RESIDENTIAL WATER HEATING: FUEL CONSERVATION, ECONOMICS, AND PUBLIC POLICY

PREPARED FOR THE NATIONAL SCIENCE FOUNDATION

JAMES J. MUTCH

R-1498-NSF
MAY 1974

Rand
SANTA MONICA, CA. 90406

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Solar corona photographed at the total eclipse of June 8, 1918, Green River, Wyoming.

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PREFACE

This report is part of Rand's continuing research program on *The Evaluation of Measures to Conserve Energy* funded by a grant from the National Science Foundation, with Deane N. Morris as the principal investigator. The general focus of the program is on the rapid increase in demand for energy in all sectors of the U.S. economy, the conflict between this demand and the national goal of reducing our dependence on foreign energy supplies, and the implications of this conflict for governmental policymaking.

One of the important energy-consuming services of the residential sector is domestic water heating, which ranks second only to environmental space heating in this respect. The purpose of this report is to bring together the pertinent data on this subject and to summarize possible procedures for reducing the quantities of energy needed for furnishing residential hot water.

The impacts of future changes in the prices of fossil fuel based energy, as well as the impacts of measures requiring water heater design changes and improvements are analyzed. This report should be of interest to legislators, policymakers, and others who are involved in energy conservation. Forthcoming reports will deal with the other major energy-consuming end uses of the residential sector.

Other Rand reports related to this study include:

R-1116-NSF/CSA, *California's Electricity Quandary: III. Slowing the Growth Rate*, by R. D. Doctor, et al., September 1972.

R-1297-NSF, *Residential Energy Use: An Econometric Analysis*, by K. P. Anderson, October 1973.

SUMMARY

Hot water is one of the largest and, at the same time, least apparent uses of energy in the home. If we are surprised to learn that it accounts for 15 percent of residential energy consumption and 3 percent of energy for all uses in the United States, it is probably because our water heaters are installed in obscure places and forgotten until they break down. The energy they consume is often overshadowed and hidden in our monthly fuel bills by space heating, air conditioning, lighting, cooking, and other more obvious uses. Moreover, water heaters now on the market are relatively inexpensive and uniform items compared to other major appliances; we may not stop to consider efficiency when purchasing them.

In the United States, residential water heaters consume substantial amounts of electricity, natural gas, fuel oil, and liquefied petroleum gas (LPG), also called bottled gas. The purpose of this study is to examine possible alternatives that may reduce the amount of fossil fuel based energy needed to furnish residential hot water. Two categories of alternatives are considered: those that reduce thermal losses from the water heating system and those that reduce the non-renewable energy requirements of the system. The economic cost or benefit of each measure to the consumer is examined as a function of the price of fuel, allowing comparison of different fuel conservation approaches in terms of their life cycle costs. Finally, the potential of government policy as a tool for implementation of economically beneficial fuel conservation alternatives is discussed.

Alternatives that may reduce thermal losses from residential water heating systems include application of thicker tank insulation than is now available on water heaters, lowering the temperature at which hot water is maintained in the tank, insulating exposed hot water plumbing, and installing a timing mechanism to automatically shut down the water heater during periods when little or no hot water is used.

Standard electric water heaters normally have 2 inches of fiberglass or mineral wool insulation covering the tank, while fossil fuel

units usually have 1 inch. Heat lost through the insulation accounts for about 20 percent of the annual energy use for a typical electric unit and about 35 percent for typical fossil fuel units. Thicker tank insulation is perhaps the most effective means of reducing these losses. Depending on the amount of insulation added, annual fuel savings of 5 to 11 percent of total use are possible for electric units and savings from 21 to 26 percent are possible for fossil fuel units. Factory installation is economically superior, but this option is not normally available to consumers in today's market. Retrofitting extra insulation to a standard unit gives essentially identical performance but requires a higher investment and is therefore justified only at higher fuel prices.

Lowering the hot water storage temperature is capable of reducing annual fuel use by about 5 percent per 10°F reduction on units with standard tank insulation. After addition of thicker insulation, this drops to about 2 percent per 10°F reduction. To the extent that temperature reduction does not interfere with the availability of hot water in the home, it yields a net fuel cost saving to the consumer since it requires no additional investment. Insulating exposed plumbing and automatic shutdown during non-use may reduce fuel use by 1.6 percent and about 0.5 percent, respectively, but can only be economically justified at extremely high fuel prices.

The table summarizes measures to reduce thermal losses from water heating systems.

Reducing non-renewable energy requirements to heat water can be accomplished by employing solar energy. Solar technology has been available for some time and is used in many parts of the world. In the United States, high investment costs and historically low prices of competing fuels have prevented its widespread use. However, application of improved technology to lower costs and the increasing prices of fossil fuel based energy forms suggest that solar energy may become a competitive option. From our analysis, it appears that combination solar-electric water heaters, which use an electric booster to provide hot water during extended cloud cover, may now be competitive with

EFFECT OF ALTERNATIVE MEASURES TO REDUCE THERMAL LOSSES FROM RESIDENTIAL WATER HEATERS

Alternative Measure	Extent of Measure	Type of Water Heater	Fuel Price Necessary to Justify	Percent Reduction In Annual Fuel Use
Increased tank insulation	4 inches to 7 inches	electric	1¢ to 4¢/kWh	8.2 to 11.0
	3 inches to 5 inches	fossil fuel	10¢ to 40¢/therm	21.6 to 25.0
Lower hot water temperature	per 10°F reduction	electric	(a)	4.5
		fossil fuel	(a)	5.8
Hot water plumbing insulation	per 25 ft of exposed tubing	electric	3.5¢/kWh	1.6
		fossil fuel	70¢/therm	1.6
Automatic water heater shut down	during periods of non-use	electric	15¢/kWh	0.2
		fossil fuel	90¢/therm	0.6

NOTE: Percentage reductions in fuel use are not directly additive.

[a]Lower hot water temperature is economically justified at any fuel price since it requires no additional investment.

all-electric systems in areas of the United States where solar conditions are good and electricity is relatively expensive. Although combination solar-fossil fuel units are also a possible substitute, they can be economically justified as alternatives to conventional units only at very high fuel prices. Hence, they were not considered here. Solar water heaters may, of course, be designed to generate any amount of hot water by providing a large enough solar collector surface. But, since the collector is the most expensive component, the size and capacity justified are very sensitive to the price of competing fuels.

Although many of these alternatives are to the consumer's economic benefit, effective penetration of the manufacture, marketing, and installation of more efficient water heaters in the residential sector may require adoption of suitable policies by appropriate government bodies. Both price policies--those that change the investment and operating costs of water heating systems--and non-price policies--those that explicitly encourage the production and utilization of efficient devices through consumer education, tax incentives, or performance standards--can be effective in implementing conservation on a widespread basis. However, caution must be exercised in formulating price policies to avoid regressive effects on low-income families.

It appears from this analysis that, in the long run, depending on future fuel prices, *effective policies could reduce aggregate end use energy consumption by residential water heating by between 26 and 68 percent in the United States. These equate to savings of 40 to 68 percent in raw energy requirements that, by 1990, could amount to savings between 580,000 and 980,000 equivalent barrels of oil per day.*

ACKNOWLEDGMENTS

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1. INTRODUCTION

Hot water at the tap is a commodity that we have customarily taken for granted in the United States. In the home, it is used to wash dishes and clothes, for general household cleaning, for showering and bathing, and for other personal hygiene. A typical family may use between 50 and 80 gallons of hot water each day, or about 15 to 20 gallons per person.

It is estimated that residential water heating accounts for about 15 percent of energy use in the home and 3 percent of the energy for all uses in this country [1]. After space heating, it constitutes the largest single use of energy in the home and, from 1960 to 1968, its energy consumption increased an average of 5.2 percent per year, compared to an annual increase in total energy consumption for all uses of 4.3 percent [1].

In 1970, over 95 percent of all occupied households had hot water systems of which about 55 percent were natural gas-fired systems, 25 percent were electric, 10 percent were oil-fired, and 5 percent fired by liquefied petroleum gas (LPG). The remaining homes either did not have hot water systems or used coal, wood or other fuels. As shown in Table 1, the saturation* of water heaters by these fuels varies considerably in different regions of the country [2]. Figure 1 shows the regions referred to in Table 1. A homeowner's choice of fuel depends on the proximity of his home to existing fuel services, on the relative prices of the fuels available to him, and on his own preference, among others [3]. For example, the 75 percent saturation of natural gas water heaters in the West South Central region is not surprising since the country's most productive gas fields are located there and the price of natural gas has been low. Conversely, in the New England States, both natural gas and electricity have been relatively expensive compared to fuel oil, leading to a fuel oil water heater saturation of over 40 percent. The effect of location (urban or rural) on fuel choice is primarily a result of the fact that in most areas of the country

*The saturation of an appliance is the fraction of total households which own that appliance.

Table 1

1970 SATURATION OF WATER HEATING SYSTEMS
BY TYPE OF FUEL

(Percent of all occupied housing units)

Region	Electric	Natural Gas	LPG	Fuel Oil	Other/ None
New England	21.3	31.0	4.1	41.4	2.2
Middle Atlantic	13.0	48.4	2.5	32.5	3.6
East North Central	22.9	67.9	3.9	1.6	3.7
West North Central	23.5	61.3	10.4	1.0	3.8
South Atlantic	50.1	30.9	5.1	5.3	8.6
East South Central	43.4	37.0	5.5	0.1	14.0
West South Central	8.6	75.1	9.7	--	6.6
Mountain	22.9	67.9	6.0	--	3.2
Pacific	26.1	69.2	2.9	0.8	1.0
United States	25.4	55.1	5.0	9.8	4.7

Source: Ref. 2.

