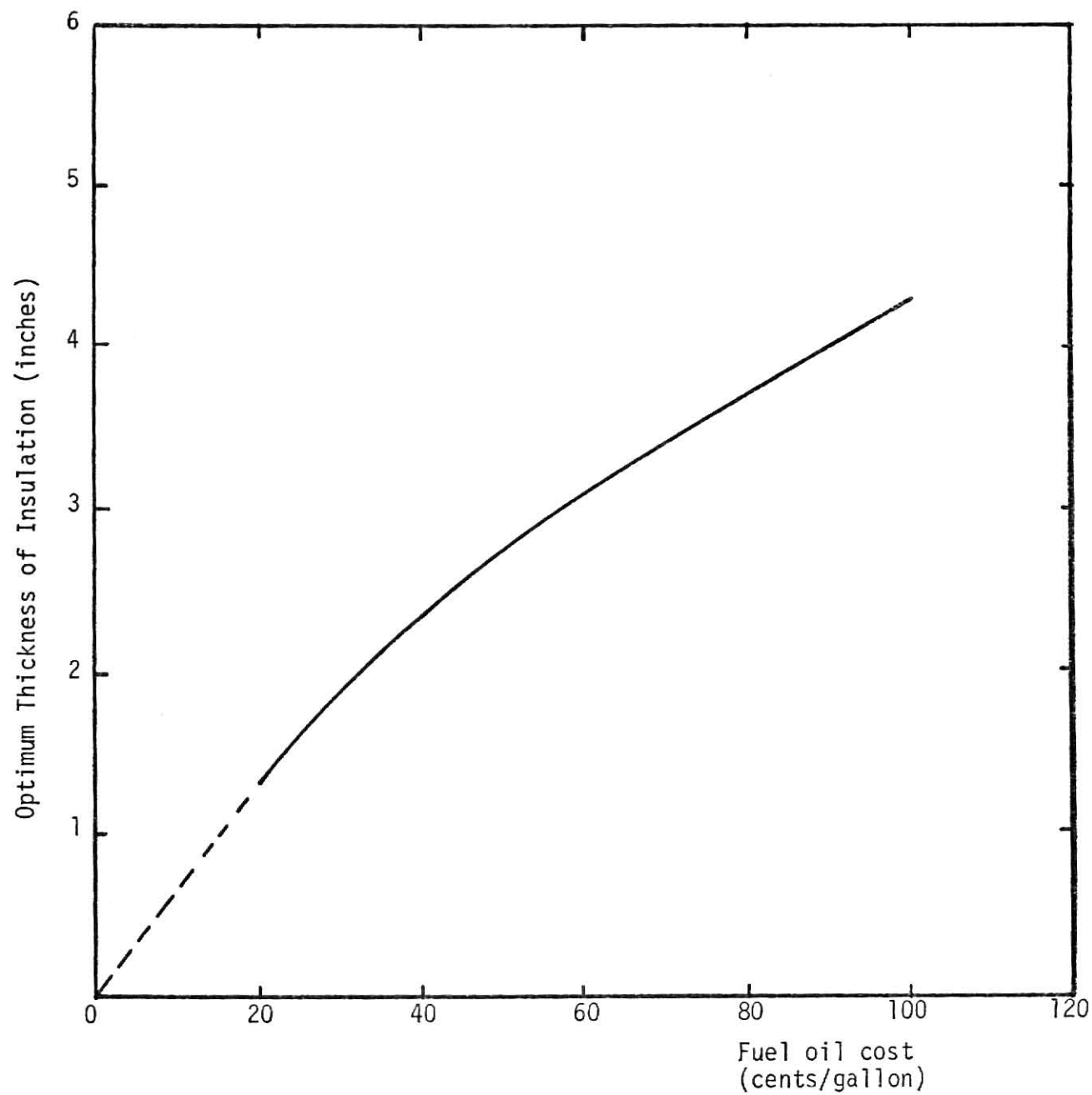


Fig. 4.6 Optimum Thickness of Insulation at Various Fuel Costs
Energy Source: Fuel Oil
Construction: Walls.

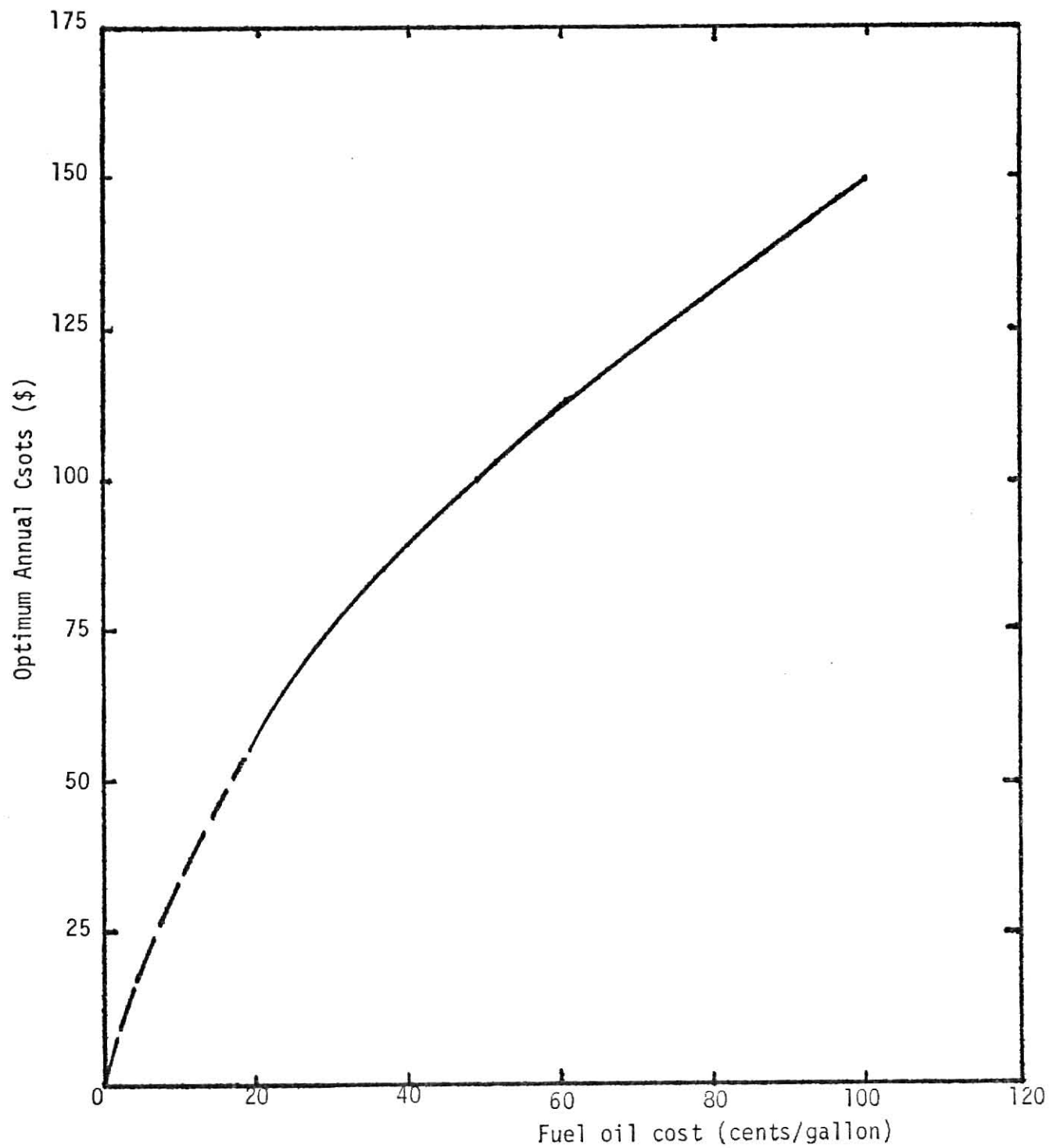


Fig. 4.7 Optimum Annual Total Costs of Heating and Insulation at Various
Energy Fuel Costs

Energy Source: Fuel Oil

Construction: Wall.

4.2 Calculation of Collector Efficiency at Manhattan, Kansas

Consider the two-story model house located in Manhattan, Kansas, at 39° latitude (North). The collector at this house is facing south and tilted 50° from the horizontal, it has two glass covers of the ordinary float type with a refractive index of 1.52, iron oxide content of 0.10 to 0.13 % and beam light transmittance τ of 92 % [55]. The glass thickness is 0.125 inches and has a diffuse radiation transmittance τ' of 0.84 for one surface, 0.76 for two surfaces. The flat plate absorber is copper, black painted with Nextel to give it an absorptance to direct solar radiation (α) of 0.96 and to diffuse radiation (α') of 0.90 [38]. The insulation under the blackened absorber plate consists of 1 inch air gap, 4 inches of glass wool, and 1.5 inches of mineral wool. The insolation in January 1st for example is 159.5 langley/day, wind speed, cloud cover, and average ambient outside temperature are 15 M.P.H., zero, and 25 F [56]. The collector temperature is assumed to be 125 F, (usually 90-160 F) [27]

Solution: -

1. Calculation of the energy absorbed by the collector q_A

$$q_A = (H_S - H_D) R_{\tau} \alpha + H_D \tau' \alpha' \quad (3.2)$$

where H_S , the total solar energy flux density on a horizontal surface is equal to 159.5 Langley/day in January 1st.

$$H_S = 159.5 \times 3.685 \times \frac{1}{8} = 73.70 \text{ Btu/(sq ft hr)}$$

and the diffuse radiation flux density

$$H_D = 0.78 + 1.07 a + 6.17 cc \quad (3.3)$$

where a is the solar altitude angle in degrees, and cc is the cloud cover.

The solar altitude angle a is equal to $(90 - \theta_Z)$, where θ_Z is the angle of incidence of direct sunlight on a horizontal surface

$$\cos \theta_Z = \sin \delta \sin \phi + \cos \delta \cos \phi \cos \omega \quad (17)$$

where δ , ω , and ϕ are the solar declination, hour angle at solar noon, and latitude angle.

$$\delta = 23.45 \sin \left[\left(\frac{360}{365} \right) \cdot (284+n) \right] \quad (18)$$

$$= -23 \text{ degrees}$$

where n is the number of the day in the year when January 1st is considered equal to 1

$$\begin{aligned} \cos \theta_Z &= \sin(-23)\sin(39) + \cos(-23)\cos(39)\cos(0) \\ &= 0.46 \end{aligned}$$

or

$$\begin{aligned} \theta_Z &= 62.61^\circ \\ a &= (90 - \theta_Z) = 27.39^\circ \end{aligned}$$

and $H_D = 30.38 \text{ Btu/(sq ft hr)}$

Now $R = \frac{\cos \theta_T}{\cos \theta_Z}$

where θ_T is the angle of incidence of direct sunlight on a tilted surface

$$\cos \theta_T = \cos(\phi-S) \cos \delta \cos \omega + \sin(\phi-S) \sin \delta \quad (19)$$

and S is the angle of collector tilt from horizontal

$$\cos \theta_T = 0.97 \text{ or } \theta_T = 14.07^\circ$$

$$R = \frac{\cos 14.07}{\cos 62.61} = 2.11$$

$$\begin{aligned}
 q_A &= (73.70 - 30.38) \times 2.11 \times 0.92 \times 0.96 + 30.38 \times 0.76 \times 0.90 \\
 &= 101.46 \text{ Btu/(sq ft hr)}
 \end{aligned}$$

2. Calculation of heat losses from plate through glass covers

$$q_L = \frac{T - T_0}{\frac{n}{c \left(\frac{T - T_0}{n + f} \right)^{1/4}} + \frac{1}{h_w}} + \frac{\sigma(T^4 - T_0^4)}{\frac{1}{\epsilon_c} + \frac{2n + f - 1}{\epsilon_G} - n} \quad (3.5)$$

where T and T_0 are the temperature of the collector plate and outside average ambient temperature in Rankine; $(460 + 125)$ and $(460 + 25)$, n is the number of glass covers (assumed 2), c is a factor to account for collector tilt [24]

$$c = 0.19 - 0.00078(S) \quad (3.6)$$

where (S) is the collector tilt angle from horizontal

$$c = 0.19 - 0.00078(50)$$

or

$$= 0.151$$

f is the ratio of thermal resistance of the outer glass cover to that of an average inner cover

$$f = 0.36 \times 10^{-0.02(V-8)} \quad (3.7)$$

where V is the speed of wind

$$= 0.36 \times 10^{-0.02(13-8)}$$

$$= 0.6037$$

h_w is the wind convection coefficient

$$h_w = 1.0 + 0.35 V \quad (3.8)$$

$$= 5.55 \text{ Btu/(sq ft hr F)}$$

ϵ_c and ϵ_G are the emissivity of collector plate and glass cover respectively, where $\epsilon_c = 0.90$ for non selective surfaces and 0.20 for selective black surfaces, and $\epsilon_G = 0.90$

$$q_L = \frac{\frac{(585-485)}{2}}{0.151 \left[\frac{(585-485)}{2+0.6037} \right]^{1/4} + \frac{1}{5.55}} + \frac{0.1713 \times 10^{-8} (585^4 - 485^4)}{\frac{1}{0.90} + \frac{2 \times 2 + 0.6037 - 1}{0.9} - 2}$$

$$= 50.00 \text{ Btu/(sq ft hr)}$$

3. Calculation of heat losses through insulation

$$q_B = U \times (T - T_0) \quad (3.9)$$

where U is the overall heat transmission coefficient of insulation and collector frame

$$U = \frac{1}{\left[\frac{1}{1.65} + \frac{1}{1.1} + \frac{4}{0.25} + \frac{1.5}{0.25} + \frac{1}{1.65} \right]}$$

$$= 0.0414 \text{ Btu/(sq ft hr F)}$$

and where T and T_0 are the temperature of the collector plate (125F), and the outside temperature (which is in our case, the temperature of the attic or 46 F)

$$q_B = 0.0414 \times (125 - 46)$$

$$= 3.27 \text{ Btu/(sq ft hr)}$$

4. Calculation of total useful heat

$$q_u = q_A - q_L - q_B \quad (3.1)$$

$$= 101.46 - 50 - 3.27$$

$$= 48.19 \text{ Btu/(sq ft hr)}$$

5. Calculation of total incident heat (beam and diffuse components), q_I

$$\begin{aligned} q_I &= (H_S - H_D)R + H_D \\ &= (73.70 - 30.38) \times 2.11 + 30.38 \\ &= 121.79 \text{ Btu/(sq ft hr)} \end{aligned}$$

6. Calculation of the efficiency

$$\eta = \frac{q_u}{q_I} = \frac{48.19}{121.79} = 0.3957$$

or

$$= 40\%$$

7. The effects of using selective black as absorber

If selective black with ϵ_c of 0.20 is used

q_L will be equal to 32.33 Btu/(sq ft hr)

q_u will be equal to 65.86 Btu/(sq ft hr)

$$\eta = \frac{65.86}{121.79} = 54\%.$$

4.3 Size of Solar Collector and Storage

The size of the flat plate solar heat collector depends upon the efficiency of heat collection, the outside design temperature, the amount of building heat losses, and capital costs. Table 4.11 shows the percentage of heat collected to heat required and Fig. 4.8 shows the daily heat needed and heat collected for the two-story model house in Kansas. The house is at an outside temperature of -10F, and with 4 inches of insulation as per FHA requirements and in accordance with table 4.3. The collector efficiency is assumed to be 40% in accordance with calculations in section 4.2. From Fig. 4.8, it is seen that collector (1)

Table 4.11 Percentage of Solar Heat Collected to Space Heat Losses for
Two-Story Model House

($T_0 = -10^\circ\text{F}$, 4 inch insulation)

Month	Collector No. 1	Collector No. 2
	(50 % of Floor Area)	(25 % of Floor Area)
	%	%
Jan.	102	51
Feb.	177	88
Mar.	319	159
Ap.	778	389
May		
June		
July		
Aug.		
Sept.		
Oct.	698	349
Nov.	183	91
Dec.	106	53

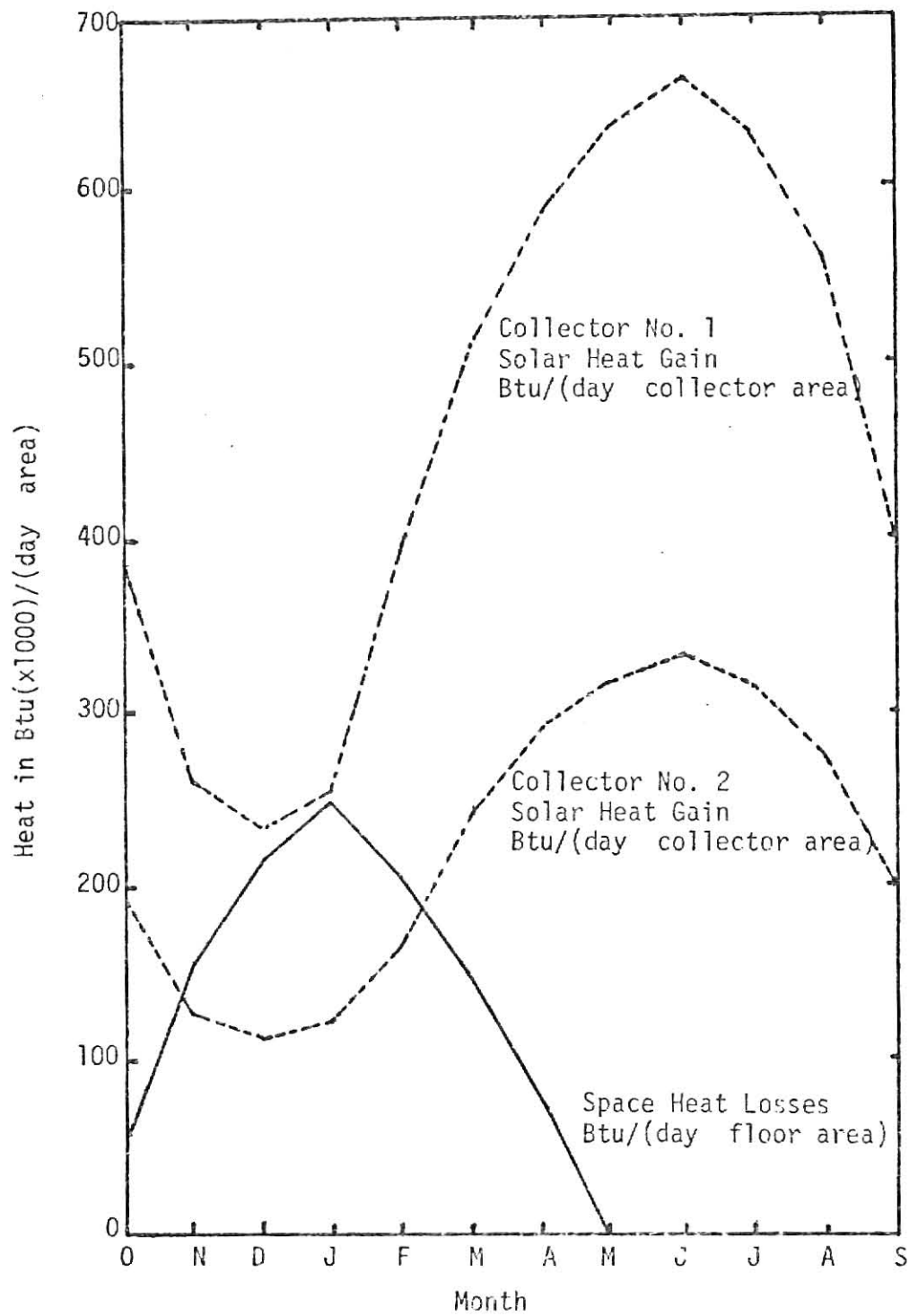


Fig. 4.8 Daily Heat Losses and Solar Heat Collected at Kansas Two-Story Model House ($T_0 = -10^\circ\text{F}$, 4" insulation)

with an area equal to half the floor area to be heated is more than sufficient to meet heating requirements. Collector (2) with an area equal to 25% of floor area to be heated will furnish half the heating load in December and January, ninety percent of the heating load in November and February and all the heating load in March, April and October.

The size of heat storage volume depends upon the characteristics of storage medium, space availability, costs, and efficiency of utilization of this stored energy. A storage of 1,000,000 Btu in water requires a volume of 267 cu ft or a cylindrical tank 6 feet in diameter and 10 feet in length since the water has specific heat of 1 Btu/(lb F), density of 62.4 lb/cu ft, heat capacity of 62.4 Btu/(cu ft F), and where hot water is stored at 150 F and utilized at a temperature of 90 F.

$$1,000,000 = 62.4 (150-90) \cdot V$$

$$V = 267.09 \text{ Cu.Ft.}$$

This volume can hold $267 \times 62.4 = 16723.20$ lbs of water or $\frac{16723.20}{8.34} = 2000$ gallons of water. If hot water is stored at 125 F, then we need 3500 gallons of water. This stored energy represents a two-days heat supply for the two-story model house ($T_o = -10\text{F}$, 4 inch insulation).