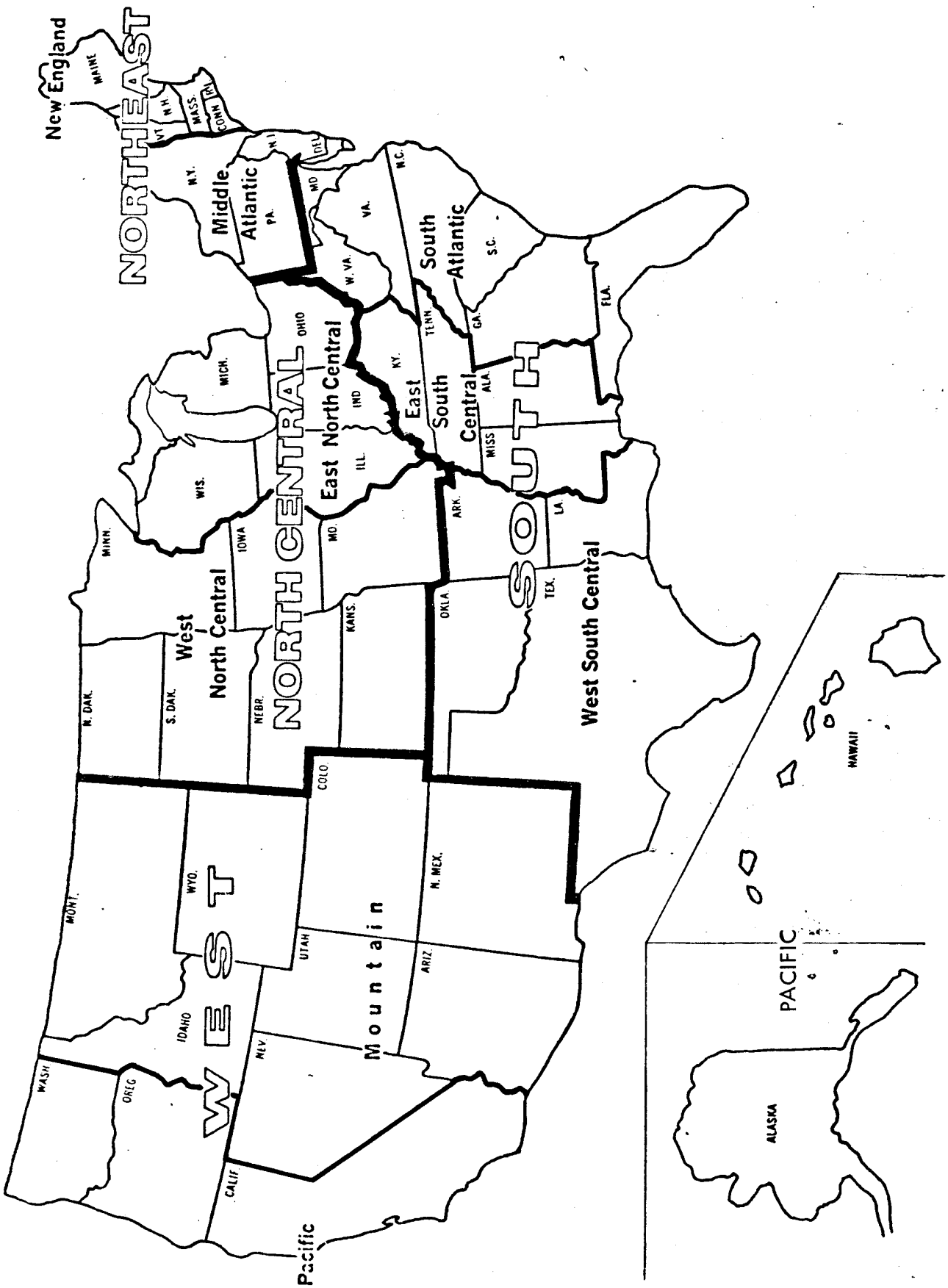

Fig. 1 — Regions and geographic divisions of the United States

natural gas pipeline service is available only in urban areas. Thus, the saturation of natural gas water heaters is generally higher in predominantly urban regions and lower in mainly rural regions.

The increasing amount of energy devoted to residential water heating may be explained both by growth in the stock of installed units and by increasing consumption per unit. For example, the average energy consumption of a standard electric water heater increased from 3675 kWh per year in 1950 to 4219 kWh in 1969 [4]. The reason for this is the increasing demand for hot water in the household spurred by greater affluence and convenience. Modern quick-recovery water heaters are capable of providing virtually unlimited supplies of hot water to the household, eliminating the need for careful planning of hot water use.

The use of more hot water has also led to the installation of heaters with greater storage capacity. During the 1950's, residential electric water heater sales were in the 30- to 40-gallon capacity range. During the 1960's, sales were predominantly in the 40- to 50-gallon range [5]. A similar trend has occurred in sales of other types of water heaters. Currently, the size of residential water heaters sold centers around 50 gallons for electric units and 40 gallons for fossil fuel units. The trend to larger units has led to increased energy consumption per unit because of the greater heat loss associated with the increased surface area of the storage tank. For example, other things being equal, a 50-gallon electric water heater with 2 inches of insulation will use about 7 percent more electricity than a similar 30-gallon unit; a 40-gallon natural gas heater with 1 inch of insulation will consume about 5 percent more gas than a 30-gallon unit.

The purpose of this study is to examine changes that can be made in water heating technology to reduce its energy requirements. To do this, we examine each measure in an economic cost-benefit framework in which the costs are the incremental dollars which must be invested by the consumer to institute the measure, and the benefits are the dollars saved in operating (fuel) expenses over the lifetime of the water heater.

Government policies are suggested which will encourage the implementation of these measures and the consequent reduction in water heating energy requirements.

By combining these micro-analyses with housing unit and saturation projections, we examine how the aggregate demand for water heating energy might respond to various future government policies. This is intended to aid policymakers in determining which policies will be most effective in conserving residential water heating energy and what the consumer costs of those policies will be.

It should be noted that the measures and policies examined in this study are aimed at reducing the energy required to heat a given amount of water to some acceptable temperature, i.e., *to reduce heat losses from the system.* Reducing the amount of hot water used in residences is not considered *per se*, although policies which result in higher cost to the consumer may have such an effect as well.

II. RESIDENTIAL WATER HEATING SYSTEMS

DESCRIPTION

Virtually all residential hot water systems are of the storage-distribution type. These contain a central water storage tank equipped with one or more thermostatically controlled heating elements. Cold service water is introduced near the bottom of the tank to keep it nearly full as hot water is drawn for use. When the tank water temperature falls below the desired temperature, the thermostat turns on the heating element until that temperature is again reached. Most water heaters have a manually adjustable thermostat, typically with three temperature selections:

- o *warm* or *low*: 110 - 120°F
- o *medium* or *normal*: ~ 140°F
- o *hot* or *high*: ~ 160°F

Larger commercial units may have settings as high as 180°F.

The interior of the storage tank is usually lined with fiberglass to inhibit corrosion, and the tank surface is covered with a blanket of fiberglass or mineral wool insulation to retard heat loss and to prevent burns if touched. Insulation is normally 2 inches thick on electric water heaters and 1 inch thick on other types.* The entire unit is enclosed in a steel jacket.

Natural gas, LPG and oil water heaters have a burner underneath the tank firing into a heat transfer flue that runs up the center of the tank and vents into the atmosphere. A standing pilot light provides burner ignition. Heat inputs range from about 35,000 to 75,000 Btu per hour for a 40-gallon unit. Direct burner efficiency, the fraction of combustion heat transferred to the water, is about 70 percent for natural gas and LPG units and about 67 percent for oil-fired types.**

*Thicker insulation on electric units is itself evidence of the conservation potential of increased insulation. The higher cost of electricity requires better insulation to make electric water heaters a marketable alternative to other types.

**Determined from manufacturers' ratings. See Appendix A.

Electric water heaters come in two types. The standard heater has either one or two immersion-type resistance heating elements, each usually rated at about 8500 Btu/hour (2500 watts). The quick-recovery heater has an upper and a lower element of a higher rating, usually between 13,500 and 19,000 Btu per hour (4000 to 5500 watts) each. This design provides faster recovery of hot water during periods of high use. Since the heating elements are immersed directly in the water, heat transfer to the water is nearly 100 percent efficient.*

DISPOSITION OF ENERGY USE IN RESIDENTIAL WATER HEATERS

Before considering measures to reduce water heating energy requirements, we examine the amount of fuel consumed in average use and the energy balances within the several types of water heaters.

The energy that must be devoted to hot water heating in a household depends on the residents' demands, the temperature at which the water is maintained, the size of the storage tank, the thickness of thermal insulation provided, and the type of fuel used to heat the water, among others. Based on published estimates of energy use and accounting for heat losses, it appears that an average household uses about 50 gallons per day of water at 140°F, which equates to about 118 therms per year of net usable heat.** Thermal losses by conduction through the tank walls and by convection up the flue (for combustion types) increase the total heat input required to provide this amount of usable heat.

Table 2 shows the estimated disposition of the annual heat input to residential water heaters. Only about 45 percent of the heat input to gas/LPG and oil units is available to the consumer as usable heat in the water. Some 35 percent of the heat is lost through the tank

*Determined from manufacturers' ratings. See Appendix A.

**One therm = 100,000 Btu. One Btu is the amount of heat required to raise the temperature of one pound of water one degree Fahrenheit; one Btu = 0.252 calorie = 1056 joule = 0.2932 watt-hour.

surface and the remainder goes up the flue. Electric units are about 80 percent efficient because the heating elements are immersed directly in the water and because the tank carries 2 inches of thermal insulation compared to only 1 inch for most combustion types.

Table 2

ESTIMATED DISPOSITION OF THE ANNUAL ENERGY INPUT TO RESIDENTIAL WATER HEATERS

Type of Water Heater	Total Heat Input	Heat Lost Through Tank Surface	Heat Lost Up Flue		Net Usable Heat
			Burner Firing	Pilot Light[a]	
50-gallon electric					
therms	150.3	31.8	--	--	118.5
percent	100.0	21.2			78.8
40-gallon gas/LPG					
therms	260.3	91.0	31.1	19.7	118.5
percent	100.0	35.0	12.0	7.6	45.5
40-gallon fuel oil					
therms	271.9	95.0	36.7	21.7	118.5
percent	100.0	35.0	13.5	8.0	43.5

NOTE: These are end-use amounts of energy. Because electricity is largely generated from fossil fuels at an efficiency of about 30 percent, an electric water heater actually requires about 500 therms per year of raw energy, for which the net efficiency is about 24 percent.

[a]Assuming a 750 Btu/hr pilot and efficiency of heat transfer to the water of 70 percent for gas/LPG units and 67 percent for oil units.

III. CONSERVATION ALTERNATIVES

Alternative measures to reduce the energy requirements for heating residential water may be oriented either toward the consumer or toward the water heating system itself. A menu of possible conservation opportunities is shown in Table 3.

Consumer-oriented measures are those explicitly causing a reduction in hot water use and are implemented either voluntarily or at the urging of public authorities. Consumers could reduce their usage by washing laundry in warm or cold water where possible, by avoiding automatic dishwashers, and by reducing waste in general. Although these measures can be very effective, they are done at the individual's discretion and probably cannot practically be ensured or enforced on an aggregate basis. They are not discussed further here.

System-oriented measures fall into two categories: reducing thermal losses from the system and reducing its non-renewable energy requirements. Measures in these categories are discussed below.

REDUCING THERMAL LOSSES

Storage Tank Insulation

As we saw in Table 2, conductive heat loss through the walls of the hot water storage tank represents about 20 percent of the electricity use of a 50-gallon electric water heater and about 35 percent of the fuel consumption of fossil fuel units. This is due to the relatively high temperature gradient between the hot water and external air and low thermal insulation levels. Most electric residential units on the market have 2 inches of fiberglass or mineral wool around the tank, while most other types have but 1 inch. Clearly, increased insulation over standard levels could reduce both energy use and the householder's fuel bill. The question is, what is the relationship of the cost of extra insulation to the fuel savings, and is there a point at which the dollars saved on fuel offset the dollars invested in extra insulation?

Table 3

OPPORTUNITIES FOR REDUCING ENERGY REQUIREMENTS
IN RESIDENTIAL WATER HEATING

CONSUMER-ORIENTED

o *Reduce Hot Water Use*

SYSTEM-ORIENTED

o *Reduce Thermal Losses*

-- increase tank insulation
-- alter heating cycle
-- lower water temperature
-- insulate water distribution system

o *Reduce Non-Renewable Energy Requirements*

-- use solar energy

The effect of increased insulation on annual energy consumption is given in Table A-2 of Appendix A and shown graphically in Fig. 2. The biggest gains with additional insulation can be made at the low insulation levels now standard on most units; incremental savings become smaller as more insulation is added. For example, going from 1- to 2-inch insulation on a 40-gallon gas/LPG unit would save about 44 therms/year (17 percent) while going from 5- to 6-inch insulation saves only 2 therms/year (1 percent). As insulation is added to a water heater, the initial cost of the unit increases while lower operating costs result from reduced heat losses. As higher initial costs are traded against lower operating costs, there should be insulation levels that yield lower total costs than other levels. Our object in this section is to examine these total costs at various insulation levels and to determine whether improvements over existing tank insulation would result in both lower total costs and lower fuel consumption.

The initial cost will be determined by the price of the water heater, including any additional insulation and larger steel jacket, and the installation cost. Extra insulation may be added either at

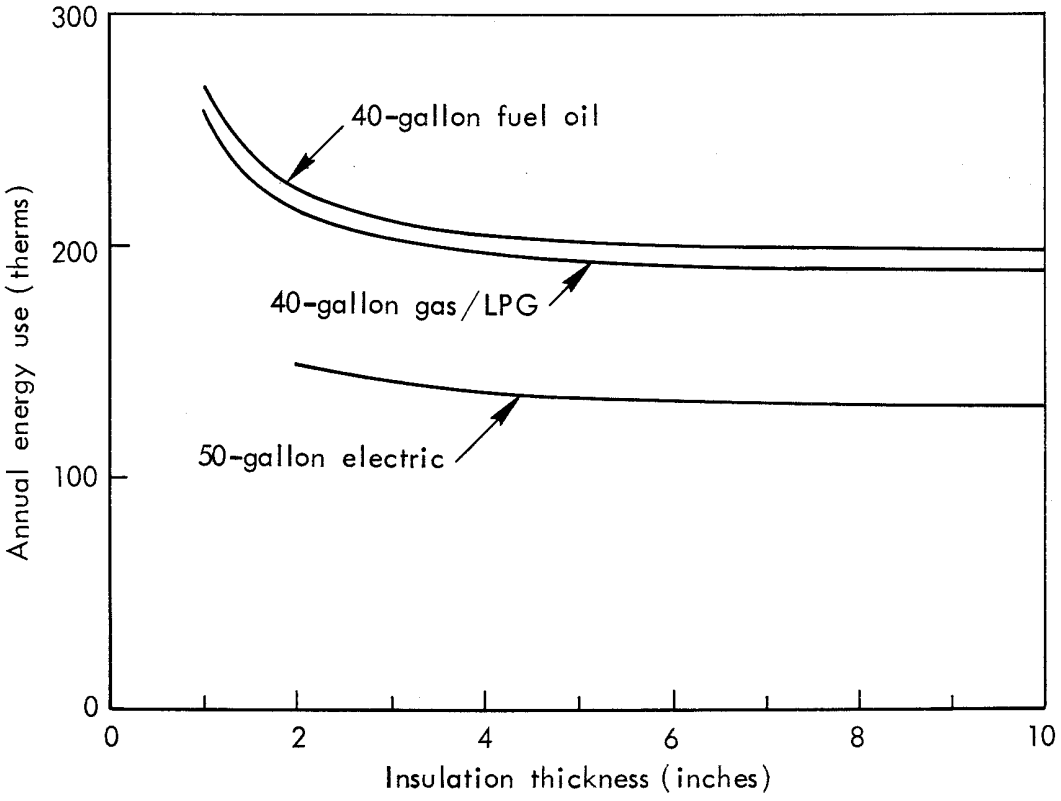

Fig. 2 — Annual energy use of residential water heaters as a function of tank insulation thickness

the factory during construction* or in the home after the unit is installed. If it is added at the factory, the consumer's total investment cost can be thought of as the cost of the unit with standard insulation, plus the cost of extra insulation, plus the incremental cost of a larger jacket, plus the cost of installing the unit in his home. We can similarly think of the total investment cost for retrofitting additional insulation after installation in the home as the sum of the standard water heater cost, the unit installation cost, the cost of extra insulation, and the cost of the labor to apply the insulation.** Typical costs for these various elements are listed in Table 4.

Table 4

INVESTMENT COST FACTORS FOR RESIDENTIAL WATER HEATERS

Item	Retail Price	Comments
50-gallon electric, 2-in. insulation	$90/unit	1972, Ref. 6
40-gallon gas/LPG, 1-in. insulation	$85/unit	1972, Ref. 6
40-gallon oil, 1-in. insulation	$85/unit	1972, estimated
Water heater installation	$35./unit	1973,[a]
Fiberglass or mineral wool insulation	$0.05/ft^2/in.	Oct. 1973, Ref. 7
Steel jacket (factory installed insulation only)	$0.55/ft^2	1973[b]
Labor (insulation retrofit only)	$1.30/ft^2	1972, Ref. 8

[a]Private communication with several plumbers.

[b]Twenty-two-gauge steel at $0.42/lb; based on personal contact with dealer. This includes 20 percent extra for installation and overhead charges.

*At present, the consumer does not have this option because most manufacturers offer only the standard level of insulation.

**In this case, extra insulation is applied over the jacket of the standard unit and a protective covering of plaster material is sprayed on.

The marginal price of fuel varies with type of fuel, location, and, for electricity and natural gas, with the amount used since they are sold on declining rate schedules. Table 5 shows the range and mean of summer 1973 marginal fuel prices paid by residential customers. In more recent months, prices of fuel oil and LPG have escalated considerably.

Table 5

MARGINAL RETAIL FUEL PRICES IN THE UNITED STATES, SUMMER 1973

Fuel	Range of Marginal Prices	Mean Marginal Price
Electricity[a]	0.70 - 3.82¢/kWh 20.5 - 112¢/therm	2.19¢/kWh 64.2¢/therm
Natural gas[b]	10.6 - 33.1¢/therm	18.7¢/therm
LPG[c]	13.0 - 21.2¢/gallon 13.6 - 22.2¢/therm	16.9¢/gallon 17.7¢/therm
No. 2 fuel oil[d]	20.4 - 23.9¢/gallon 14.7 - 17.2¢/therm	22.1¢/gallon 15.9¢/therm

Source: Ref. 9, pp. 4-6; Ref. 10, p. 25.

[a]Average price per kWh for 250-500 kWh/month; mean is an unweighted average of 23 Standard Metropolitan Statistical Areas (SMSA's).

[b]Average price per therm for 40 therms/month; mean is an unweighted average of 23 SMSA's.

[c]The range shown is bounded by the extreme statewide average prices paid by farmers in the U.S.; mean is a weighted U.S. average.

[d]Average price per gallon for 100 gallons; mean is an unweighted average of 12 SMSA's.

Although water heaters may fail for a number of reasons, the most common cause is tank corrosion leading to irreparable leaks. Published estimates of water heater lifetimes could not be found, but a consumer survey is available with information on the age distribution of residential water heaters in the existing stock [11]. A failure probability

analysis of this age distribution indicated an average lifetime between 7 and 12 years. Conversations with several manufacturers substantiate this range; a median value of 10 years is used in our analysis.

Estimated residential water heater investment costs and annual fuel use are shown in Table 6 as a function of the tank insulation thickness. Given the appropriate fuel price and the individual's discount rate, these factors may be used to estimate the life cycle cost of hot water as a function of the insulation thickness and thereby determine that thickness at which life cycle cost is a minimum. To illustrate the procedure and the effect of fuel price, an example follows.

Example: The economics of tank insulation

Conditions: Expected water heater lifetime - 10 years
Discount rate - 8 percent*
Range of fuel prices:
electricity - 1 to 4 cents/kWh
natural gas - 10 to 40 cents/therm
LPG - 10 to 40 cents/therm
No. 2 fuel oil - 20 to 40 cents/gallon
(15 to 30 cents/therm)

The life cycle cost of hot water to the consumer is his investment in the equipment plus the discounted present value of the fuel used throughout its life. Using the information in Tables 4 and 6 and the techniques discussed in Appendix B, we first determine the life cycle cost of water heaters with *standard tank insulation* over the fuel price range:

*This is an inflation-free, after-tax discount rate. (See Appendix B.)

Table 6

ESTIMATED WATER HEATER INVESTMENT COSTS AND ANNUAL FUEL USE
AS A FUNCTION OF TANK INSULATION THICKNESS

Insulation Thickness (inches)	50-Gallon Electric			40-Gallon gas/LPG			40-Gallon Fuel Oil[a]
	Investment Cost		Annual Fuel Use kWh	Investment Cost		Annual Fuel Use therms	Annual Fuel Use therms
	Factory	Retrofit		Factory	Retrofit		
1	--	--	--	*$120*	*$120*	*260.3*	*271.9*
2	*$125*	*$125*	*4400*	124	162	216.4	226.1
3	130	172	4158	129	170	204.0	213.1
4	135	180	4043	134	179	198.4	207.3
5	141	189	3982	140	189	195.1	203.9
6	147	199	3941	147	200	193.2	201.9
7	154	209	3917	155	211	192.0	200.6
8	162	221	3900	163	224	191.1	199.7
9	171	234	3888	173	237	190.6	199.1
10	181	248	3882	183	252	190.1	198.6

[a]Investment costs are the same as a 40-gallon gas/LPG unit.

NOTE: **Italicized** figures indicate current standard insulation levels.

Unit/Fuel Price	Life Cycle Cost	Unit/Fuel Price	Life Cycle Cost
50-gallon electric		40-gallon fuel oil	
1¢/kWh	$ 420	20¢/gallon	$383
2¢/kWh	715	30¢/gallon	514
3¢/kWh	1011	40¢/gallon	646
4¢/kWh	1306		
40-gallon natural gas/LPG			
10¢/therm	$ 295		
20¢/therm	469		
30¢/therm	644		
40¢/therm	819		

Then, using the same procedure, we determine the life cycle cost for each with additional insulation, either installed at the factory or retrofitted on a standard heater after installation in the home. For simplicity, the results are shown in Figs. 3a through 3c as the *marginal* life cycle cost or benefit compared to standard insulation.

Within the current range of energy prices, it appears that a reasonable amount of additional insulation installed at the factory would reduce the consumer's life cycle cost. However, since the consumer usually does not have this option in today's market, any extra insulation must be installed at his home after purchase. Labor costs make this method more expensive, but still economically justifiable for energy prices at the upper end of today's range. Shown in Table 7a is a summary of the minimum-cost insulation levels shown in the figures. The potential economic benefits to the consumer and the energy saved by improved tank insulation are both greatest for factory-installed insulation. The reduction in energy use possible by insulating to the economic optimum level ranges from 8 to 11 percent for electric units and from 21 to 25 percent for natural gas, LPG, and fuel oil units. This becomes more significant when we remember that the latter types account for three-quarters of all residences in the United States.