Table 3.1, gives the properties of various storage materials, water has the highest heat capacity, it is available and simple to heat. Its disadvantages are space, weight and cost of storage tank. If space in the basement does not constitute an opportunity loss, and if fiber glass tank is used, then the capital cost of storage will be decreased.

Storage for cooling in the summer requires a larger tank than that specified for heating for the same amount of Btu's. If water is used for

cooling at 65 F, and we want the water to remain in the liquid state, then we have only 65-32 or 33 F for our cooling utilization, and thus we require a volume of 486 cu ft

$$1,000,000 = 62.4 (65-32) \cdot V$$

$$V = 486 \text{ cu ft}$$

or a cylindrical tank 6 feet in diameter and 17 feet in length. This is a tank nearly two times as large as the tank required for heat storage in the winter. Space, weight, and initial capital cost are important factors in designing cooling storage.

4.4 Cost Analysis

The savings or net reduction in heating bill per year due to the utilization of solar energy at a collector area of 25% of floor area is given in Tables 4.12 - 4.14. The energy sources costs are those of 1973 [12]. The realization of an accurate calculations of capital cost for the solar system, that includes the collector with its frames, insulation, glass, copper absorber and supporting frames, together with the cost of storage tank, footing, water, antifreeze, pumps, motors, piping, heat exchanger, and control system and also the interest rate, is not impossible when the manufacturing of these items is standardized. Lof and Tybout [38] made a world-wide survey of solar equipment designers by mail questionnaire in 1961-62. On the basis of that survey, capital costs for noncollector components were derived and are as follows in 1961-62 dollar index:

Storage cost = $\$0.05K$ where K = storage amount in lb/ft^2
times the collector area in ft^2

Table 4.12 Two-Story Model House Heating Requirement Costs Per Various
Energy Sources

Month	Heating Requirement (MBTU/month)	Energy Sources*		
		Fuel Oil (\$/month)	Natural Gas (\$/m)	Electricity (\$/m)
Jan.	7.73	10.67	7.73	67.87
Feb.	5.59	7.71	5.59	49.08
Mar.	4.64	6.40	4.64	40.74
April	2.05	2.83	2.05	18.00
May				
June				
July				
Aug.				
Sept.				
Oct.	1.74	2.40	1.74	15.28
Nov.	4.30	5.93	4.30	37.75
Dec.	6.77	9.34	6.77	59.44
Total cost/year		45.28	32.83	288.16

*Energy Sources Costs at 1973 index [12].

Fuel Oil at 20 cents/Gallon; $1.380 \$ / 10^6$ Btu

Natural Gas at 1 \$/MCF ; $1 \$ / 10^6$ Btu

Electricity at 3 cents/Kwh ; $8.78 \$ / 10^6$ Btu

Table 4.13 Two-Story Model House Heating Requirements, Solar Heat
Collected and Deficit Costs

Month	Heating Requirements (MBTU/month)	Solar Heat Collected by Collector (2) (MBTU/m)*	Deficit MBTU/m	Deficit Cost		
				Fuel Oil (\$/m)	Nat. Gas (\$/m)	Elect. (\$/m)
Jan.	7.73	3.96	-3.76	5.19	3.76	33.01
Feb.	5.59	4.94	-0.64	0.88	0.64	5.62
Mar.	4.64	7.38				
April	2.05	7.94				
May						
June						
July						
Aug.						
Sept.						
Oct.	1.74	6.07				
Nov.	4.30	3.93	-0.36	0.50	0.36	3.16
Dec.	6.77	3.58	-3.18	4.39	3.18	27.92
Total cost/year				10.96	7.94	69.71

* Chapter 3

Table 4.14 Net Reduction in Heating Bill Due to Solar Heat Utilization
with Deficit Compensation by Various Energy Sources

Energy Source	Fuel Oil	Nat. Gas	Electricity
Gross Reduction in Heating Bill/year (\$/year)	45.28	32.83	288.16
Deficit Cost/year (\$/year)	-10.96	-7.94	-69.71
Net Reduction in Heating Bill (\$/year)	34.32	24.89	218.45

Controls = \$150.00 regardless of system size.

Pipes, Fittings ... etc = \$100.00 + 0.10 x (collector area in ft²)

Motors, pumps = \$ 50.00 + 0.20 x (collector area in ft²)

Heat exchangers = \$ 75.00 + 0.15 x (collector area in ft²)

The price of the collector per sq ft ranged from \$5.95 to \$8.90 for a combined total production of 1620 to 4000 units. The collectors mentioned here are of the water heating type, since in 1961 a robust construction of large collectors for space heating was not available. All in all, it can be said that the solar system costs for space heating fall in the neighbourhood of 12 dollars per sq ft of collector area including installation.

In this study four criteria of costs will be investigated; the complete solar system will be assumed to cost \$12, 8, 6, 4 per sq ft of collector area, or at an average net cost of \$8, 4, 2, 1 per sq ft of collector alone.

The two-story model house together with the solar system are expected to have a lifetime of 25 years, discount rate is 5%, collector area is 380 sq ft, the index year is 1973, and the inflation rate is 10% per year. The gradient-series factor method will be used to analyze and compare the present worth value of net savings in heating bill, the present worth value of capital costs, and capital recovery period. The costs of energy sources for 1973 index are as given in Table 4.12.

Sample calculation: Energy source = Fuel oil

Cost = 20 ¢/gallon; 1.380 \$/10⁶ Btu

Solar Energy contribution = \$45.28/year

Deficit = \$10.96/year

Net savings = \$34.32/year

Net savings increase/year due to 10% inflation
in fuel oil price = \$3.43/year

Solar system capital cost = $8 \times 380 = 3040$ dollars.

Now the equivalent uniform net savings per year for a period
of 25 years if the interest rate is 5% per year compounded
annually is [69]

$$A = A_1 + \left[\frac{g}{i} - \frac{ng}{i} \left(\frac{i}{(1+i)^n - 1} \right) \right] \quad (20)$$

$$= A_1 + g(A/G, i, n) \quad (21)$$

where $A_1 = 34.32$

$$g = 3.43$$

$$i = 5\%$$

$$n = 25$$

$(A/G, i, n)$ = the gradient factor for annual compounding interest.

$$A = 34.32 + 3.43 (9.5238)$$

$$= 67 \$ \text{ per year for 25 years.}$$

The present-worth value of this equal-payment series of \$67 for 25
years is

$$P = A \left(\frac{(1+i)^n - 1}{i(1+i)^n} \right) \quad (22)$$

$$= A(P/A, i, n) \quad (23)$$

$$= 67 (14.0940)$$

$$= \$944.29$$

$$\text{Benefit to cost ratio} = \frac{944.29}{3040} = 0.31$$

$0.31 < 1$, so reject the investment.

Tables 4.15 through 4.18 and Fig. 4.9 show the benefit to cost ratio matrix of the solar system for various energy sources at present and projected future costs. For example, Table 4.15 shows that if the energy source available is fuel oil at 20 cents/gallon, then the investment in a solar system is not recommended even though the solar system cost drops to \$4/(sq ft of collector area).

Table 4.16 shows that if fuel oil price is increased 100% (40 cents/gallon), and the solar system cost drops to \$4/(sq ft), then the investment in solar system will be selected.

Table 4.17 shows that if natural gas is available then capital investment in solar system will not be realistic unless the cost of natural gas is increased three folds with respect to 1973 index, and the solar system cost is about \$4/(sq ft of collector area).

Table 4.18 shows that if electricity is the energy source, then capital investment in solar system is realistic at the present time.

Fig. 4.9 shows that capital investment in the solar system is recommended only if the price of fuel oil or natural gas is increased threefolds and the solar system cost is decreased to about \$5/(sq ft of collector area). If electricity is the energy source used, then the investment in solar system is recommended.

Table 4.15 Cost Analysis of Investment in Solar Systems if Fuel Oil is Available at 20 cents/Gallon.*

Index Year	Solar System Cost (\$/sq ft)	Net Savings/year Due to Solar System (\$/year)	Equivalent Uniform Net Savings (\$/year)	Present Worth Value of Net Savings (\$)	Capital Investment (\$)	Benefit Cost Ratio	Comment
1968	12	34.32	67	944	4560	0.21	Reject
1975	8	34.32	67	944	3040	0.31	Reject
Near Future	6	34.32	67	944	2280	0.41	Reject
Far Future	4	34.32	67	944	1520	0.62	Reject

*Where $i = 5\%$ $n = 25$ years

Table 4.16 Benefit Cost Ratio Matrix at Different Fuel Oil Costs and
Different Solar System Costs

Solar System Cost \$/ (sq ft)	Fuel oil cost (¢/G)				
	20	40	60	80	100
12	0.21	0.42	0.63	0.84	1.05*
8	0.31	0.62	0.932	1.24*	1.55*
6	0.41	0.82	1.23*	1.64*	2.05*
4	0.62	1.24*	1.8638*	2.48*	3.10*

* = Accept Capital Investment in Solar System

Table 4.17 Benefit Cost Ratio Matrix at Different Natural Gas Costs
and Different Solar System Costs

Solar System Cost \$/ (sq ft)	Natural Gas Cost (\$/MFC)				
	1	2	3	4	5
12	0.15	0.30	0.45	0.60	0.75
8	0.23	0.45	0.69	0.90	1.15*
6	0.30	0.60	0.90	1.20*	1.50*
4	0.45	0.90	1.35*	1.80*	2.25*

* = Accept Capital Investment in Solar System

Table 4.18 Benefit Cost Ratio Matrix at Different Electrical Energy
Costs and Different Solar System Costs

Solar System Cost \$/ (sq ft)	Electrical Energy Cost (¢/Kwh)				
	3	6	9	12	15
12	1.32*	2.64*	3.96*	5.28*	6.6*
8	1.98*	3.96*	5.94*	7.92*	9.9*
6	2.65*	5.31*	7.97*	10.63*	13.29*
4	3.98*	7.97*	11.90*	15.95*	19.93*

* = Accept Capital Investment in Solar System

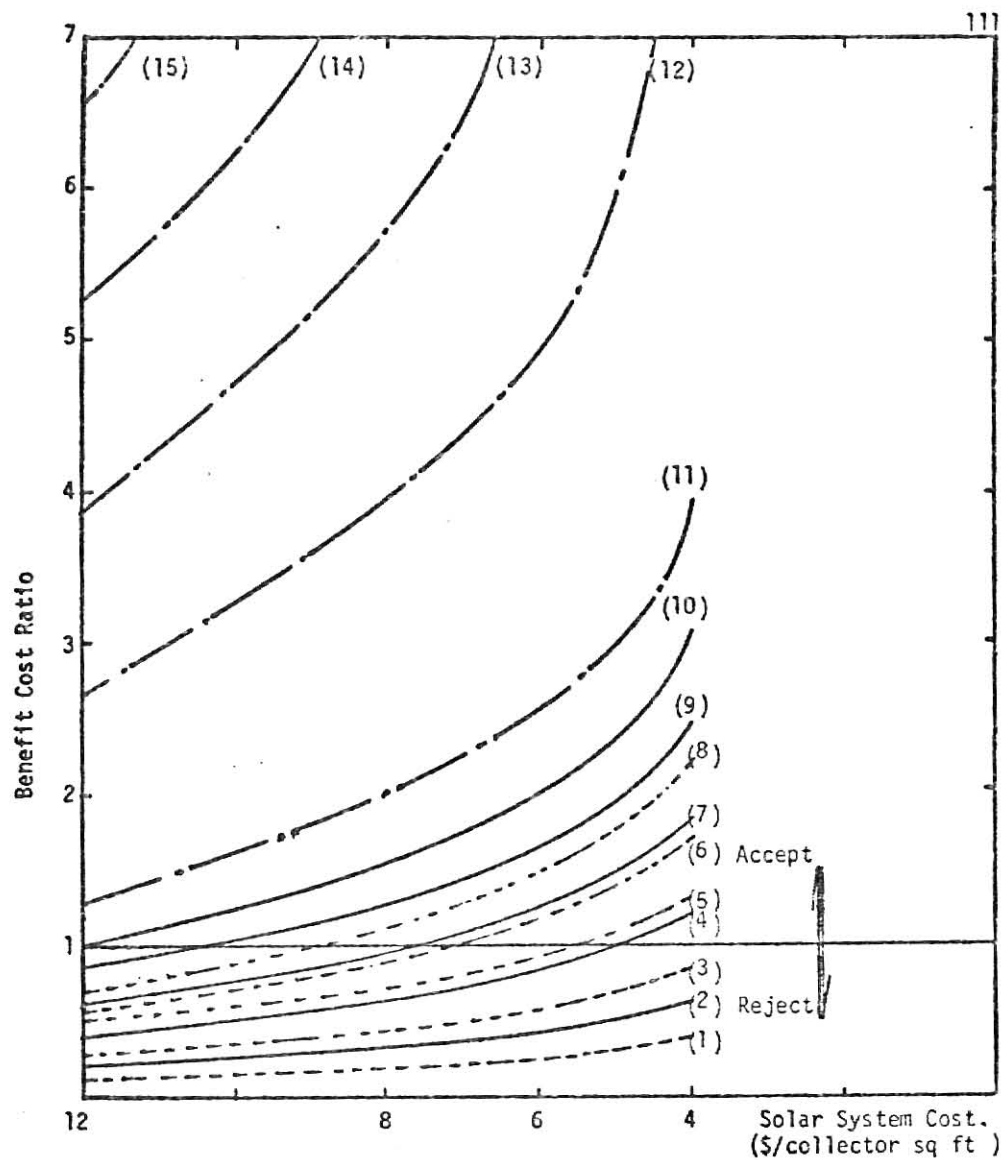


Fig. 4.9 Benefit Cost Ratio for Various Energy Sources at Various Prices

(1),(3),(5),(6),(8) = Natural gas at \$1,2,3,4,5/MCF,
 (2),(4),(7),(9),(10) = Fuel oil at 20,40,60,80,100 cents/Gallon
 (11),(12),(13),(14), = Electricity at 3,6,9,12,15 cents/KWH.
 (15)

4.5 Solar Cooling

The process by which the sun's energy is used indirectly to produce cooling is known as absorption refrigeration (Appendix B) [3]. Temperatures in the 200 F range for the lithium bromide - water vapor system, and 175 F for the ammonia-water system are not easy to obtain with present solar collectors even if two glass covers and a selective surface are used. Special type solar collectors may be required at present if cooling efficiencies of 0.4 or more are anticipated.

Since installation of two separate solar collectors with auxiliaries for winter and summer operation constitutes a high capital cost, and since the technology for incorporating one solar collector for both heating and cooling is not yet commercially or economically mature, a preliminary study will be investigated here in accordance with the following assumptions:

1. The collector used for winter heating will be assumed capable of summer cooling but at an efficiency of 20% instead of 40% [74].
2. Solar cooling will incur an additional capital cost of \$2000 for heat pump modifications, or auxiliaries [75].
3. Average cooling utilization is 12 hours/day.
4. The extra capital cost of \$2000 due to solar cooling will be incorporated in the price of the collector as given here:

Area of collector = 380 sq ft

Extra capital cost = \$2000

or

Capital cost/(sq ft) of collector is about \$6

So, for our analysis, this value will be added to the initial cost values of the collector which now become \$18,14,12,10 instead of \$12,8,6,4.

4.5.1 Cooling Load Calculations

Given the two-story model house situated in Manhattan, Kansas, at an elevation of 1140 feet above sea level [56], and in accordance with the following conditions [1,14]

Outside design dry-bulb temperature	= 95 F
Outside design wet-bulb temperature	= 78 F
Outside average relative humidity	= 47
Inside design dry-bulb temperature	= 78 F
Inside design wet-bulb temperature	= 65 F
Inside relative humidity	= 50
House length	= 38 ft.
House width	= 24 ft.
House volume (air conditioned)	= 15298 ft ³
South wall area	= 546 ft ²
North wall area	= 546 ft ²
East wall area	= 336 ft ²
West wall area	= 324 ft ²
South glass area	= 60 ft ²
North glass area	= 60 ft ²
East glass area	= 60 ft ²
West glass area	= 30 ft ²
South door area	= 21 ft ²
North door area	= 21 ft ²
West door area	= 42 ft ²

Table 4.19 shows the calculations of the total cooling load for the two-story model house. The maximum cooling load occurs at 3:00 pm or at the time of maximum heat gain through the roof [2]. For medium construction roofs exposed to the sun the design temperature differential is 53 F. All calculations were carried in accordance with ASHRAE recommendations [1]. Table 4.20 shows a typical hourly cooling load calculations in the month of August.

Table 4.21 shows that the solar energy collected by collector (2) is adequate for supplying the required cooling load.

Table 4.22 shows that \$105 will be saved per year due to utilization of solar energy for cooling at 1973 energy price index.

Table 4.23 shows that between \$139 and \$323 will be saved per year due to utilization of solar energy for heating and cooling purposes.

Table 4.24 and Fig. 4.10 show that if heating and cooling is supplied by electrical energy at 1973 price index, then capital investment in solar system is highly recommended. If fuel oil supplies the heating load while electrical energy supplies the cooling load at 1973 price index then investment in solar system should wait till costs of solar system approaches \$10 per sq ft.

However, if projected future cost of energy sources is double that of 1973 price index then investment in solar system is recommended even at a cost of \$18 per sq ft of solar collector.

All in all, a comparison of Fig. 4.9, and Fig. 4.10 shows that it is more economical to design the solar system for both heating and cooling. It also shows that if energy sources remain at their 1973 price index, then more incentives will be required for solar energy utilization.

Table 4.19 Two-Story Model House Cooling Load Calculations

Sensible Load Transmission	Btu/hr
1. Roof 912 sq ft x 53 F x 0.035	1691.76
2. S. Wall 546 sq ft x 25 F x 0.054	737.10
3. N. Wall 546 sq ft x 8 F x 0.054	235.87
4. E. Wall 336 sq ft x 13 F x 0.054	235.87
5. W. Wall 324 sq ft x 18 F x 0.054	314.93
6. Floor 912 sq ft x 10 F x 0.0546	497.95
7. S. Door 21 sq ft x 25 F x 0.380	199.50
8. N. Door 21 sq ft x 8 F x 0.380	63.84
9. W. Door 42 sq ft x 18 F x 0.380	287.28
10. N. Glass 60 sq ft x 8 F x 0.450	216.00
11. E. Glass 60 sq ft x 13 F x 0.460	351.00
Solar Radiation	
12. S. Glass 60 sq ft x 12.4 Btu/(sq ft hr)	744.00
13. W. Glass 30 sq ft x 13.6 Btu/(sq ft hr)	408.00
Internal Load	
14. Ventilation	3998.61
15. People 4 x 200 (sensible)	800.00
16. People 4 x 250 (latent)	1000.00
17. Lights and equipment	3413.00
18. Total	15188

Table 4.20 Two Story Model House Typical Hourly Cooling Load in August.*

	8	Time (A.M.)			2	4	6	Time (P.M.)		
		10	12					8	10	12
1. Roof	0	638	1276		1659	1723	1340	638	319	191
2. S. Wall	-117	-59	354		707	766	590	354	236	118
3. N. Wall	-117	-59	0		178	295	354	354	236	118
4. E. Wall	36	544	562		254	217	254	217	180	108
5. W. Wall	0	0	70		170	455	700	734	280	105
6. Floor	-200	0	300		600	700	600	400	100	0
7. S. Door	-32	-16	96		192	208	160	96	64	32
8. N. Door	-32	-16	0		48	80	96	96	64	32
9. W. Door	0	0	64		160	416	640	672	256	96
10. N. Glass	-103	-54	0		162	270	324	324	216	108
11. E. Glass	54	810	837		378	324	378	324	216	162
Solar Radiation										
12. S. Glass	60	264	618		744	636	474	222	0	0
13. W. Glass	-51	63	240		414	432	342	108	0	0
Internal Load										
14. Ventilation	0	0	2000		3998	2000	0	0	0	0
15. People	0	0	800		800	800	0	0	0	0
16. People	0	0	1000		1000	1000	0	0	0	0
17. Lights & Equip.	0	0	3413		3413	3413	3413	0	0	0
18. Total in Btu/hr	-507	2115	11630		14877	13735	9667	4539	2167	1070

* Grand total cooling load in 9 hours = 59293 Btu

Average cooling load per hour = 6588 Btu

12-Hour day cooling load = 79057 Btu

Table 4.21 Two-Story Model House Daily Cooling Load Versus Solar Heat Collected by Collector (2), and Equivalent Cooling Capacity

Month	Cooling Load* (Btu/day)	Solar Energy Collected by Collector (2) (Btu/day)	Equivalent Cooling Capacity (20% of Collected Energy) (Btu/day)
May	79,057	806,660	161,332
June	79,057	837,100	167,420
July	79,057	783,830	156,766
Aug.	79,057	702,972	140,594
Sept.	79,057	502,260	100,452

*Cooling load is calculated for the month of August with an outside temperature of 95F. Other months may require less cooling.

Table 4.22 Total Savings Per Cooling Season Due to Solar Energy Utilization

Month	Required Cooling Load/Month (Btu x 10 ⁶)	Available Cooling Capacity (Btu x 10 ⁶)	Savings at (3¢/Kwh), or (\$8.78/10 ⁶ Btu)
May	2.40	5.00	\$21.07
June	2.37	5.02	20.81
July	2.40	4.85	21.07
Aug.	2.40	4.35	21.07
Sept.	2.37	3.01	20.81
Total Savings/Season			\$104.83

Table 4.23 Net Reduction in Heating and Cooling Bill Per Year Due to
Solar Energy Utilization

Energy Source	Fuel oil	Nat. Gas.	Electrical Energy
Net Reduction in Heating Bill (\$/Y)	34.22	24.89	218.45
Net Reduction in Cooling Bill (\$/Y)	(104.83)	(104.83)	104.83
Total Savings (\$/Y)	139	130	323

Table 4.24 Benefit Cost Matrix for Various Energy Sources at Various Prices and Solar System Costs

Solar System Cost \$/(sq ft)	Energy Source				
	Fuel Oil for Heating and Electricity for Cooling		N. Gas for Heating and Electricity for Cooling		Electricity for Heating and Cooling
	1973**	Double***	1973	Double	1973
18	0.56	1.11*	0.52	1.05*	1.30*
14	0.72	1.43*	0.67	1.34*	1.67*
12	0.84	1.67*	0.78	1.57*	1.95*
10	1.01*	2.00*	0.94	1.88*	2.34*

* Accept Solar System

** Energy Sources at 1973 Price Index [12]

*** Energy Sources at Double 1973 Price Index

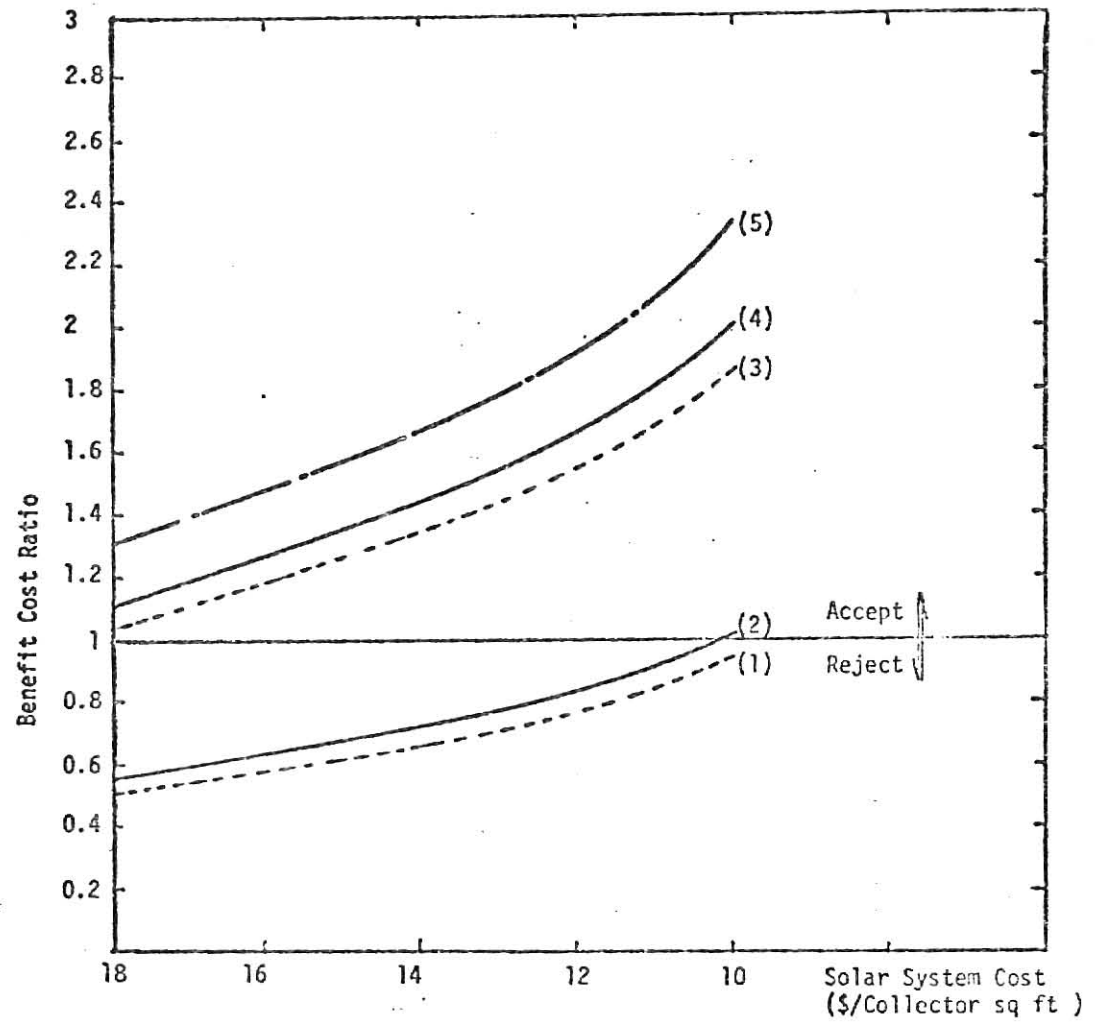


Fig. 4.10 Benefit Cost Ratio for Various Energy Sources and Costs

- (1),(3) = Natural Gas for heating and Elect. for cooling at 1973 index, and its double
- (2),(4) = Fuel Oil for heating and Elect. for cooling at 1973 index, and its double
- (5) = Electrical energy for both heating and cooling at 1973 index.

5. Conclusions

The results of solar heating and cooling of a two-story model house in Kansas demonstrate that solar energy is technically and economically feasible for environmental control. The results show that a typical single family house with a floor area of 1520 ft^2 can be solar heated and cooled adequately, and at the same time provide a net savings of 130 to 323 dollars per year depending on solar energy to substitute natural gas or electricity.

Besides, the results show that solar heating and cooling is more economical than solar heating alone. At the present time, with solar system prices of 10 to 14 dollars per ft^2 of solar collector, and at 1973 index of natural gas and fuel oil prices, the solar system will pay for itself in about 30 years. If electricity is the energy source, then the solar system will pay for itself in about 10 years. Solar energy in the long run will not only save money and conserve energy but it will also provide a pollution free atmosphere, and a better quality of life.

6. Acknowledgement

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Appendix A

Solar Energy

The source of the sun's energy lies deep within its interior. Four million tons of matter are converted into energy every second by the transmutation of hydrogen to helium with subsequent emission of gamma rays. This transmutation involves a multi nuclear motion which is catalyzed by carbon. Only one percent of the hydrogen in the sun is transformed into helium in a billion years [17]. The gamma rays generated in the sun is not what we receive on earth as light. Much of the heat and light of the sun is due to the collision of the material particles involved in the hydrogen-helium cycle. Gamma radiation has the shortest wave length known (of the order of a hundred-millionth of a millimeter). As these gamma radiation stream outward from the centre of the sun, they collide with nuclei and electrons or are scattered in near-collisions. At each event, some of the energy is shared out with the particles struck, and the remaining photons of radiation, having less energy than before, have a longer associated wave length. The radiation leaving the sun and passing out into space is now distributed throughout a wide range of wave lengths with most of the energy between a ten-thousandth of a millimeter and a hundredth of a millimeter. The sun's characteristics are given in Table A-1.

Table A-1 The Sun's Characteristics

Diameter of the sun	1.39×10^6 Km.
Mass of the sun	2200×10^{24} metric tons
	about 330,000 times that of earth
Temperature of sun's center	15×10^6 degrees centigrade
Temperature of sun's surface	5×10^3 degrees centigrade
Mean value of solar constant	1.395 Kilowatts per square meter
Total radiation continuously intercepted by the outer atmosphere of earth	173×10^{12} Kilowatts
Total radiation reaching earth's surface	85×10^{12} Kilowatts
Total radiation continuously released by the sun	380×10^{21} Kilowatts

Appendix B

Solar Cooling

The most promising heat-operated cooling device is the closed cycle absorption machine [43,58]. Fig. B.1 shows such a system with conventional heat source being replaced by solar collector. The absorption-refrigeration cycle employs water vapor as refrigerant and lithium bromide solution as absorbent. The cooling effect is produced in the evaporator where water vaporizes at low pressure and at temperatures in the 40 to 50 F range. The vapor is then absorbed, and the resulting lithium bromide solution is pumped to the generator where heat from the solar collector or storage produce water vapor for subsequent condensation and return to the evaporator. The overall performance of solar cooling, E , is

$$E = \epsilon \times \eta$$

where

ϵ = solar heat exchanger efficiency, or the ratio of useful energy delivered, to the solar radiation incident upon the exchanger

η = the ratio of cooling obtained to output of solar heat exchanger

For domestic use, the lithium bromide-water vapor system has been employed, whereas for large industrial use, ammonia-water systems are common [26]. Solar heat substitution for fuel in absorption refrigerators requires consideration of the temperature levels at which these systems must operate. Generator temperatures in the lithium bromide-water vapor system average about 200F; in the ammonia-water system they are 175 F.

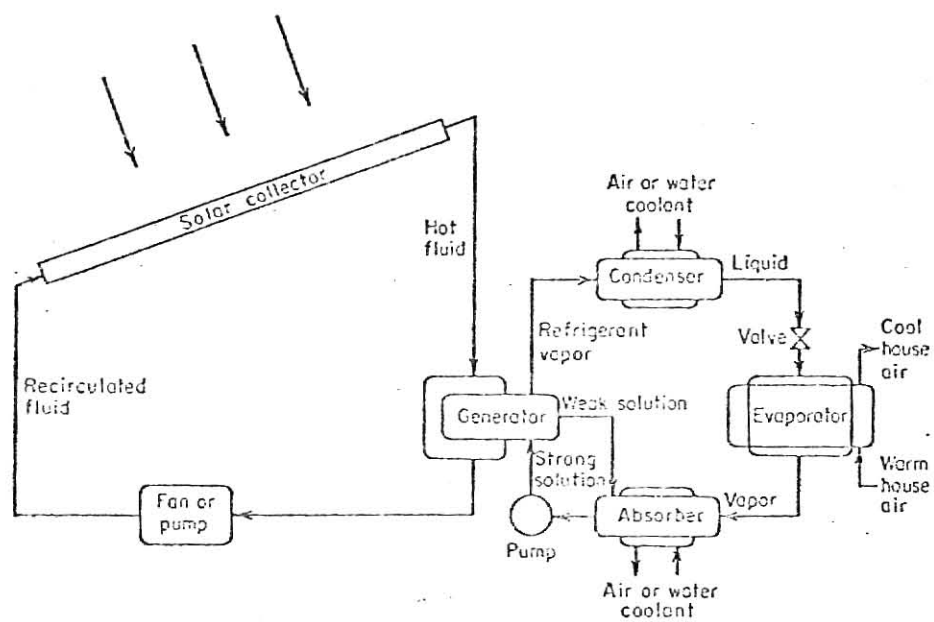


Fig. B.1 Solar Cooling by Absorption Refrigeration [75].

Appendix C

Calculation of the Coefficient of Heat Transmission [8]

1. Wall Type number (1) Fig. C.1,

$$U = \frac{1}{\frac{1}{f_i} + \frac{x}{k} + \frac{1}{f_o}} \quad (1)$$

where

U = overall coefficient of heat transmission and is the amount of heat expressed in Btu transmitted in one hour per square foot of the wall for a difference in temperature of one degree Fahrenheit between the air on the inside and outside of the wall.

f = film or surface conductance, and is the amount of heat expressed in Btu transmitted by radiation, conduction, and convection from a surface to the air surrounding it or vice versa in one hour per square foot of the surface for a difference in temperature of one degree Fahrenheit between the surface and the surrounding air. (f_i = inside film, f_o = outside film)

K = Thermal conductivity, and is the amount of heat expressed in Btu transmitted in one hour through one square foot of a homogenous material one inch thick for a difference in temperature of one degree Fahrenheit between the two surfaces of the material.

X = Thickness of wall in inches.

So for wall type number (1) as shown in Fig. C.1

$$U = \frac{1}{\frac{1}{1.65} + \frac{3/4}{4.4} + \frac{1}{0.86} + \frac{1}{0.86} + \frac{4}{9.09} + \frac{1}{6}} = 0.27 \text{ Btu/(sq ft hr F)}$$

- (1) Outside, $f_0 = 6 \text{ BTU/Hr sq ft F (Conductance) [1]}^*$
- (2) 4" = Brick Veneer
- (3) Building Paper
- (4) 1" = Wood Sheathing
- (5) Studding (neglected)
- (6) 1" Wood Sheathing
- (7) 3/4" Metal Lath and Plaster
- (8) Inside, $f_i = 1.65$

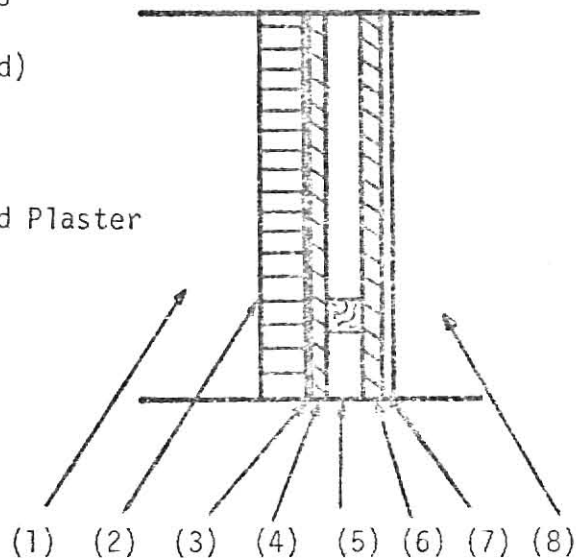


Fig. C.1 Wall Type number (1) Brick Veneer Facing

*This construction is taken from ASHRAE Handbook [1], current construction may however be different.

Table C.1 and Fig. C.2 show the effects of insulation on the coefficient of heat transmission together with the insulation factor or percentage of insulation improvement.

By the same method, the coefficient of heat transmission for floor, roof, and ceiling is given in Tables C.2 through C.4

2. Combined Coefficient of Heat Transmission "U" of Pitched Roof and Ceiling, Table C.5

$$U = \frac{U_p \cdot U_{cc}}{U_p + \frac{U_{cc}}{n}} \quad (2)$$

where

U_p = Coefficient of transmission of pitched roof

U_{cc} = Coefficient of transmission of ceiling.

n = The ratio of the area of the roof to the area of the ceiling

(let $n = 1/\cosine\ 50 = 1/0.64 = 1.56$).

3. Calculation of Attic Temperature, Table C.6

$$t_a = \frac{A_c U_c t + (A_r U_r + A_w U_w + A_g U_g) t_0}{A_r U_r + A_w U_w + A_g U_g + A_c U_c} \quad (3)$$

where

t_a = Attic temperature

t = Inside temperature (70 F)

t_0 = Outside temperature (-10,0,10,20,30,40 F)

A_c = Area of ceiling, square feet

A_r = Area of roof, square feet

A_g = Area of glass, square feet

A_w = Area of net vertical wall surface

U_c = Coefficient of heat transmission of ceiling

U_r = Coefficient of heat transmission of roof

U_w = Coefficient of heat transmission of vertical wall surface

U_g = Coefficient of heat transmission of glass.

Assumptions:

1 . $t = 70 \text{ } ^\circ\text{F}$

2 . $A_c = 921 \text{ sq ft}$

3 . $A_r = 921 \times 1.56 = 1436 \text{ sq ft}$

4 . $A_g = \text{None}$

5 . $A_w = 2\left(\frac{1}{2} \times 24 \times 14.3\right) = 343 \text{ sq ft}$

6 . $U_c = 0.719$ for no insulation, 0.042 for 6" insulation

7 . $U_r = 0.470$ for no insulation, 0.039 for 6" insulation

8 . $U_w = 0.270$ for no insulation, 0.054 for 4" insulation

Table C.1 The Coefficient of Heat Transmission (U) for Wall Type No. (1)
with Various Insulation (mineral wool) Thicknesses

Insulation Thickness in inches	Coefficient of Heat Transmission (U) Btu/(sq ft hr F)	Insulation Factor in %
0	0.27	0
1	0.13	52
2	0.09	67
3	0.07	74
4	0.054	80
5	0.045	83
6	0.038	86
7	0.0334	87
8	0.0297	88
9	0.0267	89
10	0.0243	90
11	0.0223	91
12	0.0206	92
13	0.0192	92.3
14	0.0179	92.8
15	0.0168	93.2
16	0.0158	93.6
17	0.0149	94.0
18	0.0141	94.3
19	0.0134	94.6
20	0.0128	94.8

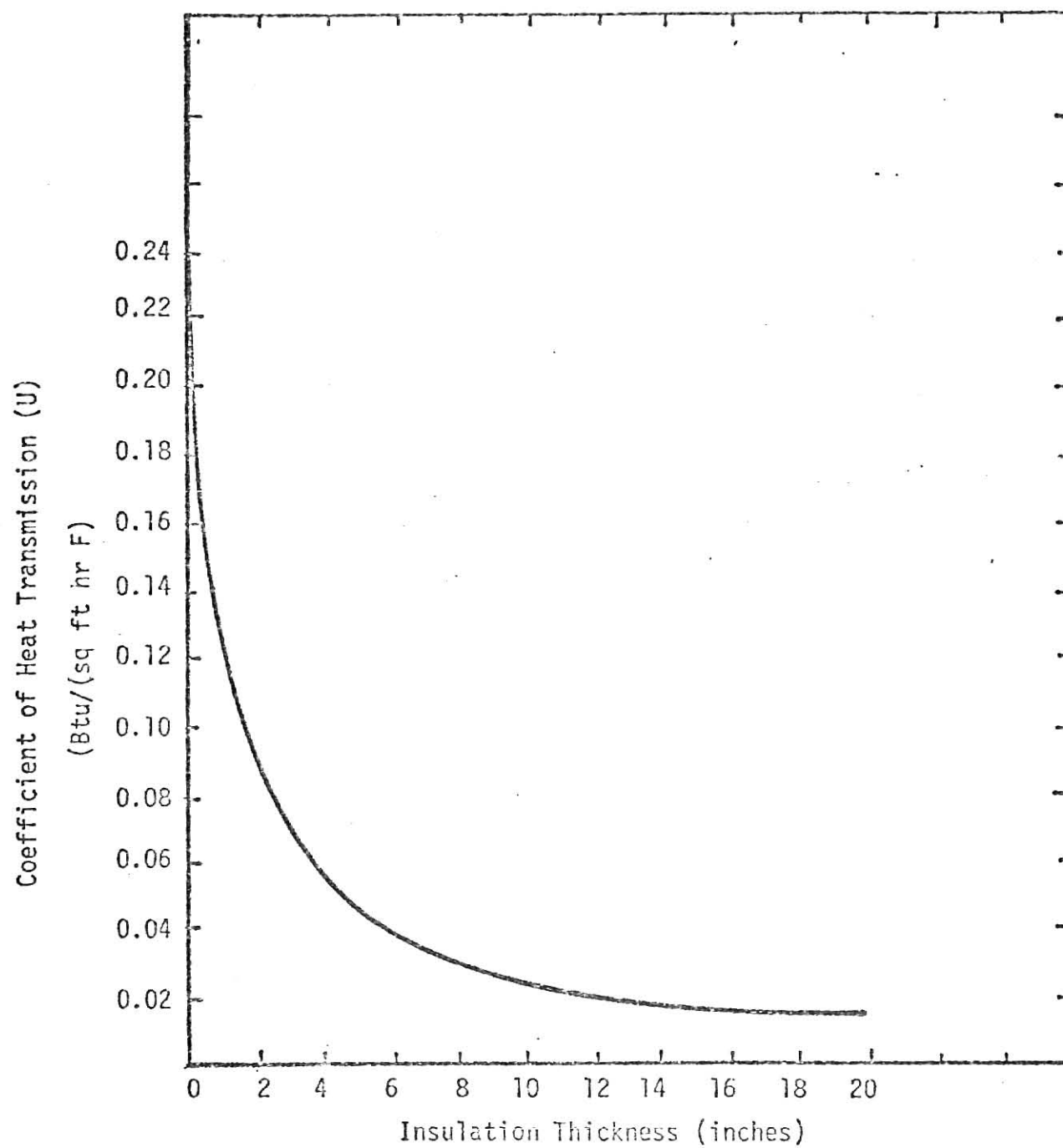


Fig. C.2 Effects of Insulation on Coefficient of Heat Transmission

Table C.2 "U" for Typical Floor Frame Construction with Various Insulation
(mineral wool) Thicknesses

Insulation Thickness in inches	"U" in Btu/(sq ft hr F)	Insulation Factor in %
0	0.28	0
1	0.138	42
2	0.0916	67
3	0.0684	75
4	0.0546	80
5	0.0454	83
6	0.0389	86
7	0.0340	87.8
8	0.0302	89.2
9	0.0271	90.3
10	0.0247	91.2
11	0.0226	91.9
12	0.0209	92.5

Table C.3 "U" for Typical Pitched Roof with Various Insulation Thicknesses

Insulation Thickness in inches	"U" Btu/(sq ft hr F)	Insulation Factor in %
0	0.47	0
1	0.14	70.2
2	0.093	80.2
3	0.0693	85.2
4	0.0553	88.2
5	0.0459	90.2
6	0.0392	91.6
7	0.0343	92.7
8	0.0304	93.5
9	0.0273	94.1
10	0.0273	94.7
11	0.0227	95.1
12	0.0210	95.5

Table C.4 "U" for Typical Ceiling Under Pitched Roof with Various
Insulation Thicknesses

Insulation Thickness in inches	"U" Btu/(sq ft hr F)	Insulation Factor in %
None	0.719	0
1	0.200	72.1
2	0.110	84.7
3	0.080	88.8
4	0.061	91.5
5	0.050	93.0
6	0.042	94.1
7	0.0366	94.9
8	0.0322	95.5
9	0.0288	96.0
10	0.0260	96.39
11	0.0237	96.71
12	0.0218	96.97

Table C.5 Combined Coefficient of Heat Transmission "U" of Pitched Roof and Ceiling with Various Insulation Thicknesses

Insulation Thickness inches	$U_{ce.}$ Btu/(sq ft hr F)	$\frac{U_{cc}}{n}$	U_p	$U_r + \frac{U_{cc}}{n}$	U	Insulation factor %
None	0.719	0.461	0.47	0.930	0.358	0
1	0.200	0.128	0.14	0.260	0.107	70.1
2	0.110	0.070	0.093	0.163	0.060	83.2
3	0.080	0.051	0.0695	0.120	0.046	87.1
4	0.061	0.039	0.0553	0.094	0.035	90.2
5	0.050	0.032	0.0459	0.077	0.029	91.9
6	0.042	0.026	0.0392	0.065	0.025	93.0
7	0.0366	0.023	0.0343	0.057	0.021	94.1
8	0.0322	0.020	0.0304	0.050	0.019	94.6
9	0.0288	0.0184	0.0273	0.047	0.016	95.5
10	0.0260	0.0165	0.0248	0.041	0.015	95.8
11	0.0237	0.0152	0.0227	0.037	0.014	96.09
12	0.0218	0.014	0.0210	0.035	0.013	96.30

Table C.6 Attic Temperature at Various Outside Temperatures and Constant Inside Temperature of 70 °F

Outside temp. t_o (F)	Attic Temp. (Insulation neglected) t_a (F)	Attic Temp. (Insulation considered) t_a (F)
-10	27.09	17.43
0	32.44	24.05
10	37.82	30.67
20	43.19	37.30
30	48.41	43.92
40	53.78	50.53

Appendix D

Analysis of Optimum Insulation and Heating Costs for the Two-Story Model House at Present and Projected Future Prices of Fuel Oil, Electricity and Natural Gas.