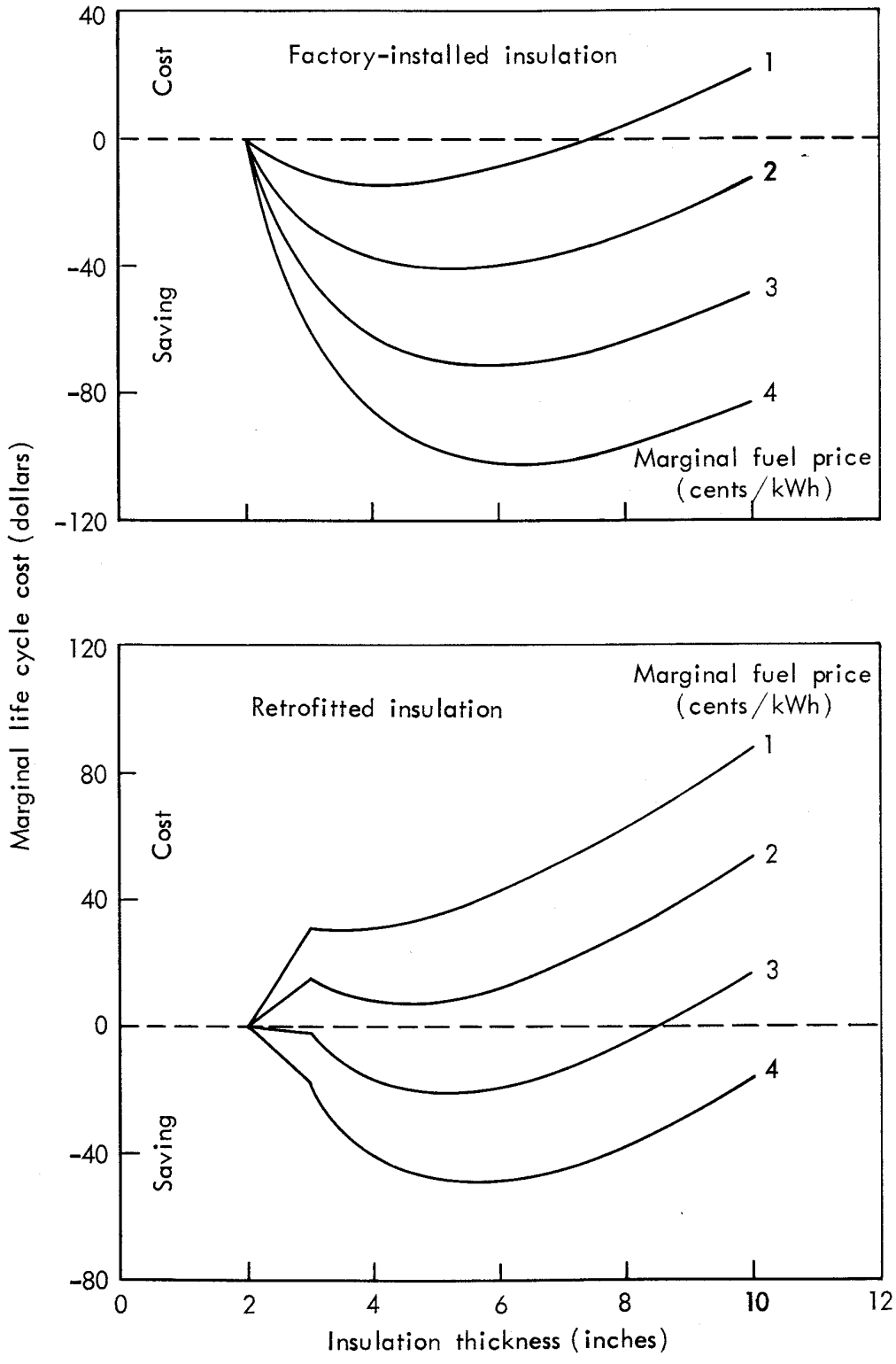

Fig. 3a — Marginal life cycle cost or benefit of extra tank insulation compared to standard insulation (50-gallon electric water heater)

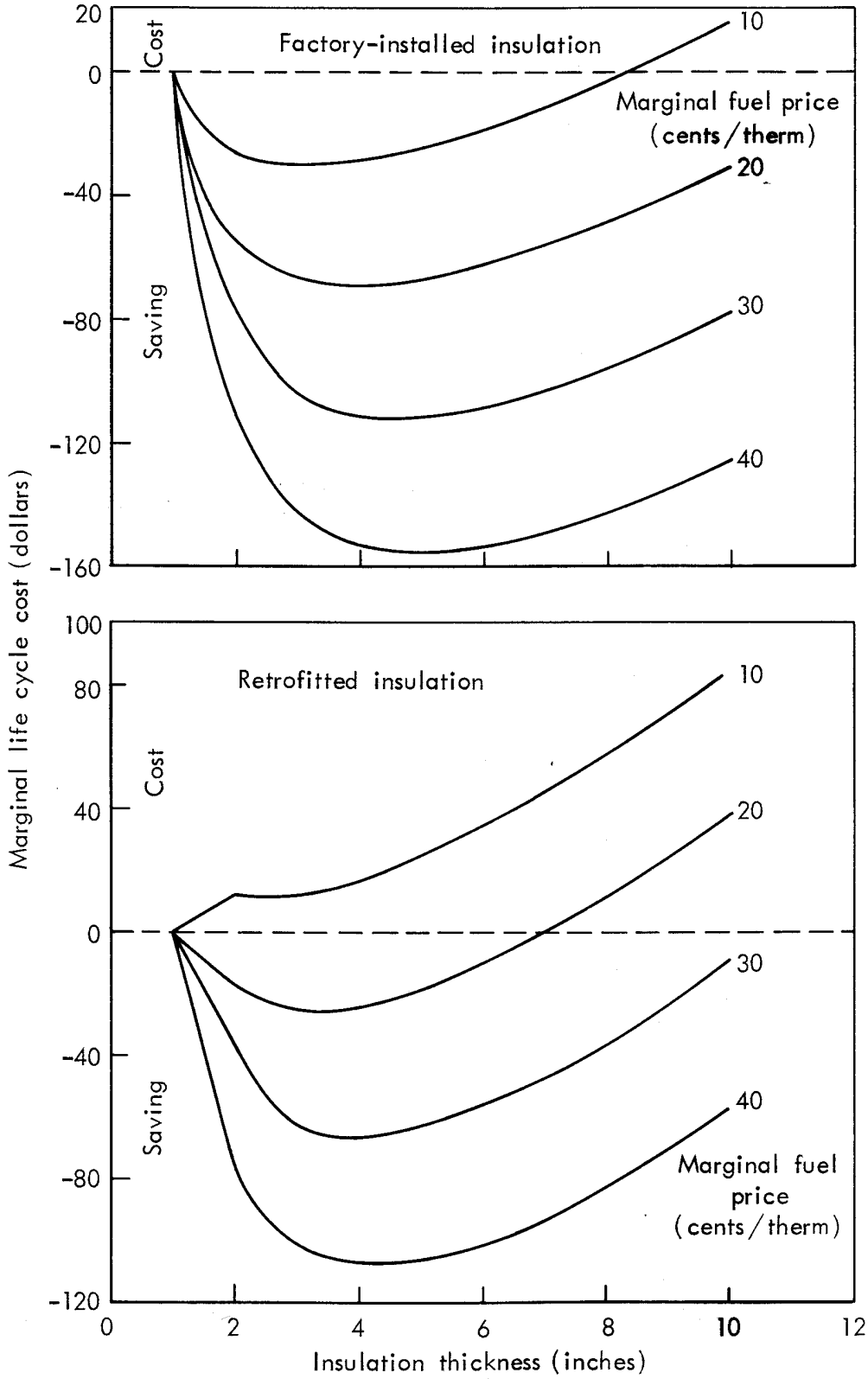

Fig. 3b — Marginal life cycle cost or benefit of extra tank insulation compared to standard insulation (40-gallon natural gas/LPG water heater)

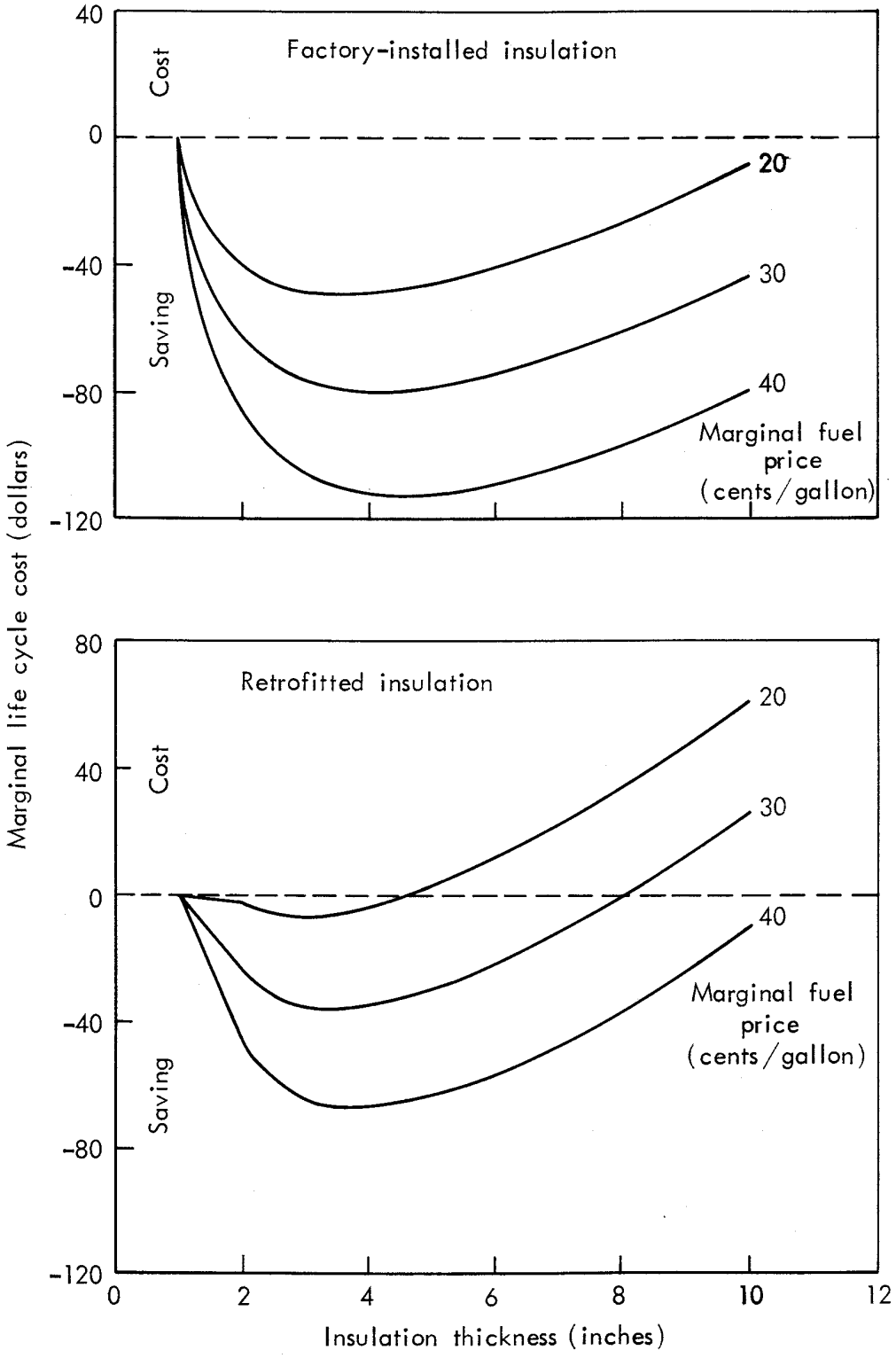

Fig. 3c — Marginal life cycle cost or benefit of extra tank insulation compared to standard insulation (40-gallon fuel oil water heater)

Table 7a

RESIDENTIAL WATER HEATER TANK INSULATION: MINIMUM-COST THICKNESS,[a] ECONOMIC BENEFIT, AND ENERGY BENEFIT WITH PRESENT RANGE OF ENERGY PRICES

Item	Factory-Installed Insulation			Retrofitted Insulation		
50-Gallon Electric						
Electricity price (¢/kWh)	1	2	4	1	2	4
Minimum-cost insulation	4"	5"	7"	2"	2"	6"
Annual cost saving	$1.40	$4.00	$10.10	--	--	$4.90
Annual electricity saving (percent)	8.1	9.5	11.0	--	--	10.4
40-Gallon Natural Gas/LPG						
Natural gas price (¢/therm)	10	20	40	10	20	40
Minimum-cost insulation	3"	4"	5"	1"	3"	4"
Annual cost saving	$2.90	$7.90	$15.50	--	$2.50	$10.70
Annual gas saving (percent)	21.6	23.8	25.0	--	21.6	23.8
40-Gallon Fuel Oil						
Fuel oil price (¢/gallon)	20	30	40	20	30	40
Minimum-cost insulation	4"	4"	5"	3"	3"	4"
Annual cost saving	$4.80	$7.90	$11.20	$0.70	$3.50	$6.60
Annual oil saving (percent)	23.8	23.8	25.0	21.6	21.6	23.8

[a]Based on 10-year lifetime and an inflation-free, after-tax discount rate of 8 percent.