Table D.1 Optimum Thickness of Insulation, and Optimum Annual Heating Costs at Various Fuel Oil Prices

Energy Source: Fuel Oil

Construction: Floor, Area = 730 sq ft , ($U = 0.28$).

Fuel Oil Price (cents/gallon)	Optimum Insulation Thickness (inches)	Optimum Annual Heating Costs (\$)	Optimum "U" (Btu/hr sq ft F)
20	1.42	27.74	0.113
40	2.41	42.20	0.080
60	3.17	53.26	0.065
80	3.92	62.61	0.055
100	4.50	70.84	0.049

Table D.2 Optimum Annual Heating Costs at Fuel Oil Price of 20 Cents/
Gallon

Energy Source: Fuel Oil

Construction: Floor

Insulation Thickness (inches)	"U"	Annual Heating Cost (\$)	Annual Insulation Cost (\$)	Total Annual Cost (\$)
0	0.28	43.06	0	43.66
1	0.138	21.22	7.30	28.52
2	0.0916	14.09	14.60	28.69
3	0.0684	10.46	21.9	32.30
4	0.0546	8.39	29.2	37.59
5	0.0454	6.92	36.5	43.42
6	0.0389	5.84	43.8	49.64

Table D.3 Optimum Thickness of Insulation and Optimum Annual Heating Costs
at Various Fuel Oil Prices

Energy Source: Fuel Oil

Construction: Ceiling, Area = 792, $U = 0.358$

Fuel Oil Price (cents/gallon)	Optimum Insulation Thickness (inches)	Optimum Annual Heating Costs (\$)	Optimum "U"
20	1.63	31.76	0.113
40	2.62	47.44	0.080
60	3.38	59.45	0.0653
80	4.13	69.61	0.0553
100	4.71	78.51	0.0494

Table D.4 Optimum Annual Heating Costs at Fuel Oil Price of 20 Cents/
Gallon

Energy Source: Fuel Oil

Construction: Ceiling

Insulation Thickness (inches)	"U"	Annual Heating Cost (\$)	Annual Insulation Cost (\$)	Total Annual Cost (\$)
0	0.358	59.72	0	59.72
1	0.200	33.36	7.92	41.28
2	0.110	18.34	15.84	34.18
3	0.080	13.34	23.76	37.10
4	0.061	10.17	31.68	41.85
5	0.050	8.47	39.60	48.07
6	0.042	7.11	47.52	54.63

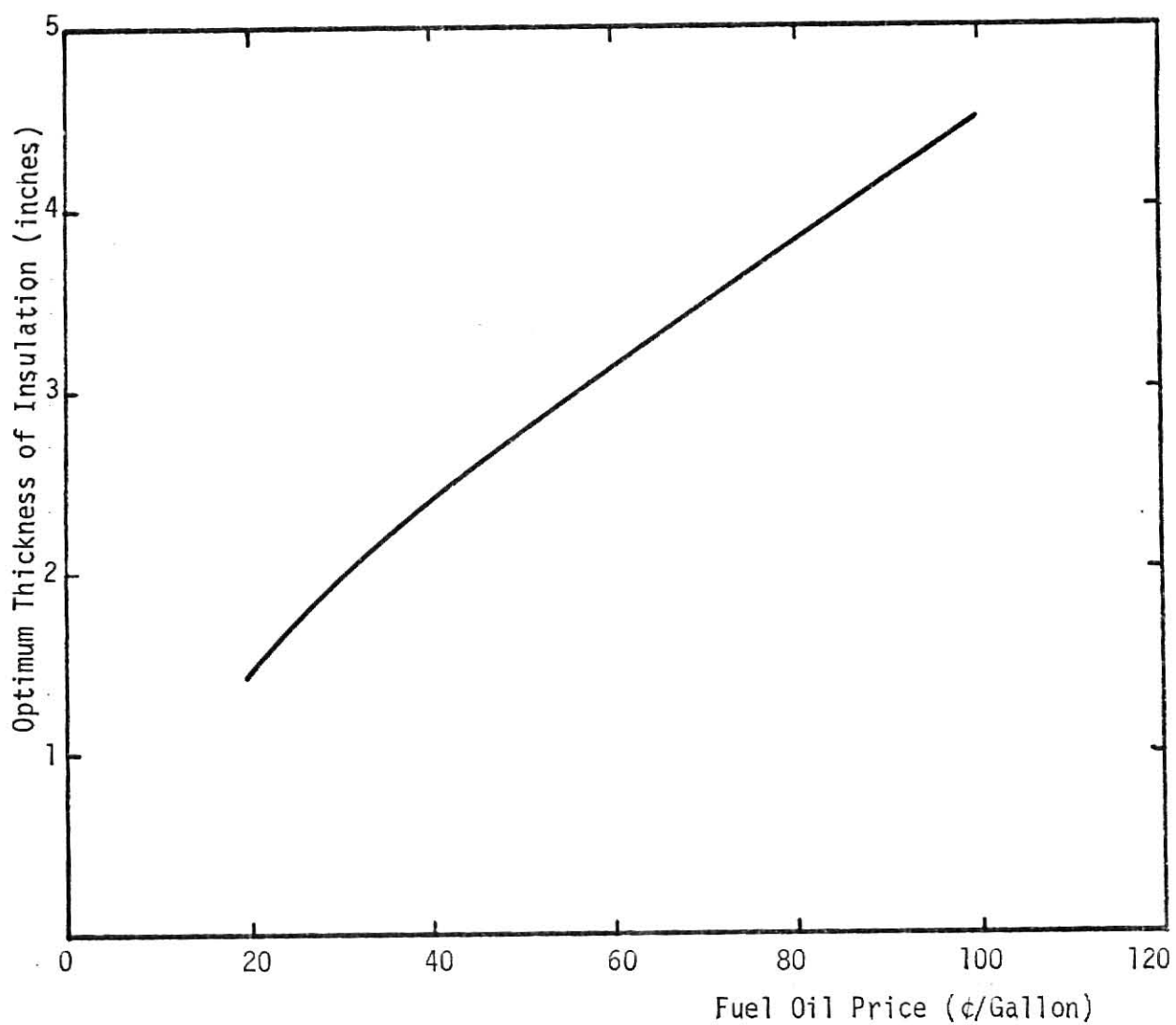


Fig. D.1 Optimum Thickness of Insulation at Various Fuel Oil Prices

Energy Source: Fuel Oil

Construction: Floor.

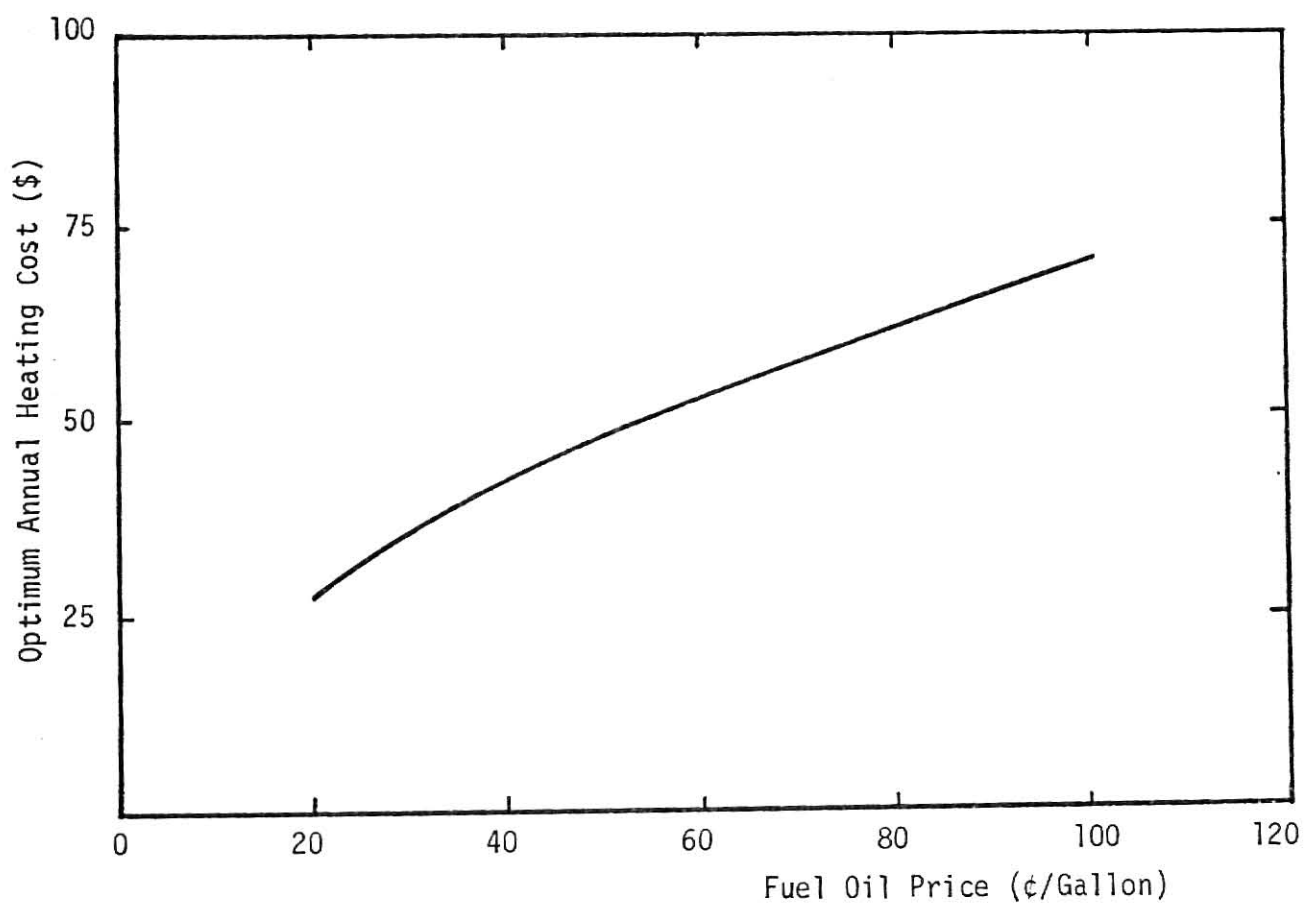


Fig. D.2 Optimum Annual Heating Cost at Various Fuel Oil Prices

Energy Source: Fuel Oil

Construction: Floor

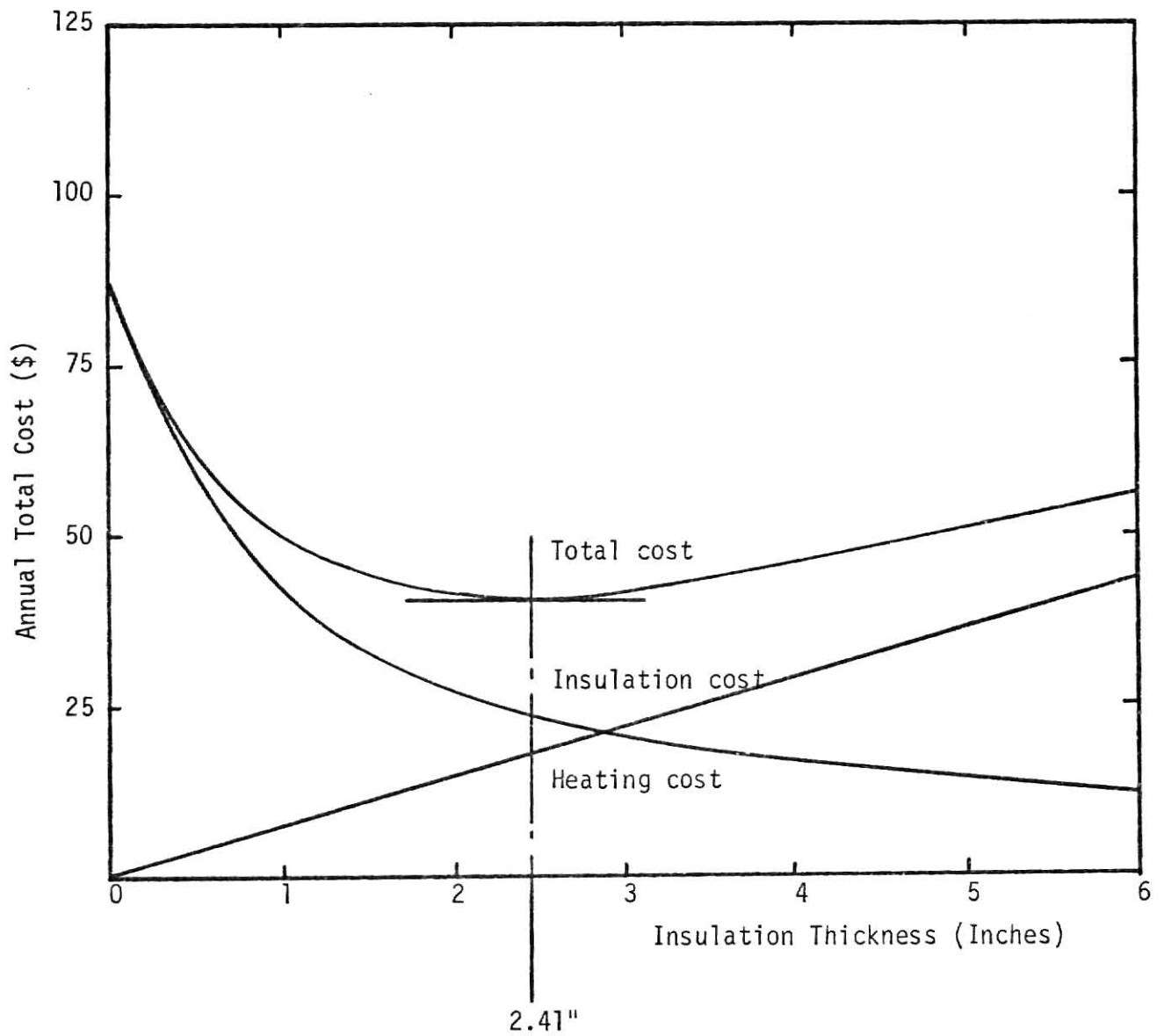


Fig. D.3 Optimum Insulation Thickness, and Total Annual Heating

Costs at Fuel Oil Price of 40 Cents/Gallon

Energy Source: Fuel Oil

Construction: Floor

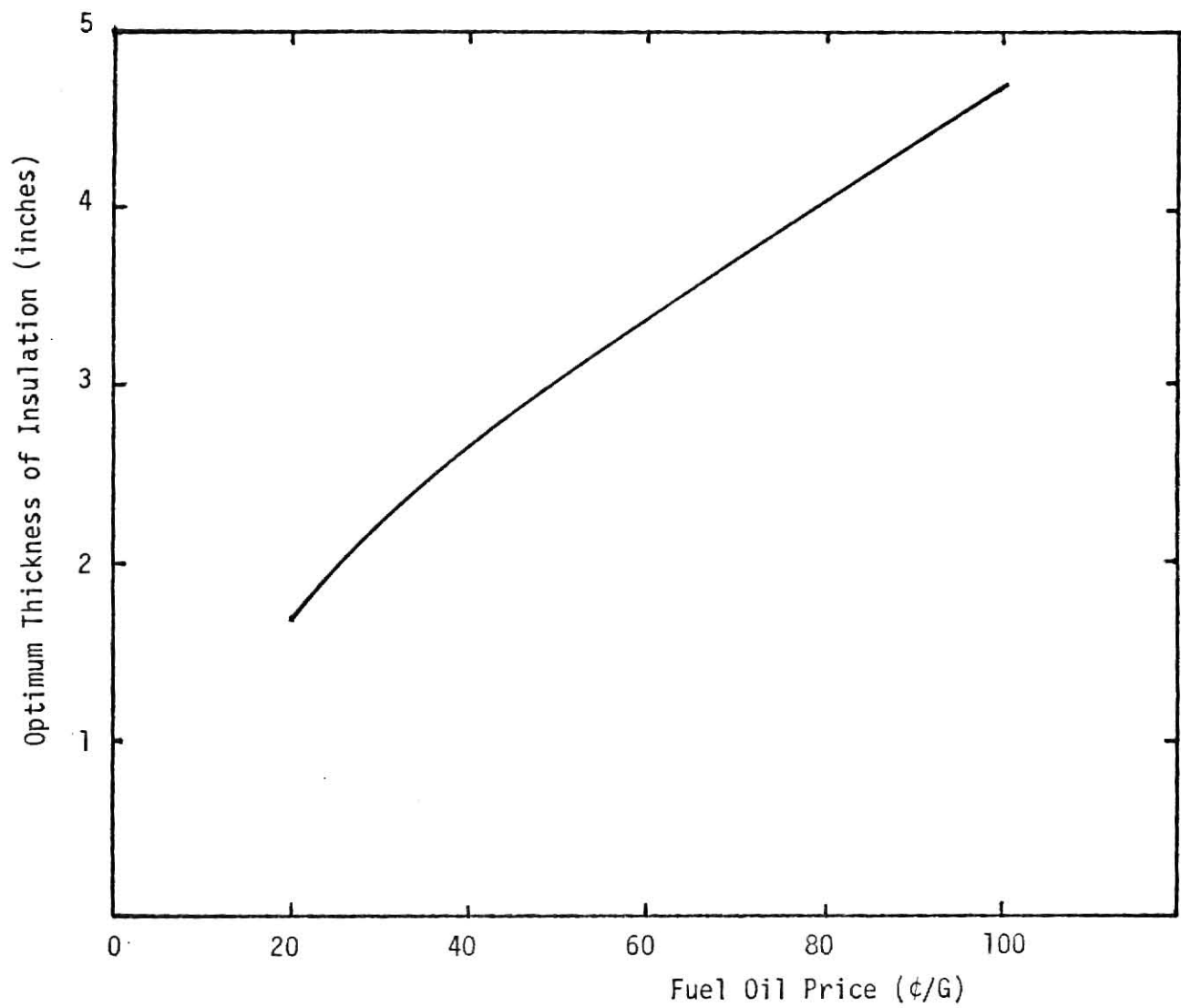


Fig. D.4 Optimum Thickness of Insulation at Various Fuel Oil Prices

Energy Source: Fuel Oil

Construction: Ceiling

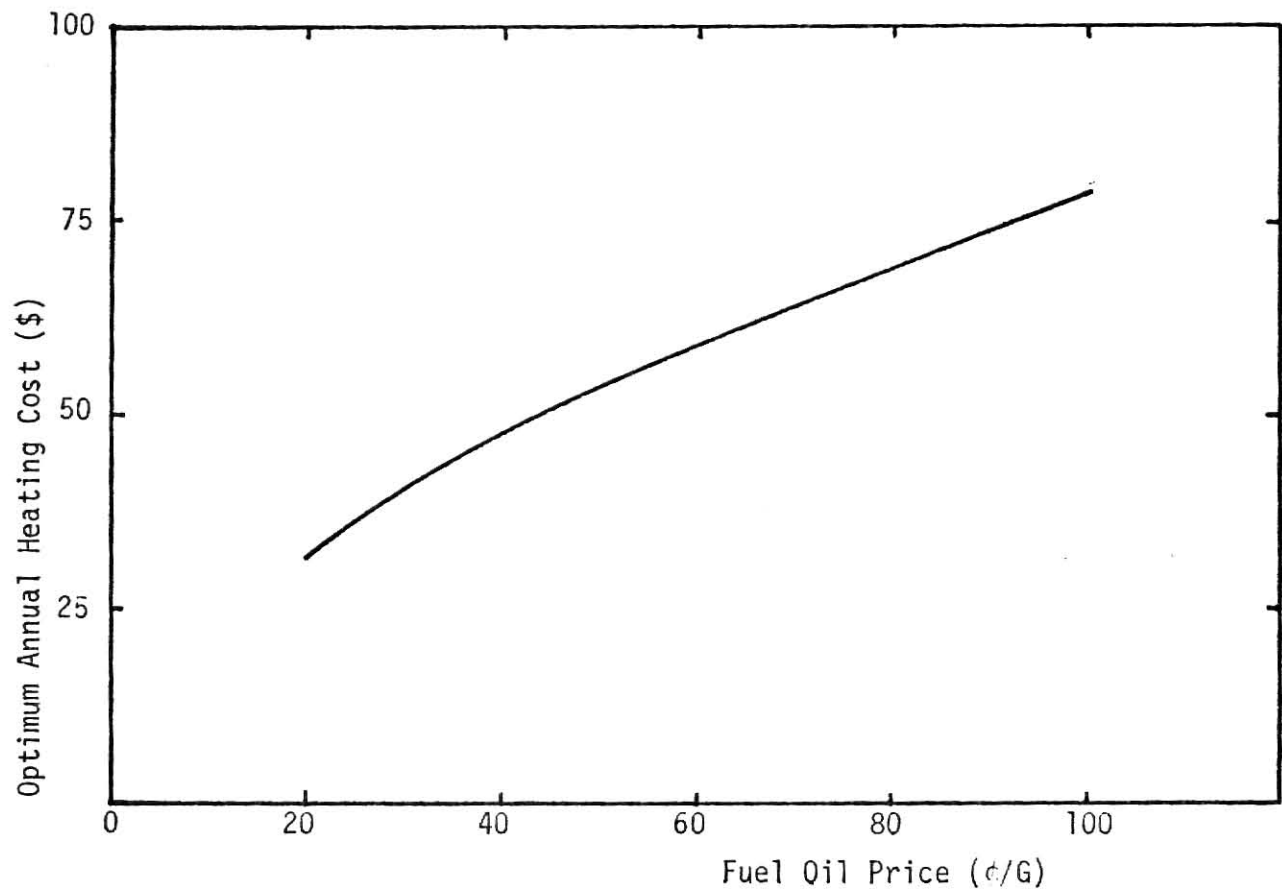


Fig. D.5 Optimum Annual Heating Cost at Various Fuel Oil Prices

Energy Source: Fuel Oil

Construction: Ceiling

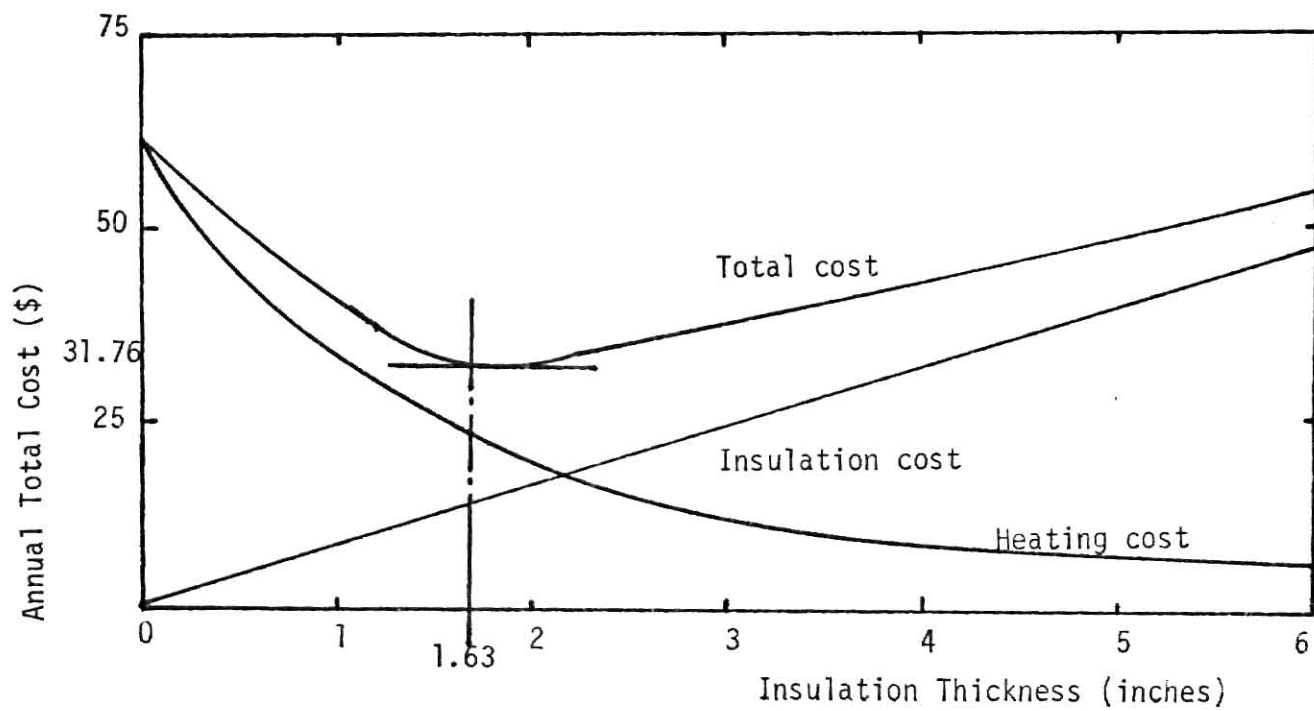


Fig. D.6 Optimum Total Annual Heating Cost at Fuel Oil Price of 20 ¢/G

Energy Source: Fuel Oil

Construction: Ceiling

Table D.5 Return on Investment (r) Per Heating Season at Various Energy Costs and Insulation Thicknesses.

Energy Source: Electrical

Construction: Walls

Insulation Thickness (Inches)	Electrical Energy Costs				
	3 ¢/Kwh (r)	6 ¢/Kwh (r)	9 ¢/Kwh (r)	12 ¢/Kwh (r)	15 ¢/Kwh (r)
0	0	0	0	0	0
1	93.84	187.68	281.62	375.36	469.2
2	120.63	241.26	361.89	482.52	603.15
3	133.99	267.98	401.97	535.96	669.95
4	144.74	289.48	434.22	578.96	723.70
5	150.73	301.46	452.19	602.92	753.65
6	155.37	310.74	466.11	621.48	776.85

Table D.6 Optimum Thickness of Insulation and Optimum Annual Costs of Heating and Insulation at Various Energy Costs

Energy Source: Electrical

Construction: Walls.

Electrical Energy Costs cents/Kwh	Optimum Insulation Thickness (inches)	Optimum Heating Costs (\$)	Optimum "U"
3	5.01	171.65	0.0449
6	7.50	250.24	0.032
9	9.40	309.02	0.026
12	11.03	355.26	0.022
15	12.45	402.39	0.020

Table D.7 Optimum Thickness of Insulation and Optimum Annual Heating
Costs at Various Electrical Energy Prices

Energy Source: Electrical

Construction: Floor

Electrical Energy Price (¢/Kwh)	Optimum Insulation Thickness (inches)	Optimum Annual Heating Costs (\$)	Optimum "U"
3	5.166	80.757	0.044
6	7.703	116.889	0.031
9	9.650	143.821	0.025
12	11.291	168.518	0.022
15	12.737	190.814	0.020

Table D.8 Optimum Annual Heating Costs at Electrical Energy Price of 3¢/Kwh

Energy Source: Electrical

Construction: Floor

Insulation Thickness (inches)	"U"	Annual Heating Cost (\$)	Annual Insulation Cost (\$)	Total Annual Cost (\$)
0	0.28	273.932	0	273.932
1	0.138	135.009	7.30	142.30
2	0.0916	89.615	14.60	104.21
3	0.0684	66.918	21.90	88.81
4	0.0546	53.416	29.20	82.61
5	0.0454	44.416	36.50	80.92
6	0.0389	38.057	43.8	81.857

Table D.9 Optimum Thickness of Insulation, and Optimum Annual Heating

Costs at Various Electrical Energy Prices

Various Electrical Energy Prices

Energy Source: Electrical

Construction: Ceiling

Electrical Energy Price (¢/Kwh)	Optimum Insulation Thickness (inches)	Optimum Annual Heating Cost (\$)	Optimum "U"
3	5.26	89.31	0.0449
6	7.75	128.66	0.0317
9	9.67	159.04	0.0259
12	11.28	184.42	0.0224
15	12.70	207.23	0.0201

Table D.10 Optimum Annual Heating Costs at Electrical Energy Price of 3 ¢/Kwh

Energy Source: Electrical

Construction: Ceiling

Insulation Thickness (inches)	"U"	Annual Heating Cost (\$)	Annual Insulation Cost (\$)	Total Annual Cost (\$)
0	0.358	379.98	0	379.98
1	0.200	212.28	7.92	220.20
2	0.110	116.75	15.84	132.59
3	0.080	84.91	23.76	108.67
4	0.061	64.74	31.68	96.42
5	0.050	53.07	39.60	92.67
6	0.042	44.57	47.52	92.09

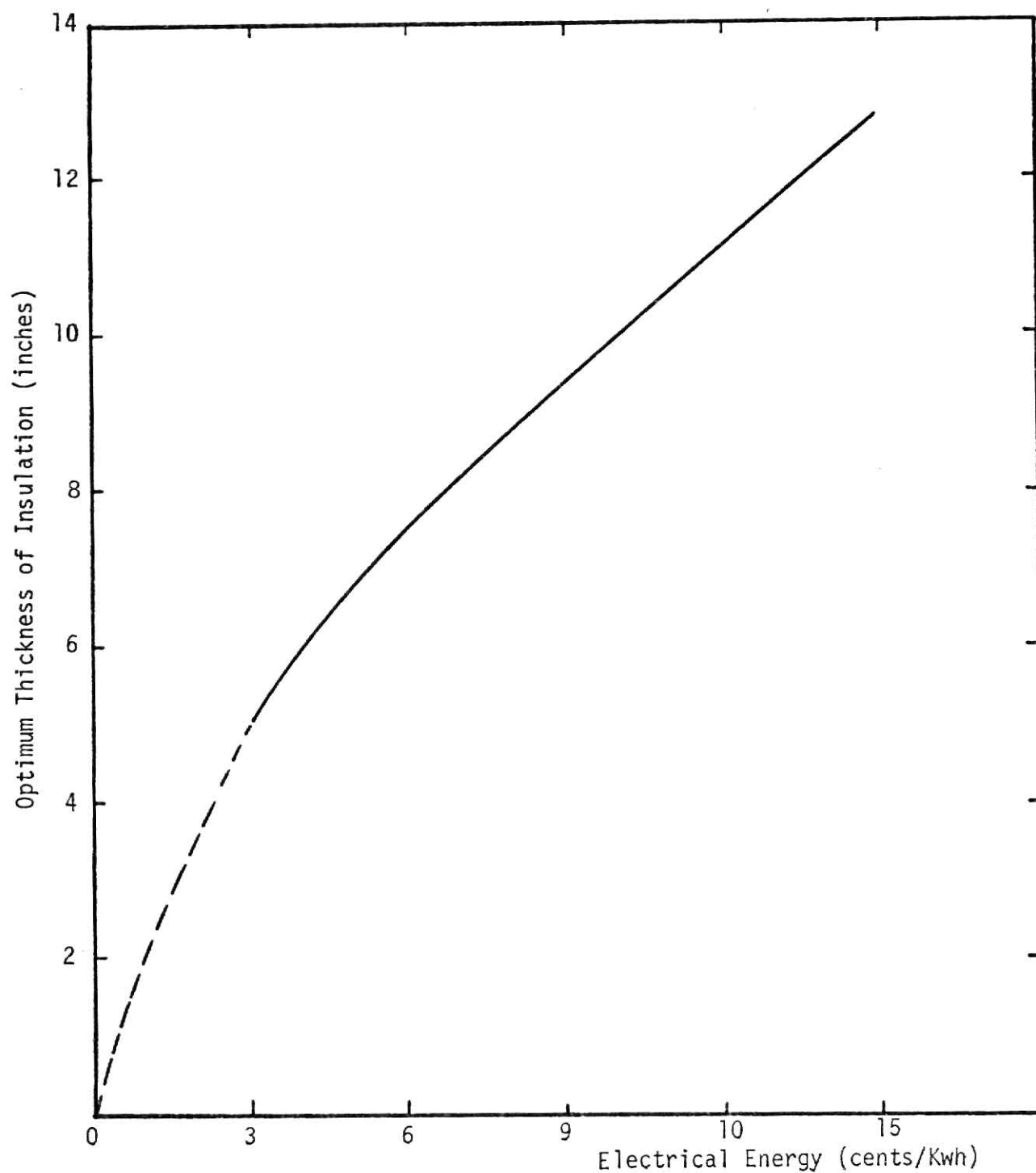


Fig. D.7 Optimum Thickness of Insulation at Various Electrical
Energy Costs

Energy Source: Electrical

Construction: Walls.

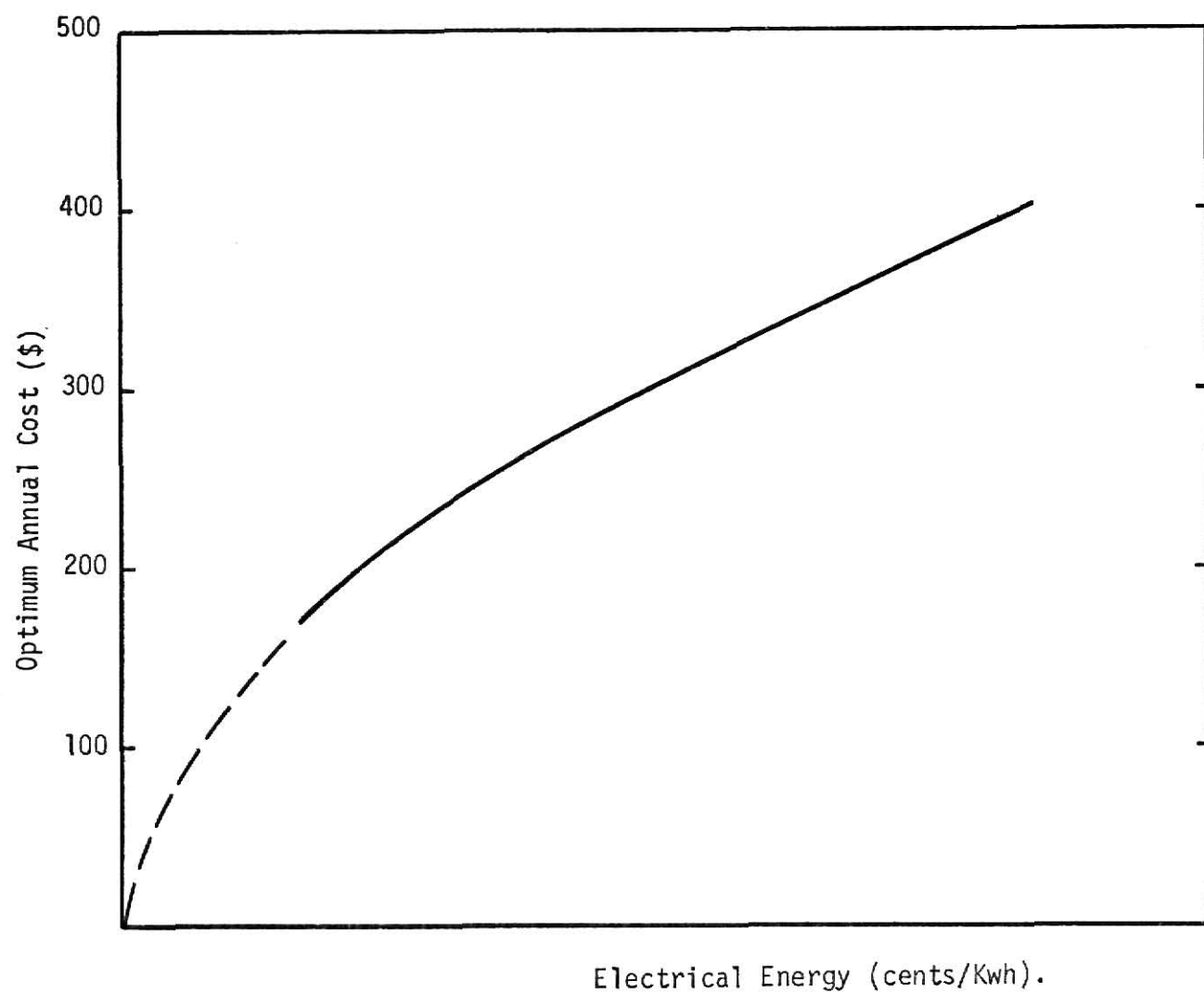


Fig. D.8 Optimum Annual Total Costs of Heating and Insulation at
Various Electrical Energy Costs

Energy Source: Electrical

Construction: Walls.

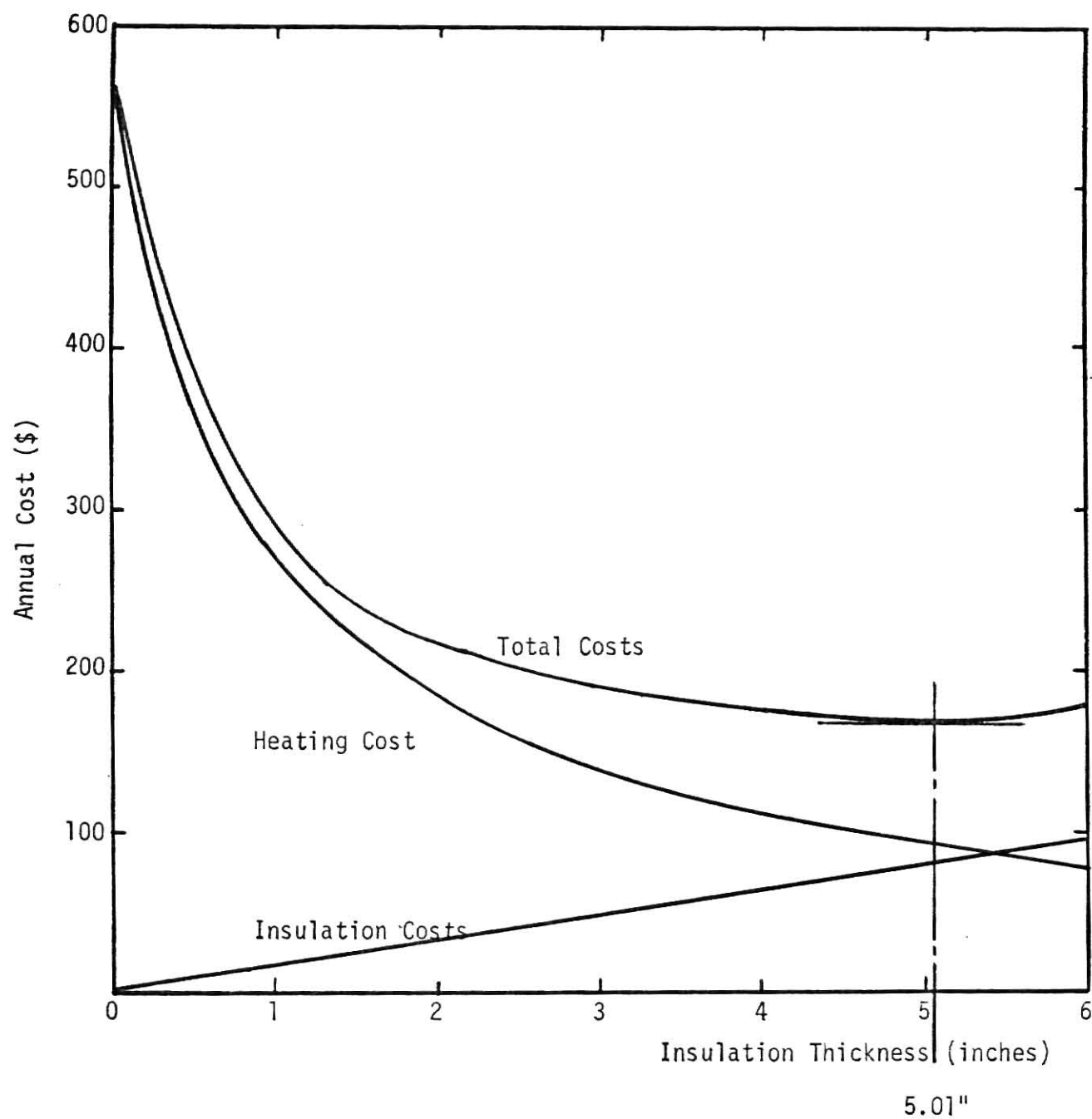


Fig. D.9 Optimum Thickness of Insulation

Energy Source: Electrical at 3 cents/Kwh

Construction: Walls.