But the cost curves also show that, depending on the price of fuel, there is a broad range of insulation levels that yield lower total costs than standard insulation; this is especially true for factory-installed insulation when additional initial costs are held to a minimum. Of particular interest is the point where the life cycle cost is equal to the cost with present standard insulation. At this point, the consumer would experience no change in total costs, but the fuel saved would be greater than at the minimum-cost point. Table 7b summarizes these equal-cost points for the different types of water heaters over the current range of fuel prices. Additional fuel savings over the minimum-cost level are generally most significant at the lower fuel prices and become less pronounced as fuel prices rise.

We should also mention that retrofitting insulation to in-use tanks also saves fuel. Although the economics are less favorable because the remaining life is shorter, additional insulation of relatively young units can still yield a positive return on the consumer's investment, especially at higher fuel prices.

Water Temperature

At a given level of insulation, the rate of heat loss through the walls of a hot water storage tank is proportional to the temperature difference between the hot water and surrounding air.* The heat loss rate from a 50-gallon electric water heater with 2-inch insulation is about 87000 Btu per day with a water-air temperature difference of 70°F. Actually, most units have adjustable thermostats which allow selection of any water temperature within a limited range, usually between about 110°F and 160°F. For surrounding air at an average 70°F, this corresponds to a water-air temperature difference range of 40°F to 90°F. Figure 4a shows the effect of this temperature difference on the annual fuel consumption of various units with standard tank insulation. If the air is at 70°F, an electric water heater will use about 9 percent

*Although the thermal conductivity of fiberglass and mineral wool insulation varies with temperature, it is a second-order effect. We assume that it is constant over the temperature range considered and that the heat loss rate obeys Eq. (1) of Appendix A.

Table 7b

RESIDENTIAL WATER HEATER TANK INSULATION: EQUAL-COST THICKNESS[a] AND ENERGY BENEFIT WITH PRESENT RANGE OF ENERGY PRICES

Item	Factory-Installed Insulation			Retrofitted Insulation		
50-Gallon Electric						
Electricity price (¢/kWh)	1	2	4	1	2	4
Equal-cost insulation	7"	>10"	>10"	2"	2"	>10"
Annual electricity savings (percent)	11.0	~11.8	~11.8	--	--	~11.8
40-Gallon Natural Gas/LPG						
Natural gas price (¢/therm)	10	20	40	10	20	40
Equal-cost insulation	8" n	>10"	>10"	1"	7"	>10"
Annual gas saving (percent)	26.6	~27	~27	--	26.2	~27
40-Gallon Fuel Oil						
Fuel oil price (¢/gallon)	20	30	40	20	30	40
Equal-cost insulation	10"	>10"	>10"	5"	8"	10"
Annual oil saving (percent)	27.0	~27	~27	25.0	26.6	~27.0

[a]Based on 10-year lifetime and an inflation-free, after-tax discount rate of 8 percent.

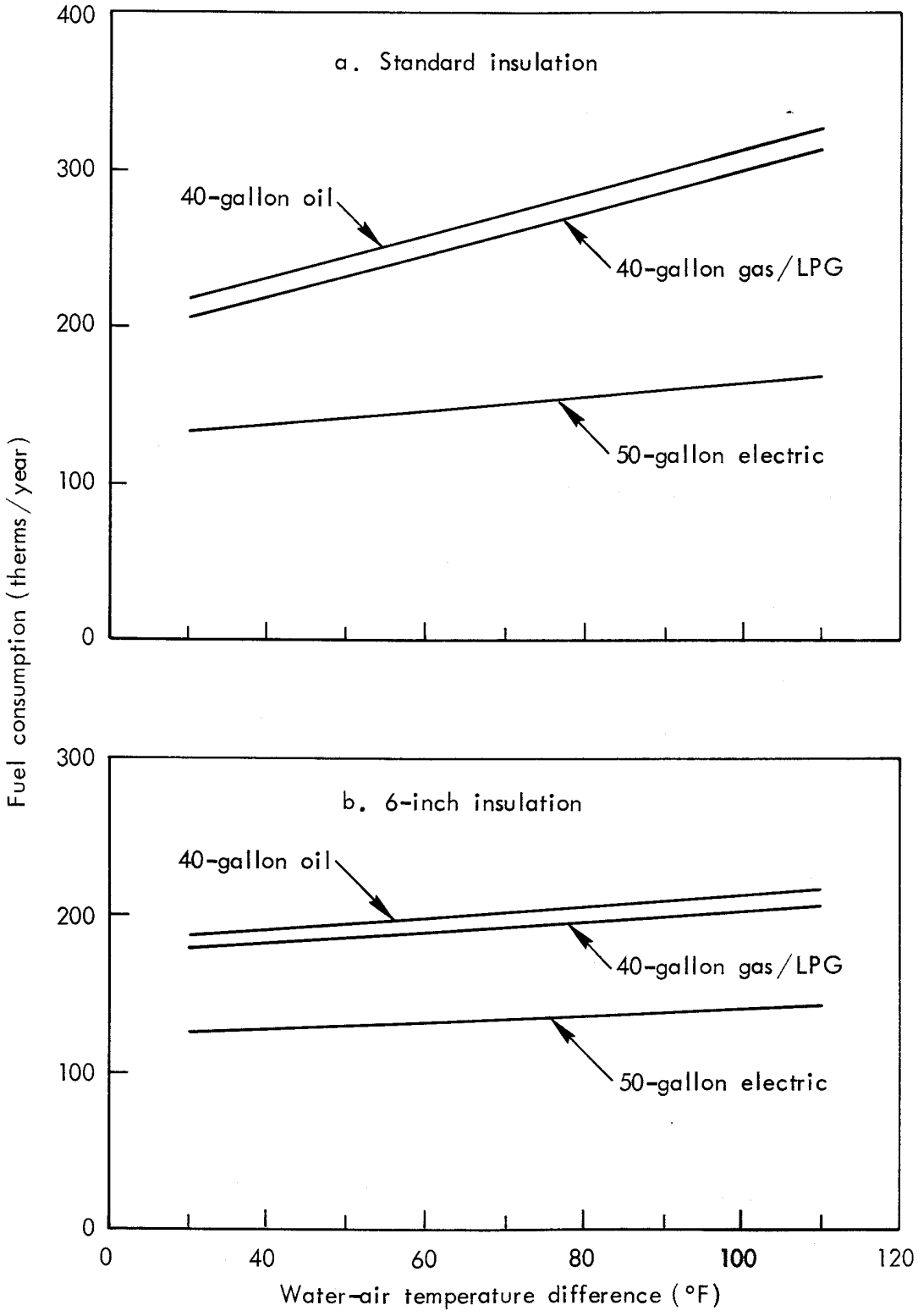

Fig. 4— Effect of hot water temperature on annual energy consumption for several types of residential water heaters

less energy with its thermostat set at 110°F than at 140°F. Under the same conditions, fossil fuel units will use 15 percent less fuel. Figure 4b shows the same situation for units with 6 inches of tank insulation. In this case, lowering the thermostat from 140°F to 110°F produces less savings: about 5 percent for all types of units. This is not surprising since the added insulation has already lowered conductive heat loss substantially.

The fuel saved by thermostat reduction is a net cost saving to the consumer because there is no investment associated with it. At current fuel prices, the economic benefit to the typical householder would be from $3.00 to $5.00 per year for each 10°F reduction in water temperature. On an individual basis, significant fuel savings may result from setting the thermostat only as high as personal needs require--perhaps about 110°F. Since the demand for hot water is basically a demand for heat, the storage tank really serves as a heat reservoir to meet that demand. Its heat storage capacity may be increased either by making it larger or by storing more heat per unit volume (hotter water). Either measure will lead to greater conductive heat losses since the heat loss rate is a function of both temperature difference and surface area (see Eq. (1) of Appendix A).

The potential energy savings from reducing water heater thermostats on an aggregate level are practically indeterminant since the distribution of current thermostat settings is not known. However, with current standard tank insulation levels, an upper bound of about 13 percent for electric units and 23 percent for other types is set by the limits of the water-air temperature difference range--about 40°F to 90°F.

The Heating Cycle

In normal applications of residential water heaters, the heating element is on continuous standby. Whenever the tank water falls below the desired temperature, either because of water usage or heat losses through the tank walls, the heater is activated by the thermostat to return the temperature to the proper level. As discussed above, the minimum acceptable temperature for domestic needs is probably about

110°F, while hot water is commonly kept at about 140°F. Installation of a low-temperature cut-in thermostat would require an additional $15 - $20 investment and would allow the water to cool to some minimum, say 110°F, at which point it would be reheated to the maximum storage temperature, 140°F. As discussed in Appendix A, such an intermittent heating cycle would save approximately 5 percent of the annual fuel consumption of water heaters with standard insulation. But if water is needed no hotter than 110°F (or, in fact, any temperature) this tactic offers no benefits over simply reducing the primary thermostat to that temperature.

During nighttime hours, there is no need to maintain any minimum temperature level since there is no demand for hot water. By shutting down the heating unit completely during this period, fuel normally used to balance standby losses would be saved. For example, with the primary thermostat set at 110°F, a shutdown from 12:00 midnight to 6:00 a.m. would produce savings of about 0.3 therm/year for electric units and 1.5 therm/year for fossil fuel units. However, in view of the added investment of about $10 in the necessary timing mechanism, prices of gas and oil would need to reach at least $0.90/therm and electricity $4.50/therm ($0.15/kWh) to make this choice economical.* Before prices reached those levels, it would become economical to add thicker tank insulation that would make the possible fuel savings even smaller.

Water Distribution System

As hot water is needed in a residence, it is conveyed from the storage tank to the point of use by distribution piping, usually 3/8- or 1/2-inch nominal diameter copper or galvanized steel. Ordinarily, the tubing is not insulated and heat is lost from the water to cooler surrounding air, especially during the winter in colder climates where lengths of pipe are exposed in unheated basements.

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*This assumes a discount rate of 6 percent which is conservative. Fuel prices would need to be even higher at the median discount rate of 8 percent.

The effects on annual heat loss of insulating exposed copper tubing with 85 percent magnesia have been examined elsewhere [8].* The results of that study are presented in Table 8 and the estimated total annual energy savings, assuming 25 feet of exposed tubing, are shown in Table 9. As a percent of total use, potential savings from basement pipe insulation range between 1.5 and 2.1 percent with a most likely savings of 1.6 percent. The estimated investment costs, including installation, are:

- o Bare 1/2-inch copper tubing, $0.97 per lineal foot [12].
- o Eighty-five percent magnesia pipe insulation, $1.00 per lineal foot [8].

Expected life of the tubing and insulation is 30 years [8]. We can determine whether pipe insulation is economically justified on the basis of life cycle cost. An example follows.