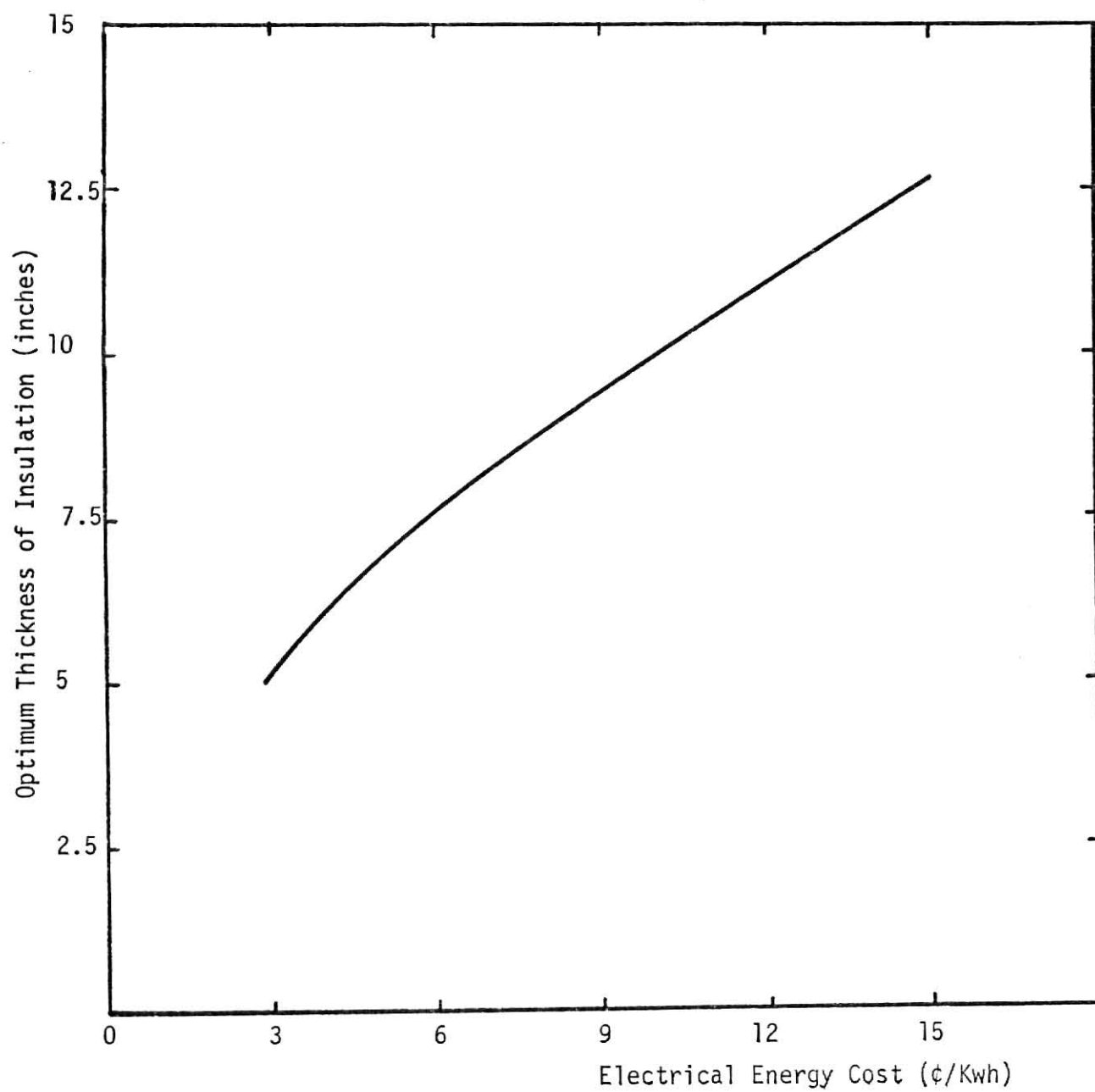


Fig. D.10 Optimum Thickness of Insulation at Various Electrical Energy Cost

Energy Source: Electrical

Construction: Floor

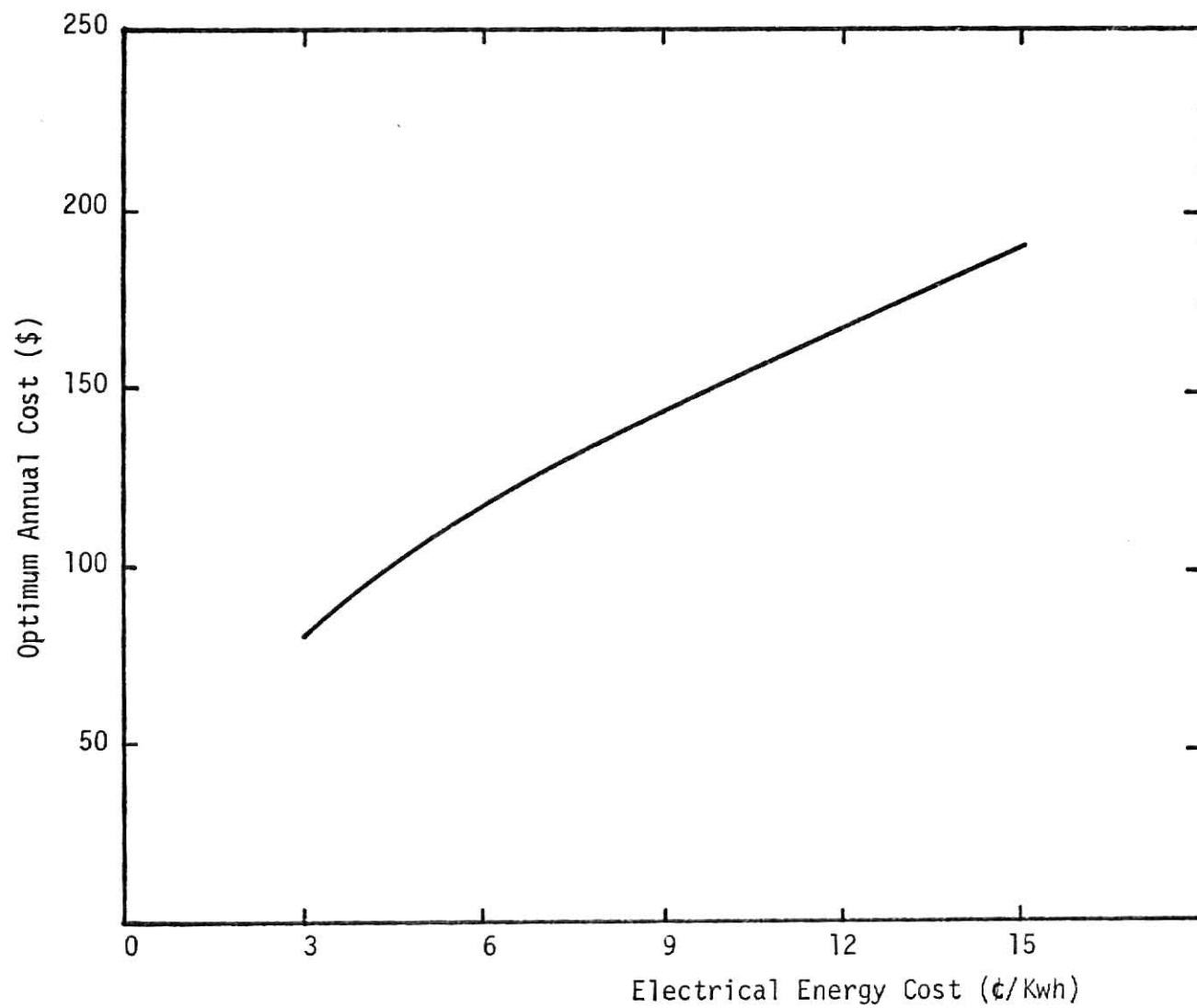


Fig. D.11 Optimum Annual Heating Cost at Various Electrical Energy Cost

Energy Source: Electrical

Construction: Floor

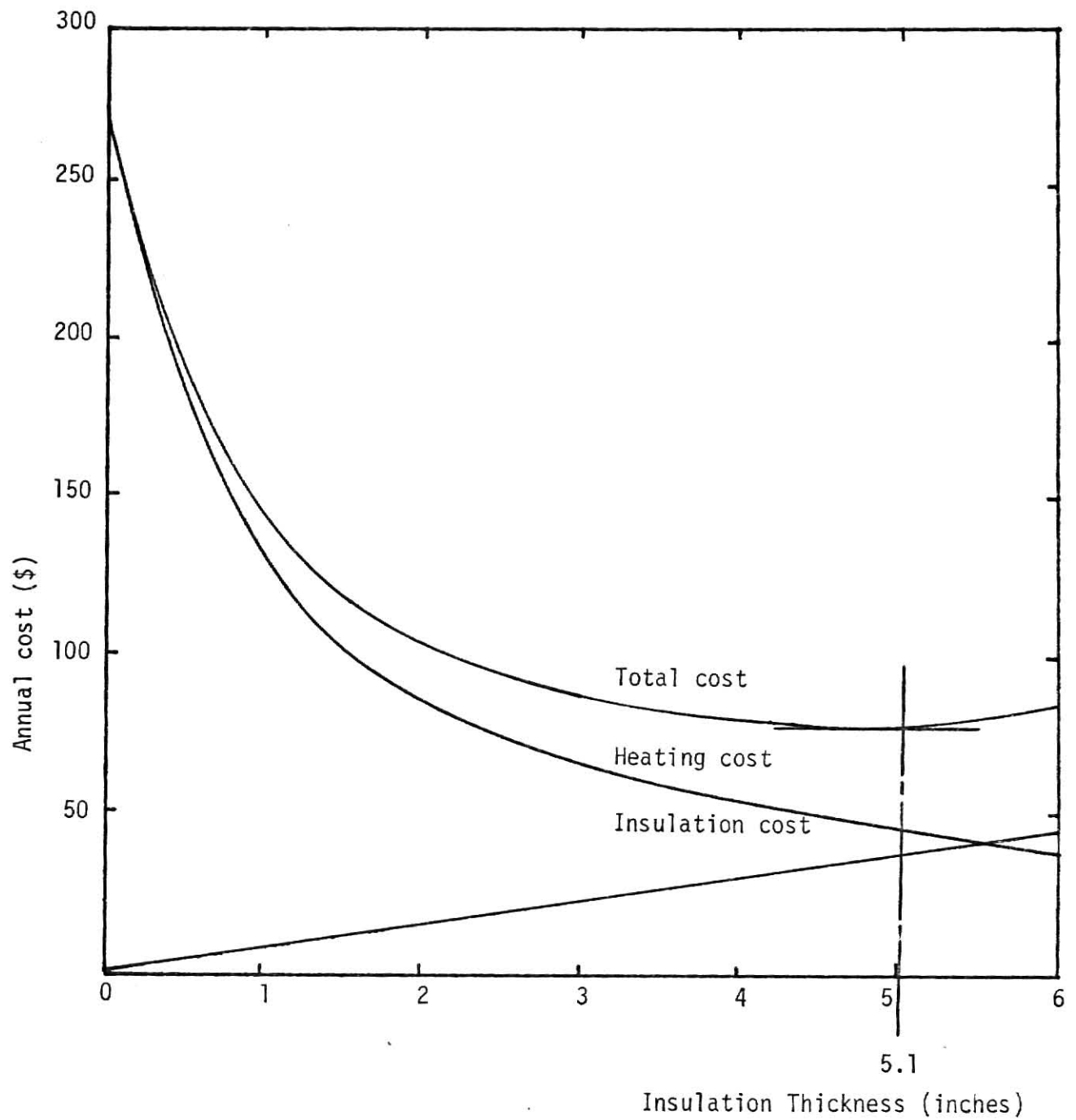


Fig. D.12 Optimum Insulation Thickness, and Total Annual Heating Costs at Electrical Energy Cost of 3 c/kwh

Energy Source: Electrical

Construction: Floor

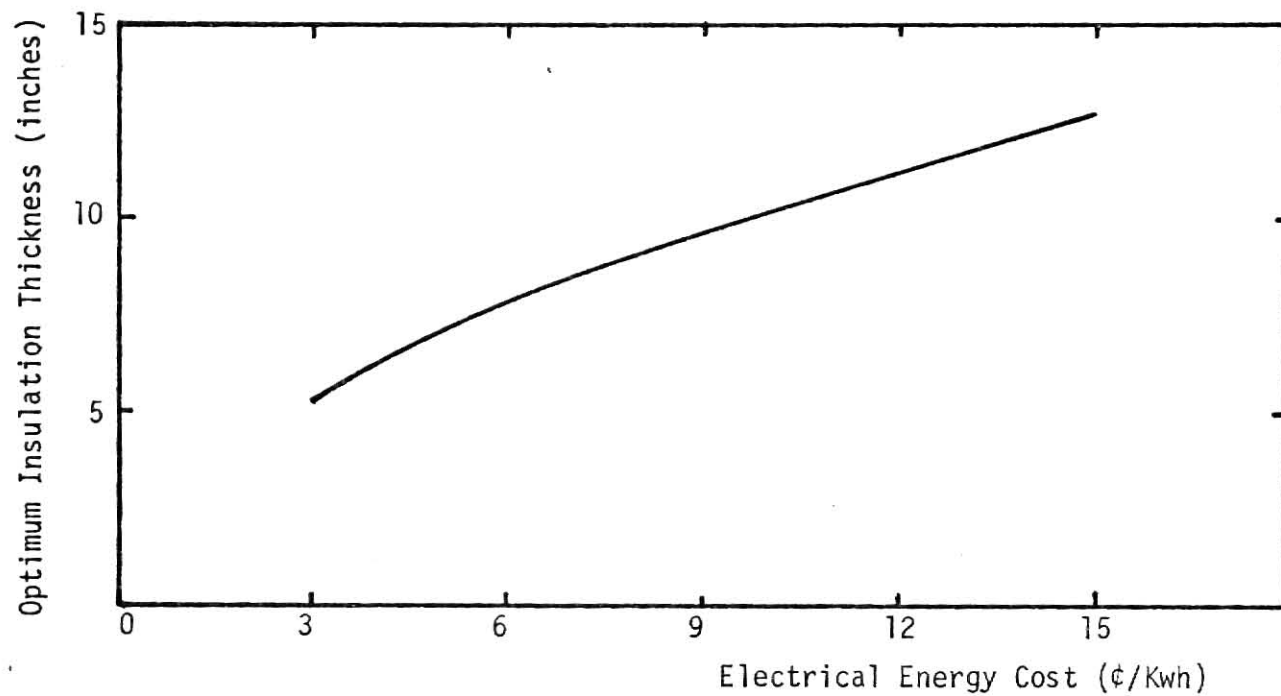


Fig. D.13 Optimum Thickness of Insulation at Various Electrical
Energy Prices

Energy Source: Electrical

Construction: Ceiling

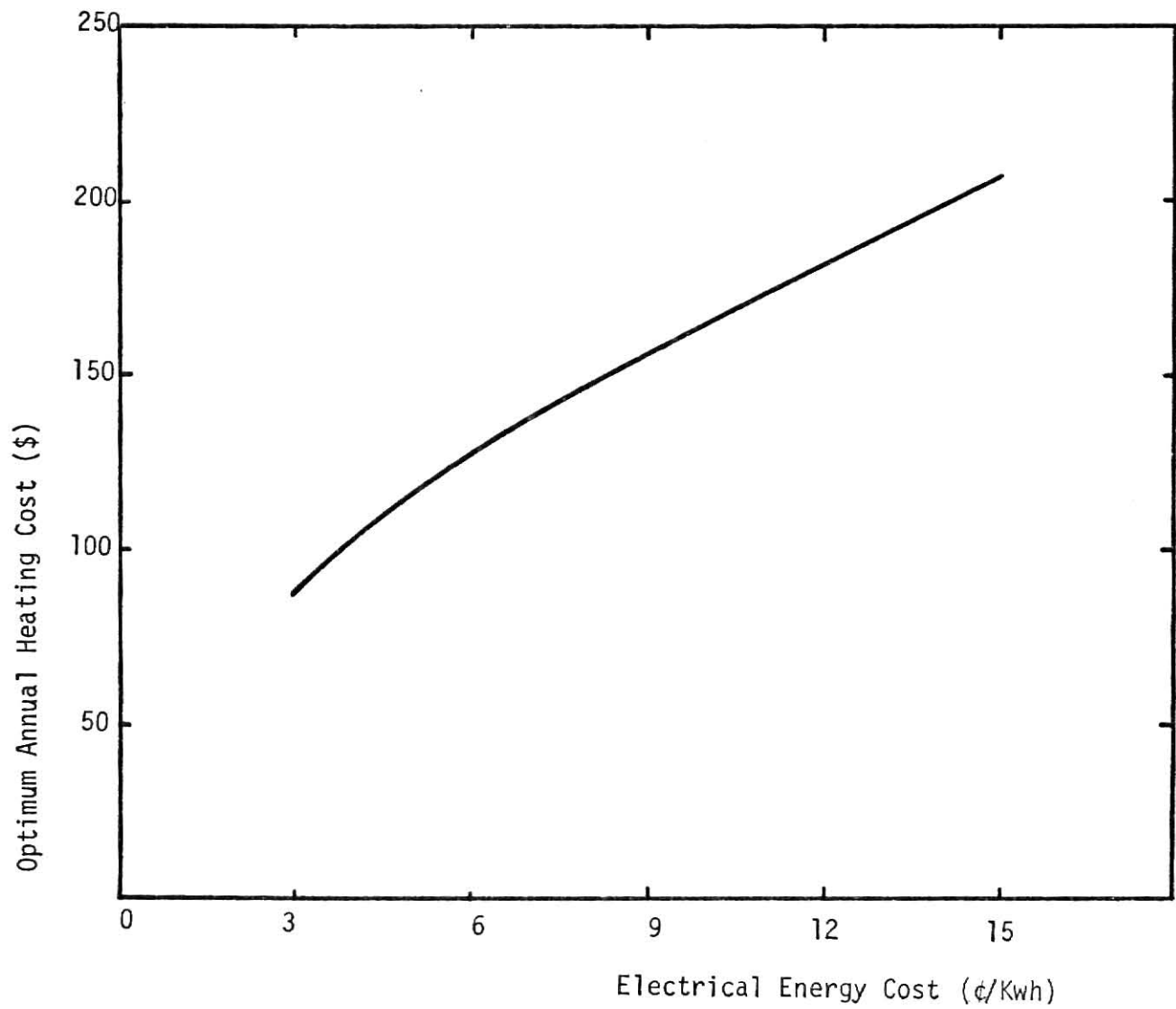


Fig. D.14 Optimum Annual Heating Cost at Various Electrical
Energy Prices

Energy Source: Electrical

Construction: Ceiling

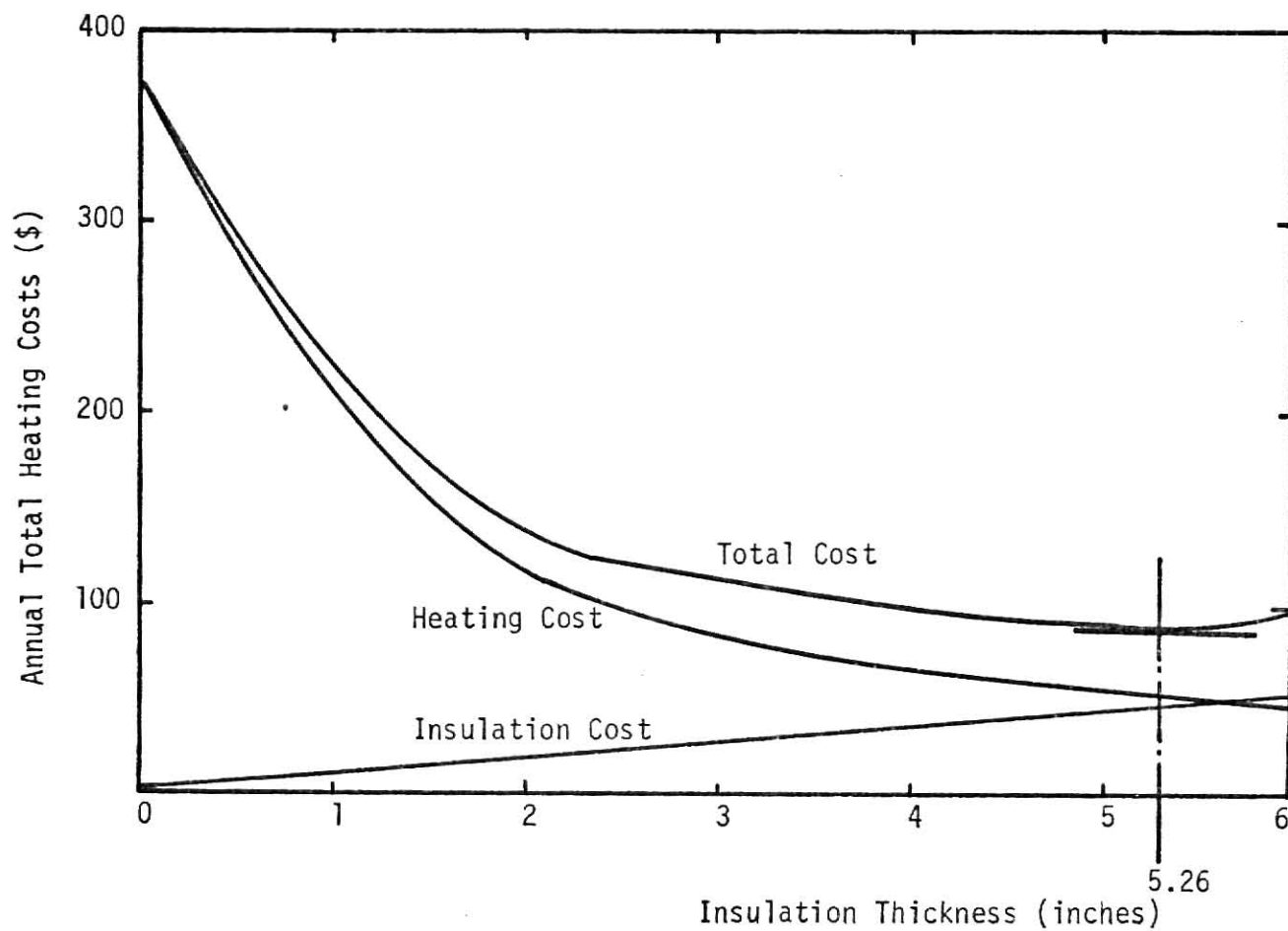


Fig. D.15 Optimum Total Annual Heating Cost at Electrical Energy

Price of (3 ¢/Kwh)

Energy Source: Electrical

Construction: Ceiling

Table D.11 Return on Investment (r) Per Heating Season at Various Energy Costs and Insulation Thicknesses

Energy Source: Natural gas

Construction: Walls.

Insulation Thickness (inches)	Natural Gas Costs				
	\$1/MCF	\$2/MCF	\$3/MCF	\$4/MCF	\$5/MCF
	(r)	(r)	(r)	(r)	(r)
0	0	0	0	0	0
1	10.69	21.37	32.05	42.74	53.42
2	13.65	27.30	40.95	54.60	68.25
3	15.16	30.32	45.48	60.64	75.80
4	16.38	32.76	49.14	65.52	81.90
5	17.06	34.12	51.48	68.24	85.30
6	17.59	35.18	52.77	70.36	87.95

Table D.12 Optimum Thickness of Insulation and Optimum Annual Costs of Heating and Insulation at Various Energy Costs

Energy Source: Natural Gas

Construction: Walls.

Natural Gas Cost \$/MCF	Optimum Insulation Thickness (inches)	Optimum Heating Costs \$	Optimum "U"
1	1.02	46.50	0.13
2	1.87	73.84	0.094
3	2.51	93.97	0.0769
4	3.06	110.93	0.0665
5	3.53	125.86	0.0596

Table D.13 Optimum Thickness of Insulation and Annual Heating Costs at
Various Natural Gas Prices

Energy Source: Natural Gas

Construction: Floor

Natural Gas Price (\$/MCF)	Optimum Insulation Thickness (inches)	Optimum Annual Heating Costs (\$)	Optimum "U"
1	1.11	22.589	0.13
2	1.96	34.811	0.092
3	2.62	44.198	0.075
4	3.17	52.113	0.065
5	3.66	59.033	0.058

Table D.14 Optimum Annual Heating Costs at Natural Gas Price of 1 \$/MCF

Energy Source: Natural Gas

Construction: Floor

Insulation Thickness (inches)	"U"	Annual Heating Cost (\$)	Annual Insulation Cost (\$)	Total Annual Cost (\$)
0	0.28	31.20	0	31.20
1	0.138	15.38	7.3	22.68
2	0.0916	10.21	14.6	24.81
3	0.0684	7.61	21.9	29.52
4	0.0546	6.08	29.2	35.28
5	0.0454	5.08	36.5	41.58
6	0.0389	4.33	43.8	48.13

Table D.15 Optimum Thickness of Insulation, and Optimum Annual Heating
Costs at Various Natural Gas Prices

Energy Source: Natural Gas

Construction: Ceiling

Natural Gas Price (\$/MCF)	Optimum Insulation Thickness	Optimum Annual Heating Cost	Optimum "U"
1	1.28	26.21	0.133
2	2.12	39.51	0.094
3	2.77	49.86	0.077
4	3.31	58.12	0.066
5	3.79	65.67	0.059

Table D.16 Optimum Annual Heating Costs at Natural Gas Price of \$1/MCF

Energy Source: Natural Gas

Construction: Ceiling

Insulation Thickness (inches)	"U"	Annual Heating Cost (\$)	Annual Insulation Cost (\$)	Total Annual Cost (\$)
0	0.358	43.28	0	43.28
1	0.200	24.18	7.92	32.10
2	0.110	13.30	15.84	29.14
3	0.080	9.67	23.76	33.43
4	0.061	7.37	31.68	39.05
5	0.050	6.04	39.60	45.64
6	0.042	5.08	47.52	52.60

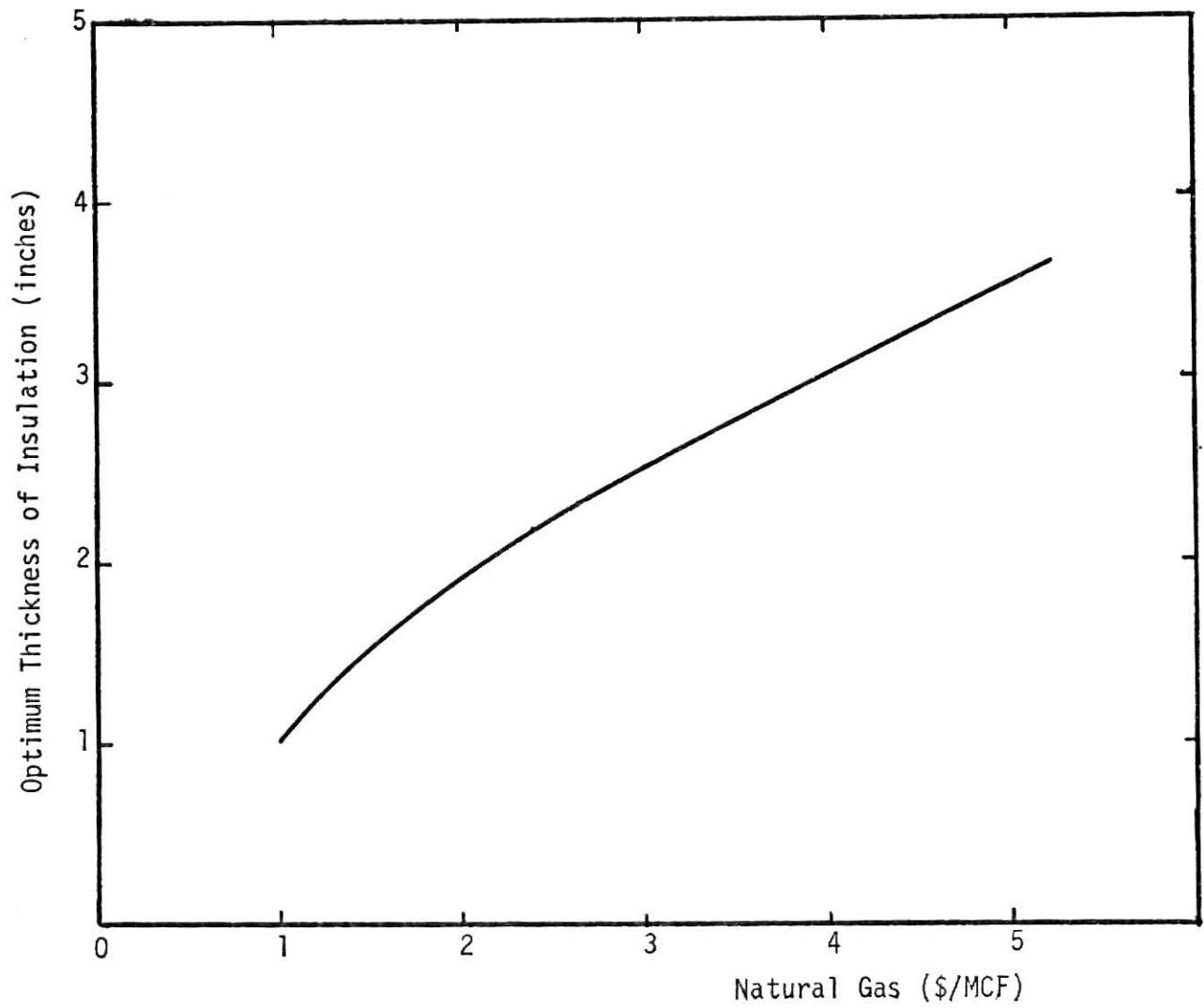


Fig. D.16 Optimum Thickness of Insulation at Various Natural Gas Costs

Energy Source: Natural Gas

Construction: Wall.

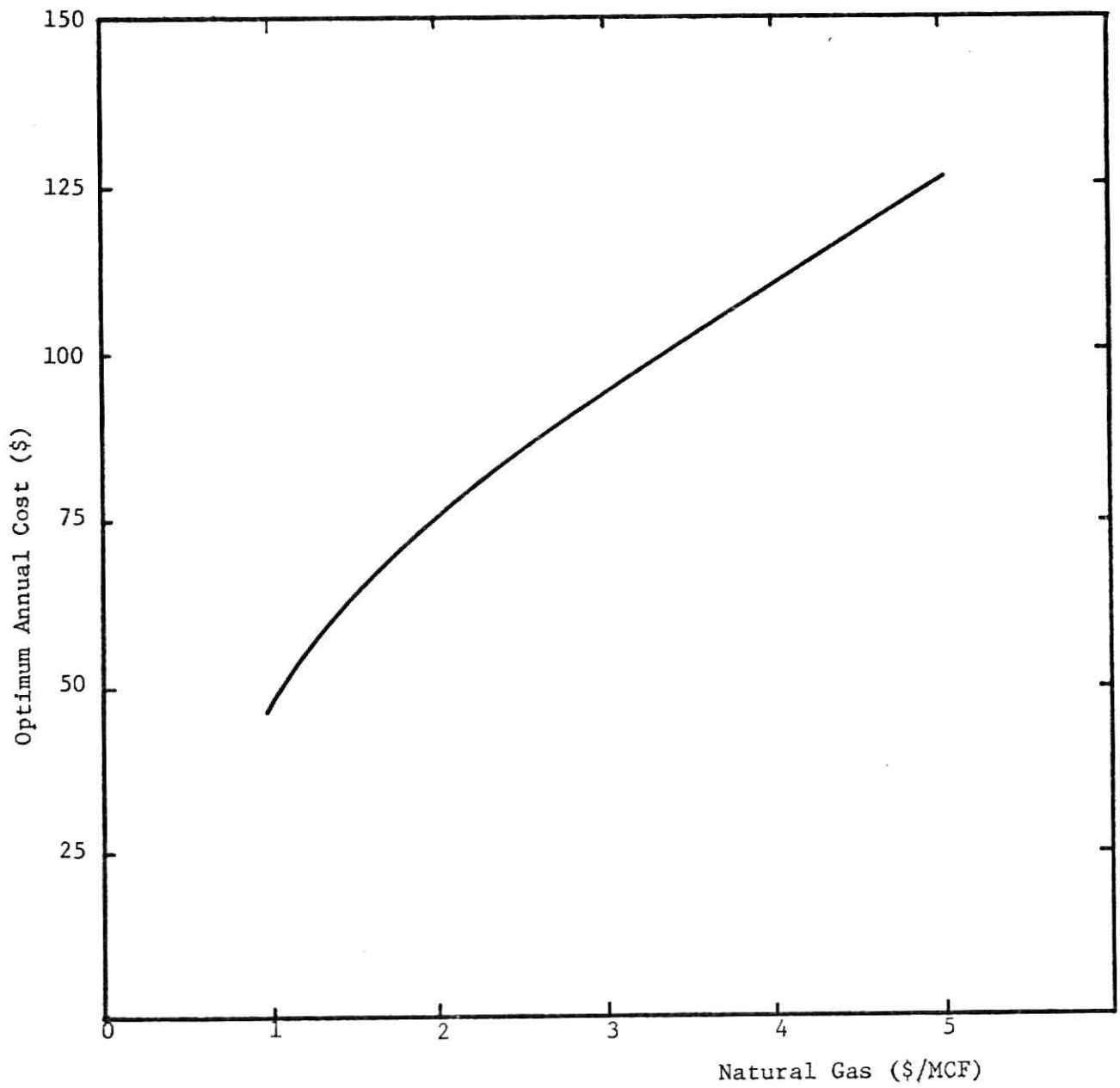


Fig. D.17 Optimum Annual Costs of Heating and Insulation at Various Natural Gas Costs

Energy Source: Natural Gas

Construction: Walls

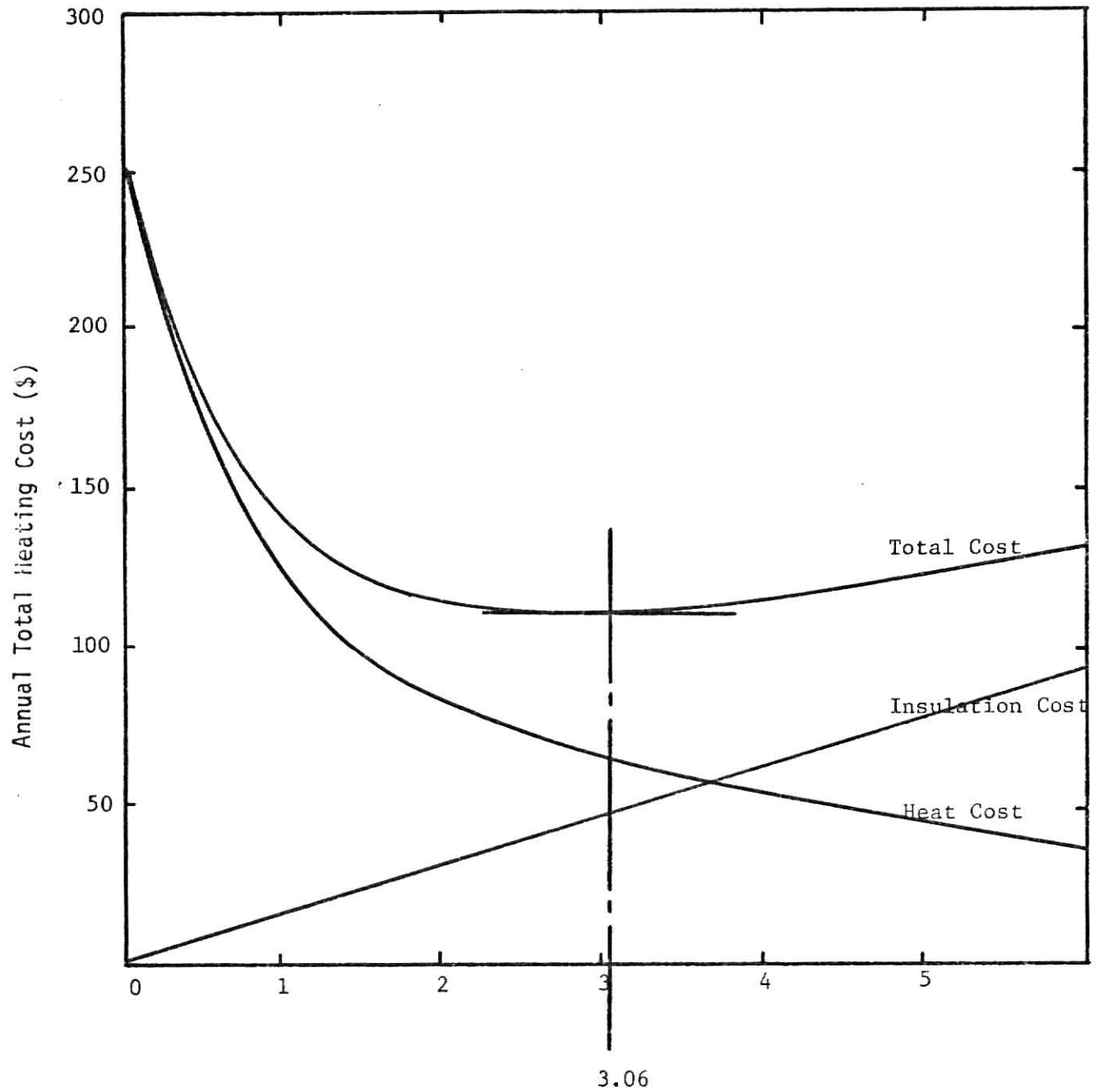


Fig. D.18 Optimum Heating Costs and Optimum Thickness of Insulation

Energy Source: Natural Gas at (\$4/MCF)

Construction: Walls.