Example: The economics of pipe insulation

Conditions: Expected plumbing lifetime - 30 years
Expected insulation lifetime - 30 years
Discount rate - 8 percent

Based on the above cost data and the information in Table 8, the marginal life cycle costs of exposed hot water plumbing with pipe insulation compared to bare plumbing are shown in Fig. 5. At current energy prices, pipe insulation cannot be justified with the exception of electric water heaters located in areas of high electricity prices.

SOLAR ENERGY: REDUCING NON-RENEWABLE ENERGY REQUIREMENTS

Solar energy is an attractive prospect because, unlike fossil fuels, it is a continuously renewable resource for as long as our sun is with us. Moreover, utilization of solar energy does not increase

*The author of that work assumed hot water at 140°F and ambient basement temperatures typical of most locations: 75°F during summer months, 65°F during fall and spring months, and 55°F during winter months.

Table 8

ANNUAL HEAT LOSS FROM ONE-HALF-INCH COPPER TUBING

(Btu per lineal foot)

Usage Schedule	Bare	Insulated	Savings
Low	32,151	24,780	7371
Typical	41,347	33,787	7560
Extreme	56,268	46,508	9760

Source: Ref. 8, p. 71.

NOTE: For water at 140°F and air at an average 65°F. Usage schedules are as follows: low-single occupant, moderate morning and evening use; typical-small family, heavy morning and evening use with intermittent use during the day; extreme-large family, heavy use throughout the day.

Table 9

ESTIMATED ENERGY SAVINGS FROM INSULATION OF EXPOSED BASEMENT TUBING

Unit	Therms Per Year			Percent of Total Use		
	Low	Typical	Extreme	Low	Typical	Extreme
50-gallon electric	2.3	2.4	3.1	1.5	1.6	2.1
40-gallon gas/LPG	4.0	4.2	5.4			
40-gallon fuel oil	4.2	4.3	5.6			

NOTE: Figures assume 25 feet of exposed copper tubing and include the net efficiencies given in Table 2.

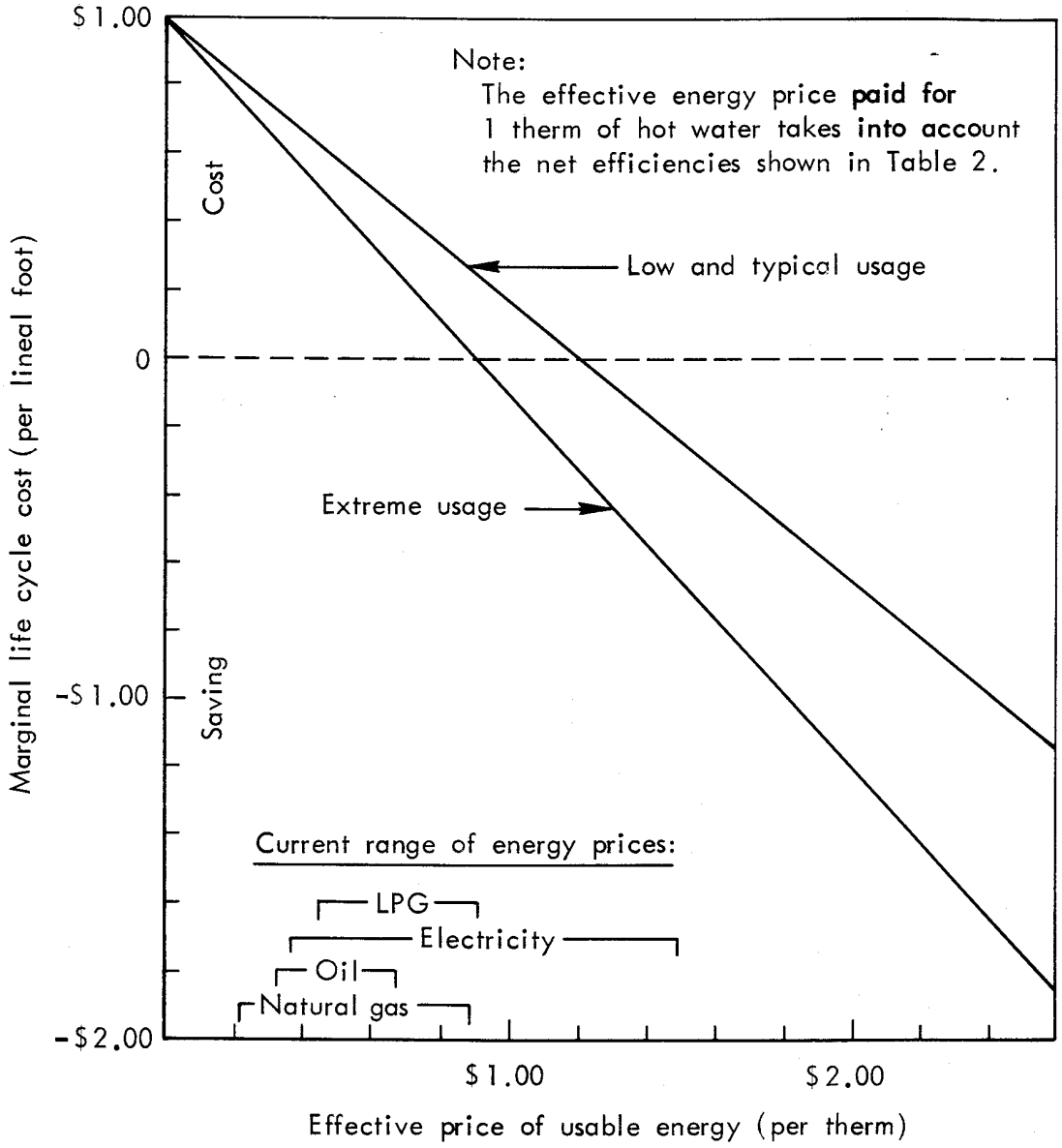

Fig. 5— Marginal life cycle cost of insulated hot water plumbing compared to bare plumbing (based on 30-year useful life and inflation-free, after-tax discount rate of 8 percent)

the heat burden on the earth's biosphere but only diverts a portion of what heat normally reaches earth to do some useful work; nor does it produce undesirable environmental side effects such as air and water pollution, solid waste, and radiological effluents.

Solar water heaters are in use in many parts of the world, including Australia, New Zealand, India, Israel, and until recently, the southeastern United States. A basic residential unit consists simply of a stationary solar collector, a hot water storage tank, and associated plumbing. Cold water passes through the collector where it is heated and into the tank where it is stored for use. If the tank is mounted higher than the collector, heated water flows naturally from the collector into the tank by thermosiphoning, or convection, and a pump is not needed. For this reason, a solar collector is often mounted on an inclined roof and the storage tank is placed above it. Although experience has been limited, a useful system life of about 10 years has been indicated [13].

Solar water heaters have most often been used in areas of the lower latitudes where other fuels are too costly or unavailable. Primary drawbacks for wider application have been their low performance during extended periods of heavy overcast and the relatively high cost of the solar collector. In this study, we have attempted to determine the economic feasibility of using solar energy, supplemented by electric resistance heat when required by cloud cover or low ambient temperatures, to furnish the domestic hot water needs of a normal family--about 50 gallons per day. Although there is not an active market in the United States today for solar water heaters, interest is rising and one suspects that higher fossil fuel prices, which seem assured in the near future, may again make solar energy a viable alternative for residential water heating.

Specifically, we have estimated the investment costs necessary to achieve various levels of solar water heating performance at three latitudes representing the northern, central, and southern tiers of states. An auxiliary electric heater is used to supplement the solar unit during periods of heavy cloud cover or low ambient temperatures. The estimated investment costs and annual performance of several systems

are given in Table 10. A complete discussion of the analysis is given in Appendix A.

Only system number 1, located in the southern region, is capable of complete solar operation. Other systems for the southern region have smaller solar collectors and lower investment costs, but rely on electricity during periods of low solar radiation and/or ambient temperatures. In the central and northern regions, year-round solar operation of systems of this design is prevented by periods of sub-freezing temperatures which would damage the collector unless it is drained of water. As one moves from southerly to northerly latitudes, the collector area (and hence the investment) needed to produce a given level of solar performance increases due to lower insolation* and colder temperatures encountered in the higher latitudes.

Obviously, in any region there is a tradeoff between the investment in solar equipment and the cost of heating water with electricity or other fuels. We can examine this tradeoff and determine the economically optimum, or minimum life cycle cost, method of generating hot water for a residence at different fuel prices. An example follows.

Example: The economics of solar water heating

Conditions: Expected useful life - 10 years
Discount rate - 8 percent

The data in Table 10 result in life cycle costs shown in Figs. 6a-6c for solar water heating systems in three regions of the United States. Life cycle costs for conventional fuel systems are plotted for comparison.** As one might expect, solar water heaters are most desirable in the southern region where good solar conditions require the least investment. Figure 6a shows that, in this region, it appears that current fuel prices, except possibly fuel oil, may be high enough to justify a solar water heater designed to provide about 84 percent of

*Insolation is the rate of delivery of all direct solar energy per unit of horizontal surface.

**These are the costs for standard units with the economic optimum level of tank insulation at each fuel price as determined earlier in the study.

Table 10

ESTIMATED COST AND PERFORMANCE OF SEVERAL RESIDENTIAL SOLAR WATER HEATING SYSTEMS FOR THREE U.S. LATITUDES

System Number	Design Month	Investment Cost	Annual Percent Hot Water From		Annual Electricity Use (kWh)
			Solar	Electricity	
Southern Region (32°N Latitude)[a]					
1	December	$782	~100	--	--
2	November	683	96.4	3.6	142
3	September	521	83.5	16.5	650
4	August	504	72.3	27.7	1092
5	June	501	65.4	34.6	1364
Central Region (40°N Latitude)[b]					
6	November	$863	83.3	16.7	658
7	September	579	69.6	30.4	1198
8	August	560	59.1	40.9	1612
Northern Region (48°N Latitude)[c]					
9	September	$660	58.3	41.7	1643
10	June	619	51.1	48.9	1927
11	August	593	52.7	47.3	1864

[a]As far north as San Diego, Dallas, and Atlanta.

[b]As far north as Denver, St. Louis, and Philadelphia.

[c]As far north as Seattle, Fargo, and Bangor, Maine.

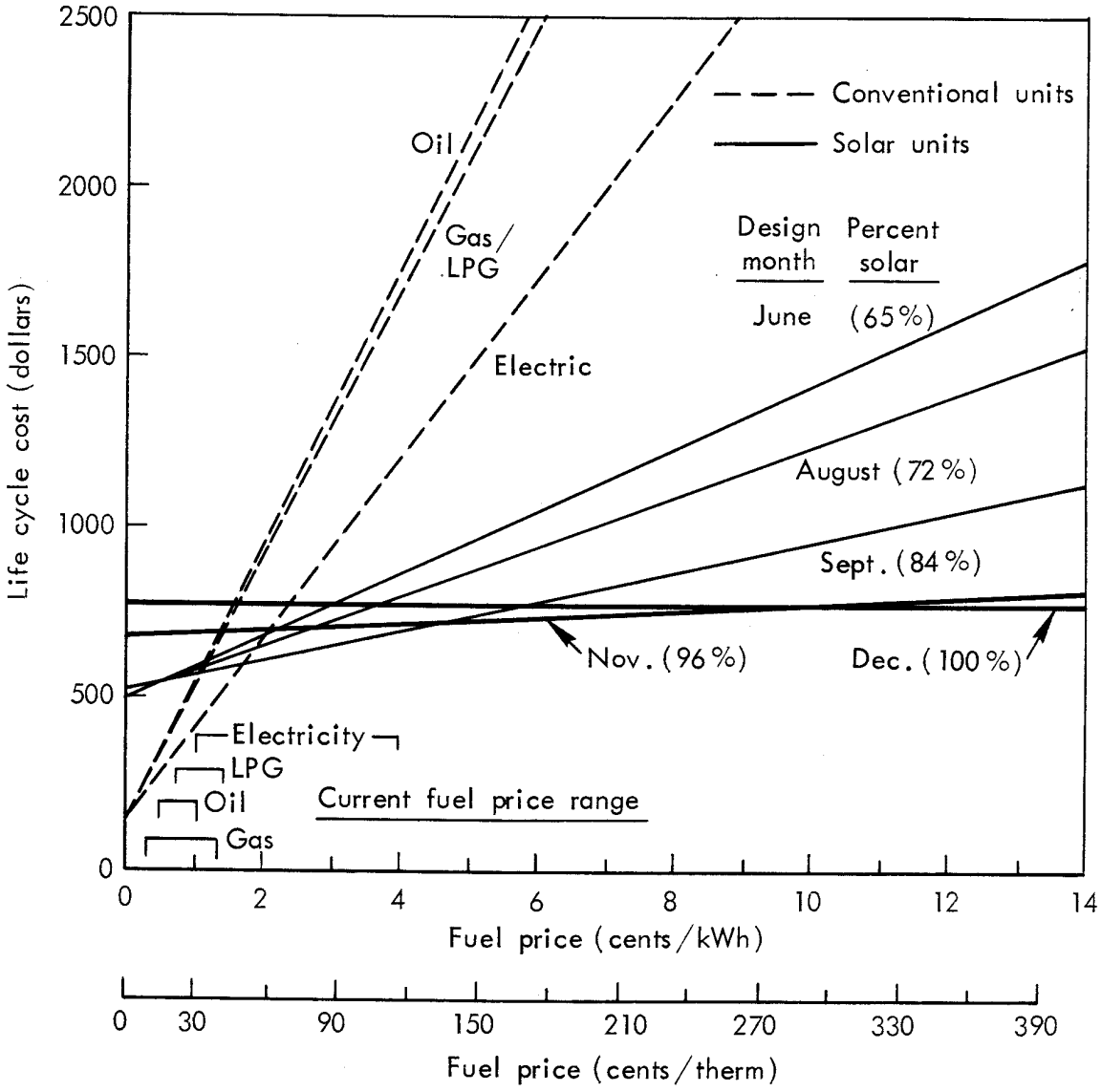

Fig. 6a — Life cycle costs of solar and conventional water heating systems — Southern United States (32° N latitude)

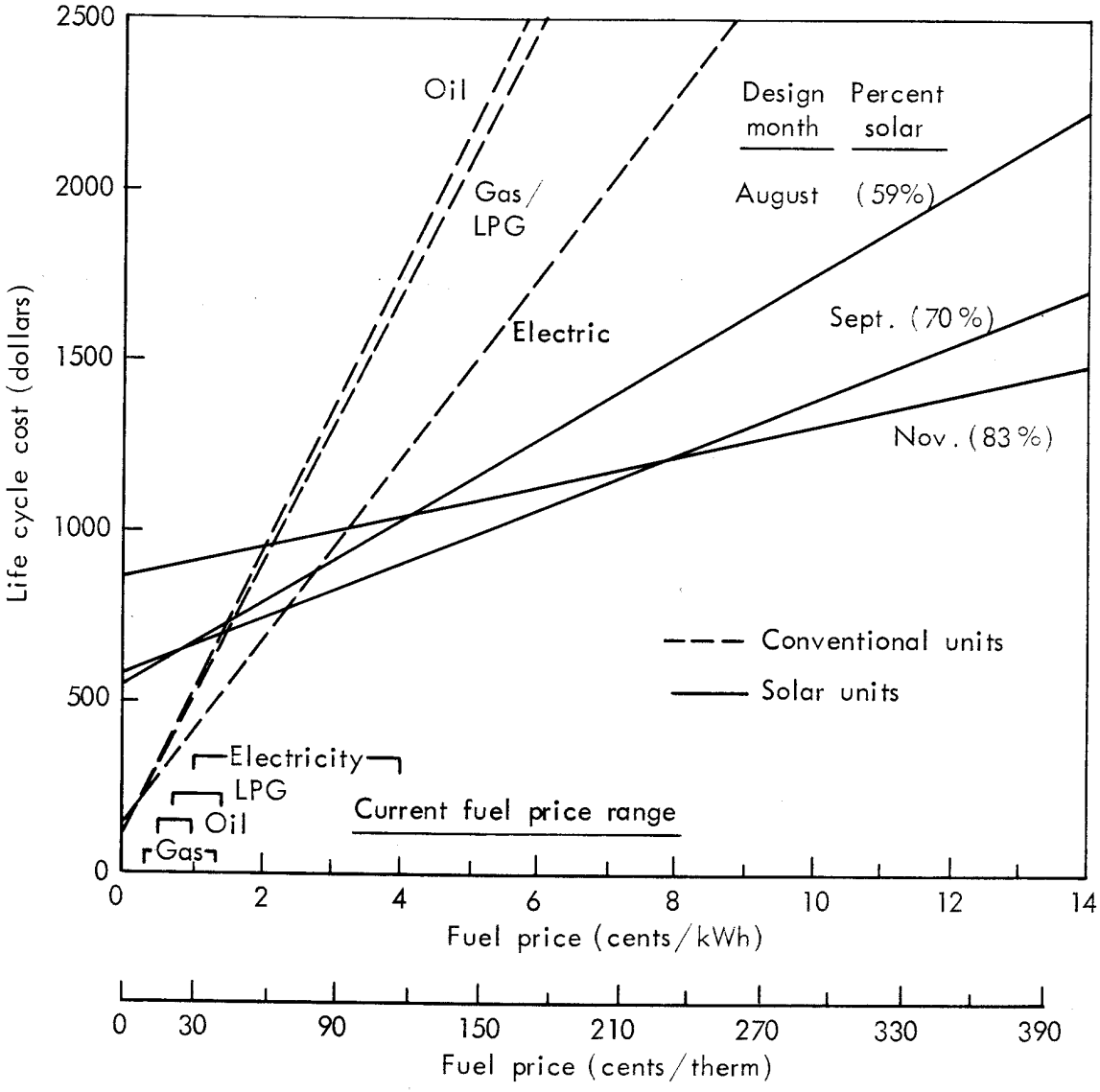

Fig. 6b— Life cycle costs of solar and conventional water heating systems— Central United States (40° N latitude)

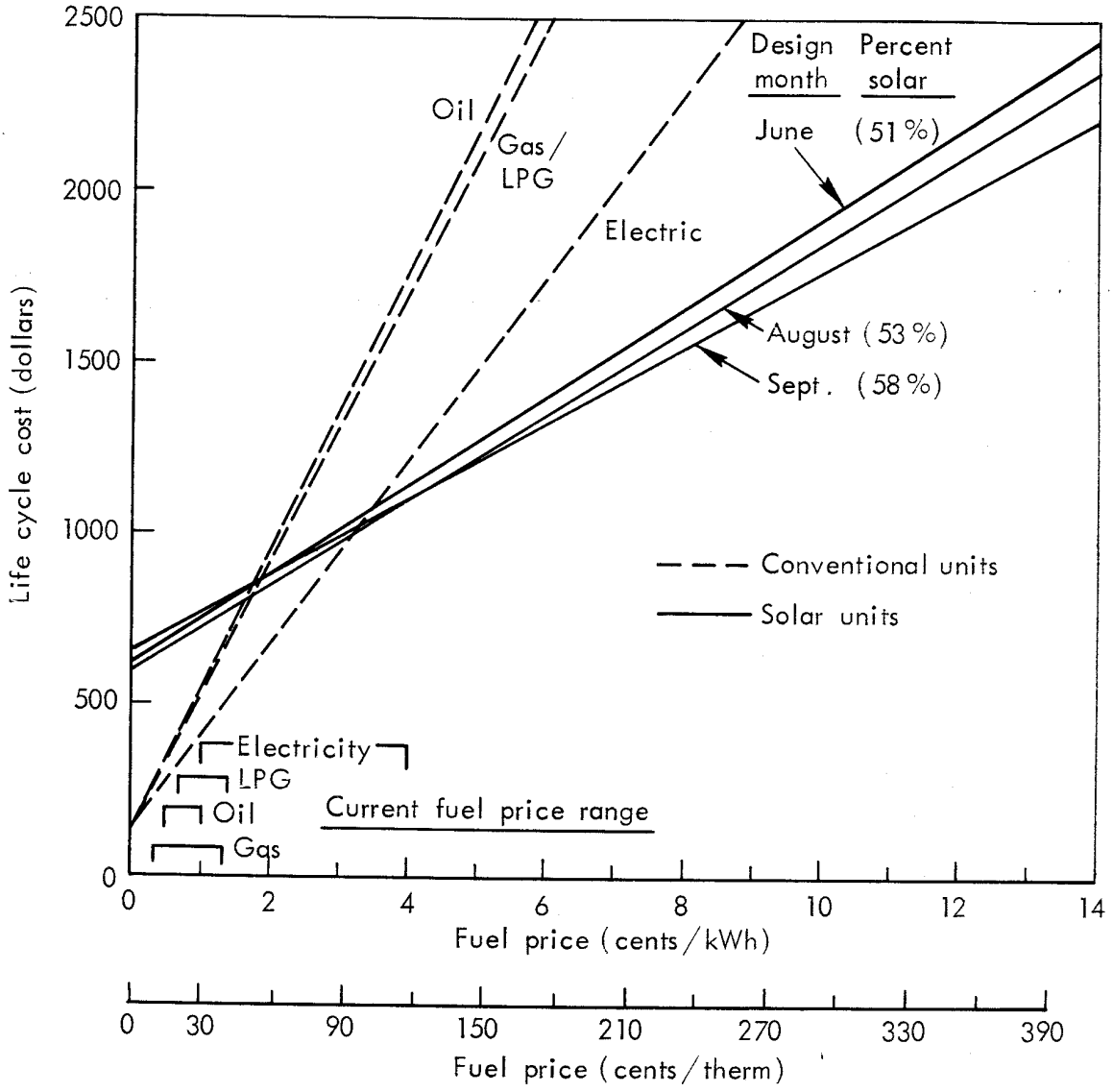

Fig. 6c — Life cycle costs of solar and conventional water heating systems — Northern United States (48° N latitude)

a typical family's hot water needs. A 96-percent-solar system appears justified at fuel prices between $1.50 and $3.00 per therm, and higher prices may warrant a total-solar system.

In the central region of the country, it appears from Fig. 6b that a 70-percent-solar water heater may be more economical than conventional electric units in areas where marginal electricity prices are in the upper half of the current range (about 2.5 cents/kWh). A larger unit with 83-percent-solar capability might be justified if fuel prices rise above $2.40 per therm.

Even in the northern region where solar conditions are poorest, Fig. 6c indicates that a solar system providing about 53 percent of household hot water may be competitive with conventional electric units at marginal electricity prices above 3 cents/kWh. A 58-percent-solar system may be justified at fuel prices above $1.20 per therm.