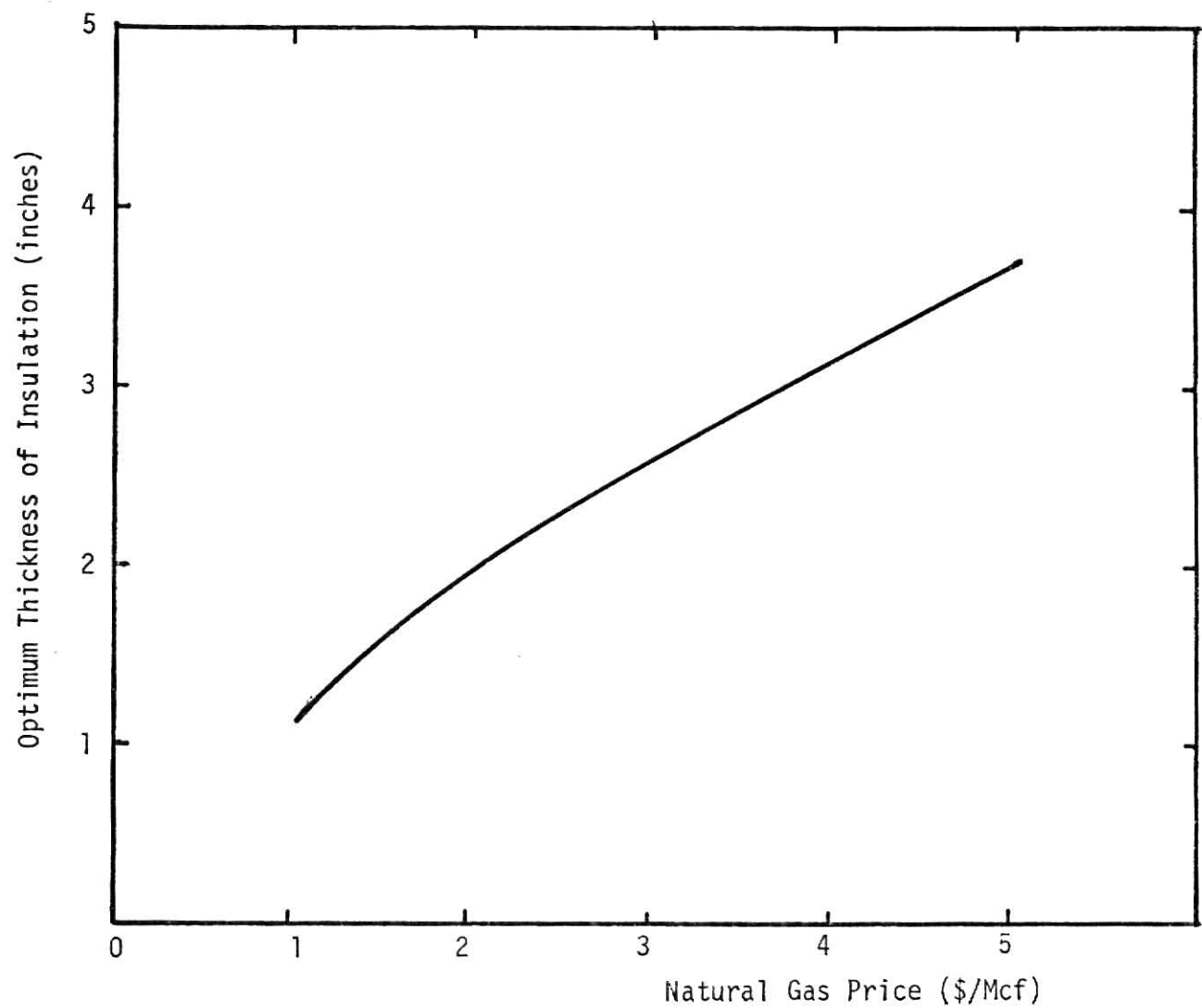


Fig. D.19 Optimum Thickness of Insulation at Various Natural Gas Prices

Energy Source: Natural Gas

Construction: Floor

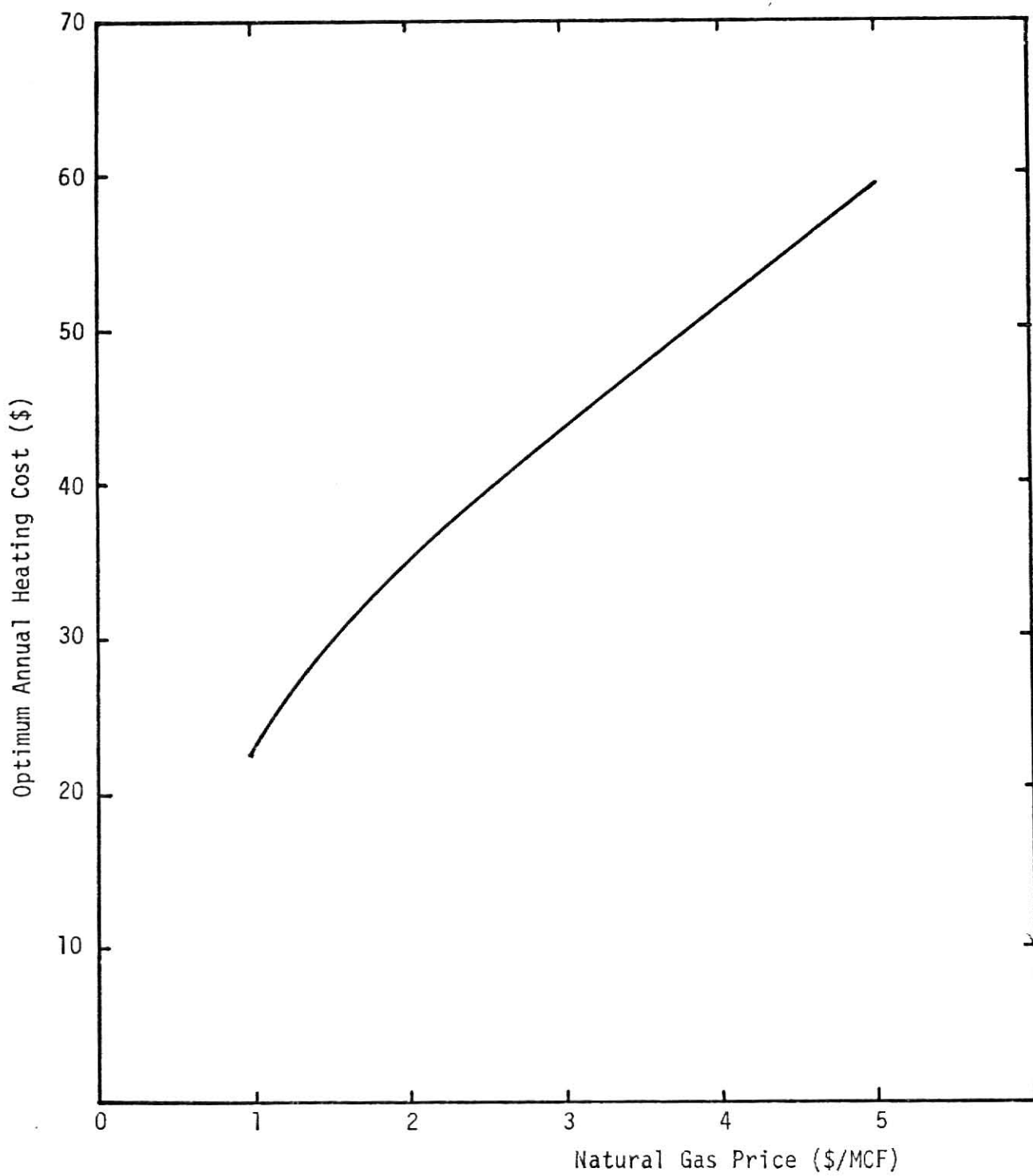


Fig. D.20 Optimum Annual Heating Cost at Various Natural Gas Prices

Energy Source: Natural Gas

Constructon: Floor

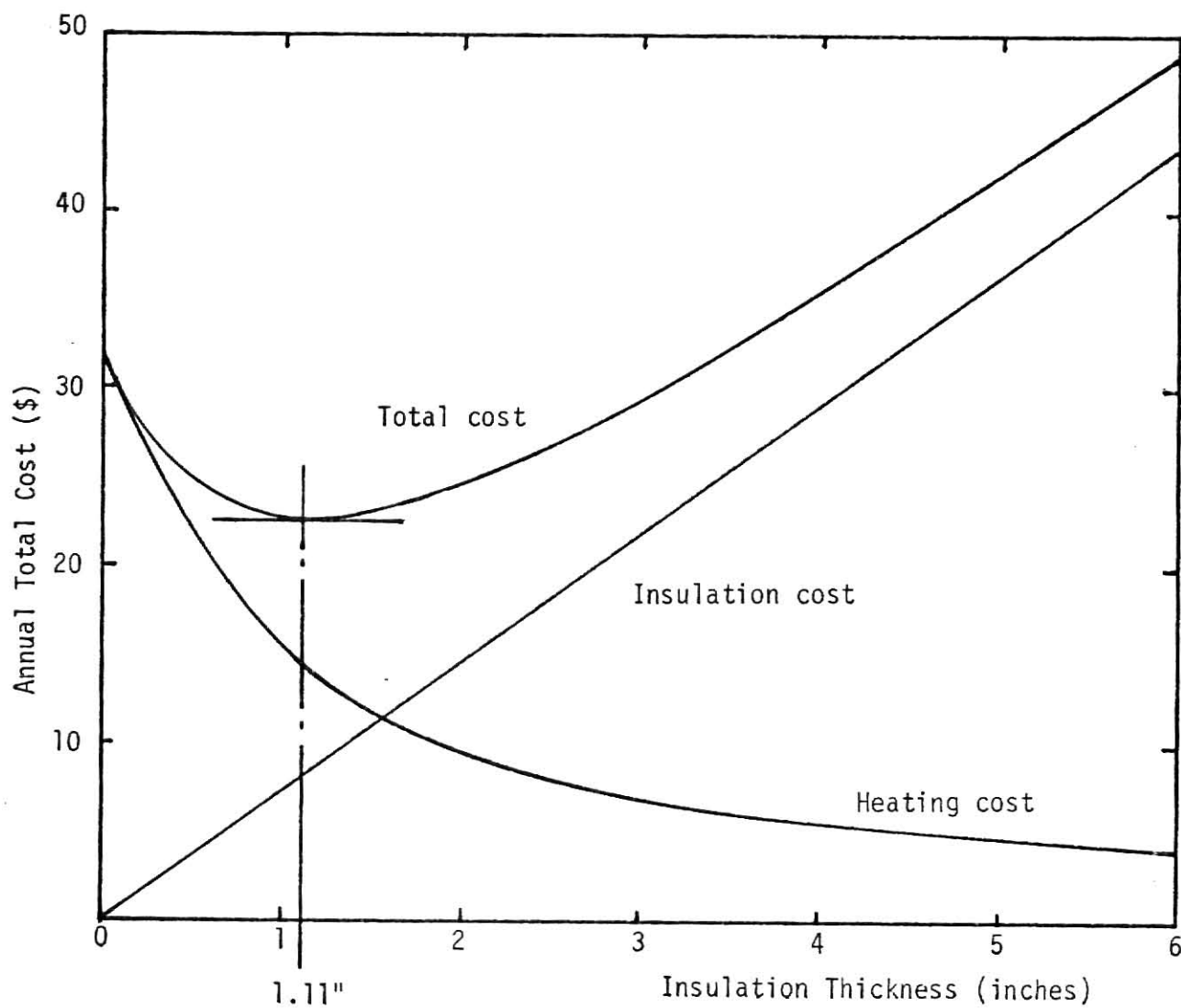


Fig. D.21 Optimum Total Annual Heating Costs at Natural Gas Price of \$1/MCF

Energy Source: Natural Gas

Construction: Floor

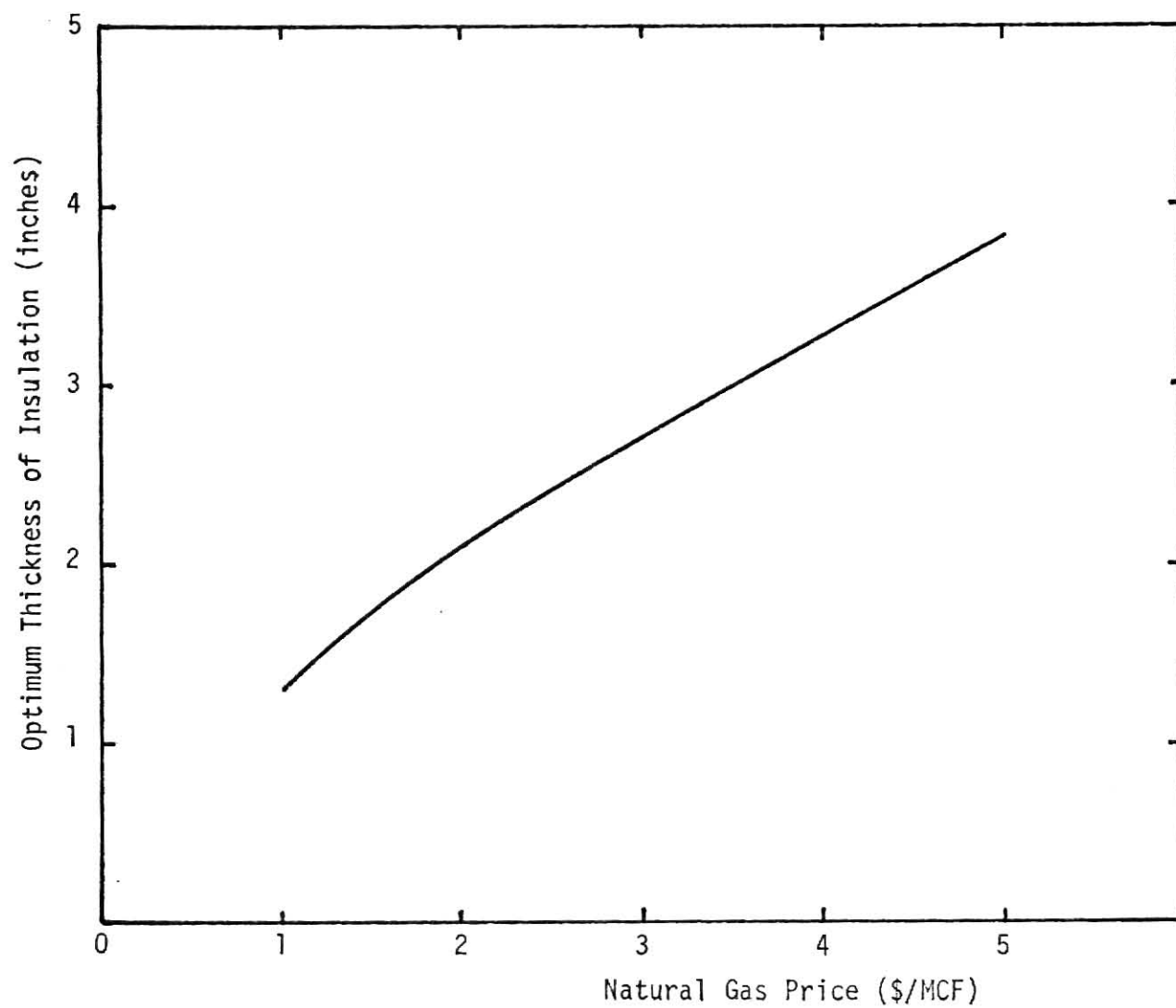


Fig. D.22 Optimum Insulation Thickness at Various Natural Gas Prices

Energy Source: Natural Gas

Construction: Ceiling

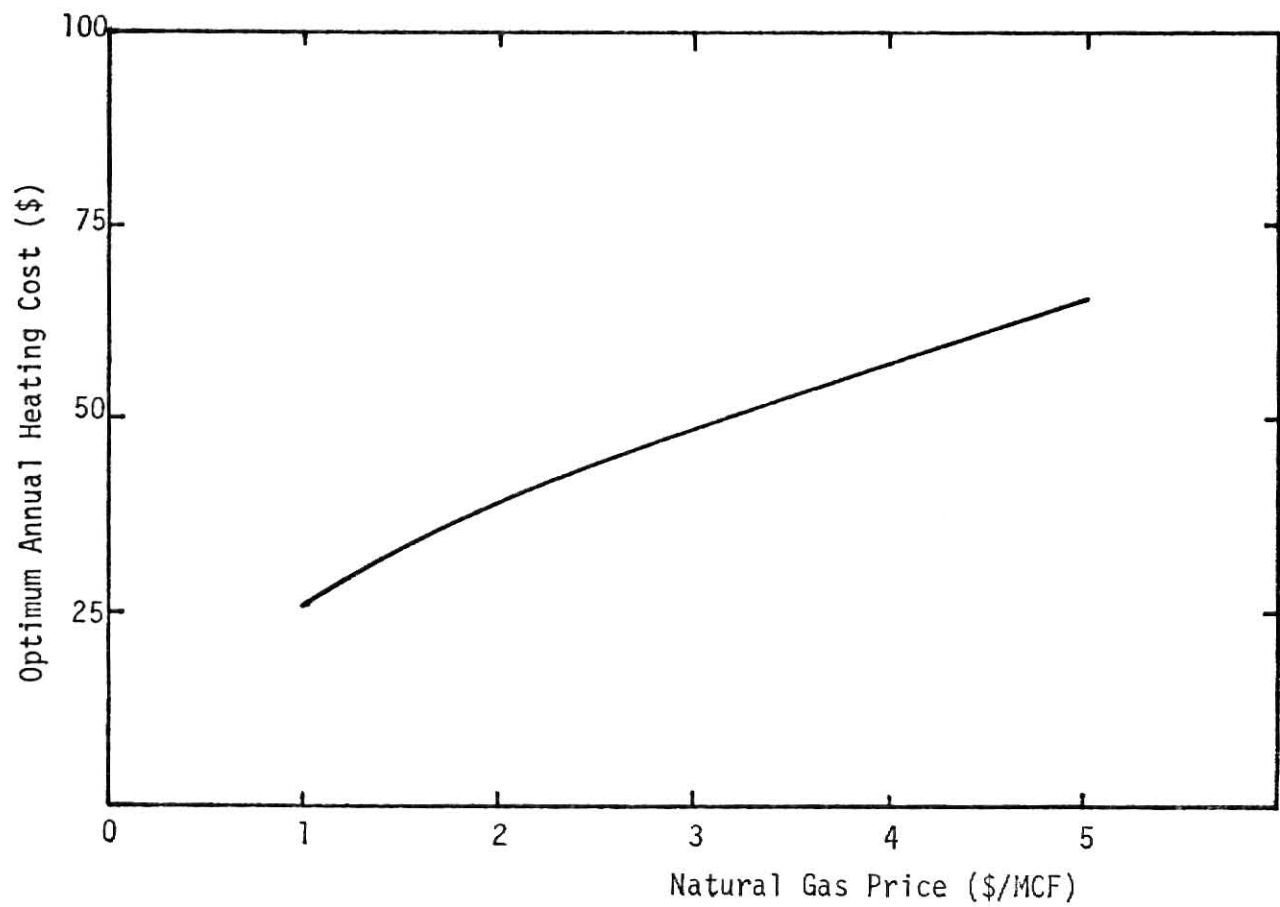


Fig. D.23 Optimum Annual Heating Cost at Various Natural Gas Prices

Energy Source: Natural Gas

Construction: Ceiling

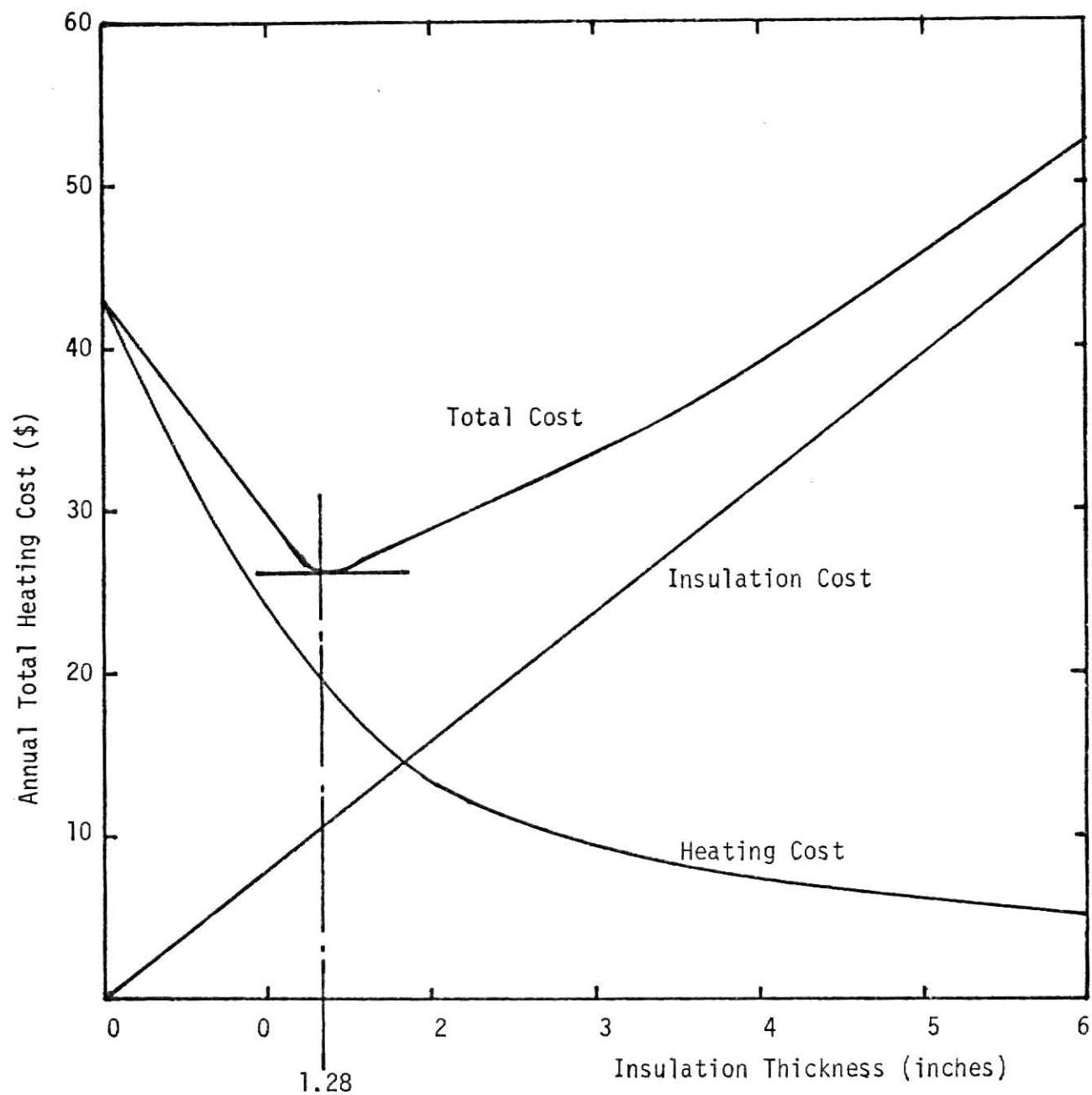


Fig. D.24 Optimum Total Annual Heating Cost at Natural Gas Price of (\$1/MCF)

Energy Source: Natural Gas

Construction: Ceiling

THE TECHNICAL AND ECONOMICAL FEASIBILITY OF SOLAR ENERGY UTILIZATION
FOR DOMESTIC ENVIRONMENTAL CONTROL IN THE STATE OF KANSAS

by

YOSEF SHUKRI SHERIF

B.S. (in Electrical Engineering)
Kansas State University, 1962

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the
requirements for the degree

MASTER OF SCIENCE

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Kansas State University
Manhattan, Kansas

1976

ABSTRACT

It has been studied and shown that utilization of solar energy for heating and cooling of residential housing in the state of Kansas is technically and economically feasible. A two-story model house with an effective area of 1520 ft^2 , and a volume of 15048 ft^3 can adequately be heated and cooled by a flat plate solar heat collector and its auxiliaries. The flat plate collector uses copper as absorber, and two glass covers as heat attenuators. It is roof mounted, south facing, and tilted 50° from horizontal. The overall operating efficiency of the collector is 40% in the winter, and 20% in the summer.

The results show that a house of this volume in Kansas can be solar heated and cooled with a net savings of 130, 139 and 323 dollars per year depending on the solar energy to substitute natural gas, fuel oil, or electricity at 1973 energy cost index. The net revenue or money savings for Kansas if a policy of solar utilization is followed at the rate of 10,000 dwellings per year will range from one to three million dollars per year. If in the year 2000 energy costs increased three folds then the savings will range from three to ten million dollars. To sum up, solar energy utilization will save money, conserve energy, decrease pollution and enhance the quality of life.