In this discussion, we have considered the economics of various options and their effect on energy consumption at the point of end use. It is important to remember that generation and distribution of electricity is only about 30 percent efficient, i.e., 3.3 Btu of fuel are burned to deliver 1 Btu of electricity to the consumer. Any strategy that aims to conserve fossil fuels by substituting solar-electric water heaters for fossil units must recognize the tradeoffs between the solar contribution, the efficiencies of electricity generation and conventional water heaters, and the availability of non-fossil electric power. Any solar-electric unit that furnishes less than about 45 percent of the required energy from the sun will actually use more raw energy than a conventional fossil fuel water heater. In the case of conventional electric units, substitution of a solar-electric system will, of course, always lower raw energy use since it reduces electricity consumption.

IV. THE ROLE OF PUBLIC POLICY

To achieve any economic benefit or conserve any fuel in residential water heating, the consumer must of course modify his standard hot water system in some manner. In the aggregate, a goal of significantly reducing fuel consumption necessitates substantial penetration of conservation measures into the domestic market. In this section, we discuss government policy alternatives that may approach this goal. By projecting water heating fuel consumption under several fuel price regimes and water heater equipment choices, we also estimate the impact alternate policies may have on the aggregate demand for fuels to heat water.

POLICY ALTERNATIVES

As in many cases, consumers will not always voluntarily opt to conserve energy even if it is economically to their benefit. The reasons for this are several:

- Consumers may not know that a conservation measure is effective or economically beneficial.
- The measure may cause some inconvenience.
- The means to implement the measure may not be available in the market place.
- Consumers may simply not want to implement the measure.

The purpose of public policy should be to encourage consumers to respond in a manner that is consistent with the public interest. In the case of residential water heating (or, for that matter, any form of energy consumption), the public interest can be defined as using the least amount of energy necessary to perform a task in an acceptable way. This ethic is not contrary to the consumer's own interests if it also results in a net economic benefit to him. For the purpose of our analysis, we assume that a desirable public policy on residential water heating would aim at conserving energy by encouraging implementation of conservation measures that result in the minimum life cycle system cost to the consumer. We should remember that the minimum cost is only one option of many; policies could be designed that also save

energy but lead to other life cycle costs, for instance, costs equal to current costs.

There are four basic types of policies suited to conserving energy in residential water heating:

- Policies aimed at encouraging voluntary conservation by consumers. These are designed to increase the availability of information on which consumers base their decisions regarding energy consumption. Examples are 1) basic consumer conservation education, 2) energy efficiency labeling of appliances (e.g., estimated annual energy use depending on tank insulation, water temperature, etc.), and 3) financial incentives for development and use of energy-conserving appliances and devices.
- Policies which change the consumer price of fuels, for instance, by taxation, regulated rate schedule changes, or price deregulation of regulated fuels. Changes in the relative prices of competing fuels affect consumer choice of fuels, while the absolute value of fuel prices determines the extent of conservation measures that are economically justified.
- Policies which change the consumer price of appliances. These include sales taxes, taxes based on estimated energy consumption, and tax relief for the development, manufacture, and purchase of more efficient equipment.
- Proscriptive policies. These are the most explicit and, in the case of residential water heaters, include 1) changes in building and plumbing code requirements to establish minimum efficiencies or maximum heat loss rates for hot water systems, 2) manufacturing standards for minimum efficiencies or maximum heat loss rates for water heaters, 3) manufacturing standards to limit the maximum water temperature thermostat setting on water heaters, and 4) bans on the manufacture, sale, or installation of certain types of equipment.

Each of these policies should consider the regional feasibility of solar water heaters as well as modifications to conventional fossil-fuel and electric units.

THE IMPACT OF PUBLIC POLICY: SOME ESTIMATES

We now attempt to quantify the potential effectiveness of public policy in reducing residential water heating energy requirements. To do this, we consider the nine census regions of the United States shown in Fig. 1 and estimate consumption in each region of the appropriate fuels for residential water heating under several assumptions about fuel prices. The target year is 1990 and we assume that the projected fuel prices and public policies are constant for a sufficient prior period to allow the equipment stock to reach an equilibrium saturation by 1990. Our purpose here is not to make a *most-likely* projection of water heating energy consumption, but to demonstrate the long-run effects of price and non-price policies.

Our methodology is to combine projections of regional occupied housing units [14] with projections of regional water heater saturation according to fuel type under several cases of future fuel prices.* Projected U.S. saturations are shown in Table 11. The aggregate regional consumption of fuels is estimated for the base fuel price case assuming use of *standard water heaters* similar to those now on the market. The potential effect of public policy is estimated by projecting fuel consumption under each price case with complete penetration of minimum life cycle cost (i.e., *economically optimum*) equipment. The net effect of conservation policies is viewed by comparing fuel use in each price case using optimum equipment with fuel use in the Base Case using standard equipment.

Four residential fuel price cases are examined and shown in Table 12. They are summarized below.

- *Base Case*. All residential fuels remain at early 1974 prices, which might occur in the absence of any change in government price policies and if new supplies and recovery technologies make fuel available at current costs.

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*Saturations are projected via Anderson's [3] stock elasticities for residential water heaters using actual 1970 saturations as a base. Income per household is assumed to increase 1.75 percent per year from 1970, while all other explanatory variables (except fuel prices) in Anderson's equations are assumed to remain at 1970 values.

Table 11

ESTIMATED 1990 SATURATIONS OF RESIDENTIAL WATER HEATERS IN THE UNITED STATES UNDER DIFFERING FUEL PRICE CASES

(Percent)

Fuel Price Case	Natural Gas	Electricity	LPG	Fuel Oil	None
Base Case	56	39	1	2	2
Case A	19	59	5	3	14
Case B	8	79	4	4	5
Case C	76	16	2	2	4

NOTE: Based on information in Ref. 3.

Table 12

RESIDENTIAL FUEL PRICE CASES

Fuel	Estimated Price Early-1974	Ratio of Price to Early-1974 Price			
		Base Case	Case A	Case B	Case C
Fuel oil	30¢/gallon	1.0	1.33	1.0	1.0
Natural gas	12¢/therm	1.0	2.08	2.08	1.0
LPG	30¢/gallon	1.0	1.33	1.0	1.0
Electricity	2.4¢/kWh	1.0	2.08	1.0	2.08

- o *Case A*. This case represents the highest residential prices likely by 1990 reflecting production costs with new technologies (e.g., shale oil, coal gasification) and/or government price policies such as fuel taxes, rate schedule changes, and price deregulation.*
- o *Case B*. The price of natural gas doubles while those of other fuels remain constant. This would most likely result either from acute scarcity of natural gas or from government policies such as selective taxation or price deregulation.
- o *Case C*. Electricity doubles in price while others remain constant. Since electricity is and, in 1990, probably still will be generated in large part from fossil fuels, this case could probably only result from selective taxation or rate schedule changes promulgated by government price policies.

The estimated 1990 U.S. fuel consumption for residential water heating is shown in Figs. 7a-7e with standard and optimum equipment under the four fuel price cases. Estimated 1970 consumption is also shown for comparison. Appendix C contains more complete estimates for the nine census regions.

In the Base Case, with constant fuel prices and standard equipment (no public conservation policies), total end use water heating energy consumption is estimated to increase to about 1900 trillion Btu** by 1990, requiring a raw energy input of 3100 trillion Btu. This is an increase of 36 percent over 1970. Use of natural gas and electricity increase while use of fuel oil and LPG decrease. The estimated potential effects of conservation policies on residential water heating end use and raw input energy consumption in 1990 are summarized in Table 13 for the four fuel price cases.

It is apparent that conservation policies have the potential to materially reduce both end use and raw energy requirements in 1990:

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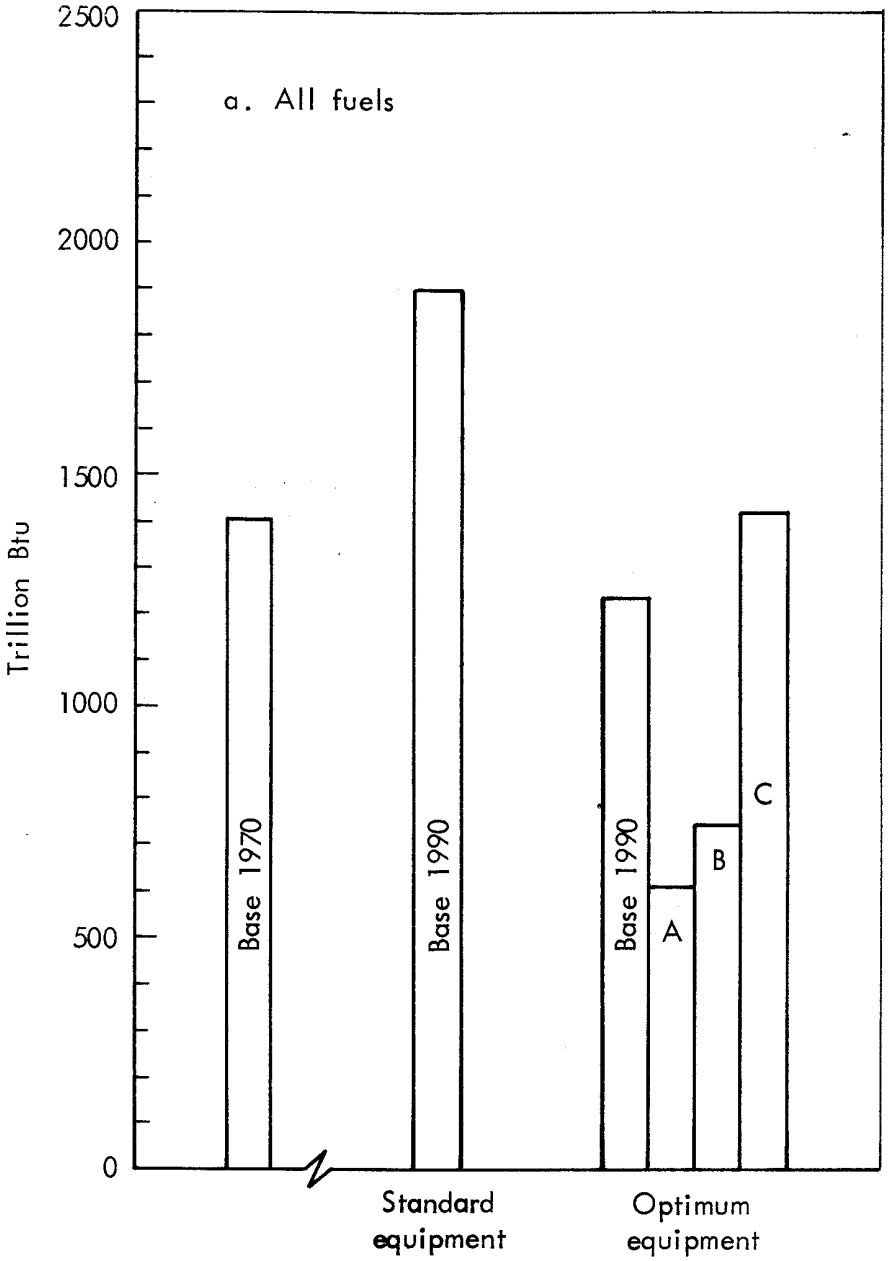
*These are estimates of the highest likely fuel prices based on preliminary results of on-going Rand research on energy costs and prices.

**One trillion = 10^{12}.



Note:
Data are for end-use consumption and do not include energy required to deliver fuels to the consumer.

Fig. 7— The effect of fuel price and equipment choice on fuel consumption in residential water heating in the United States, 1970 and 1990

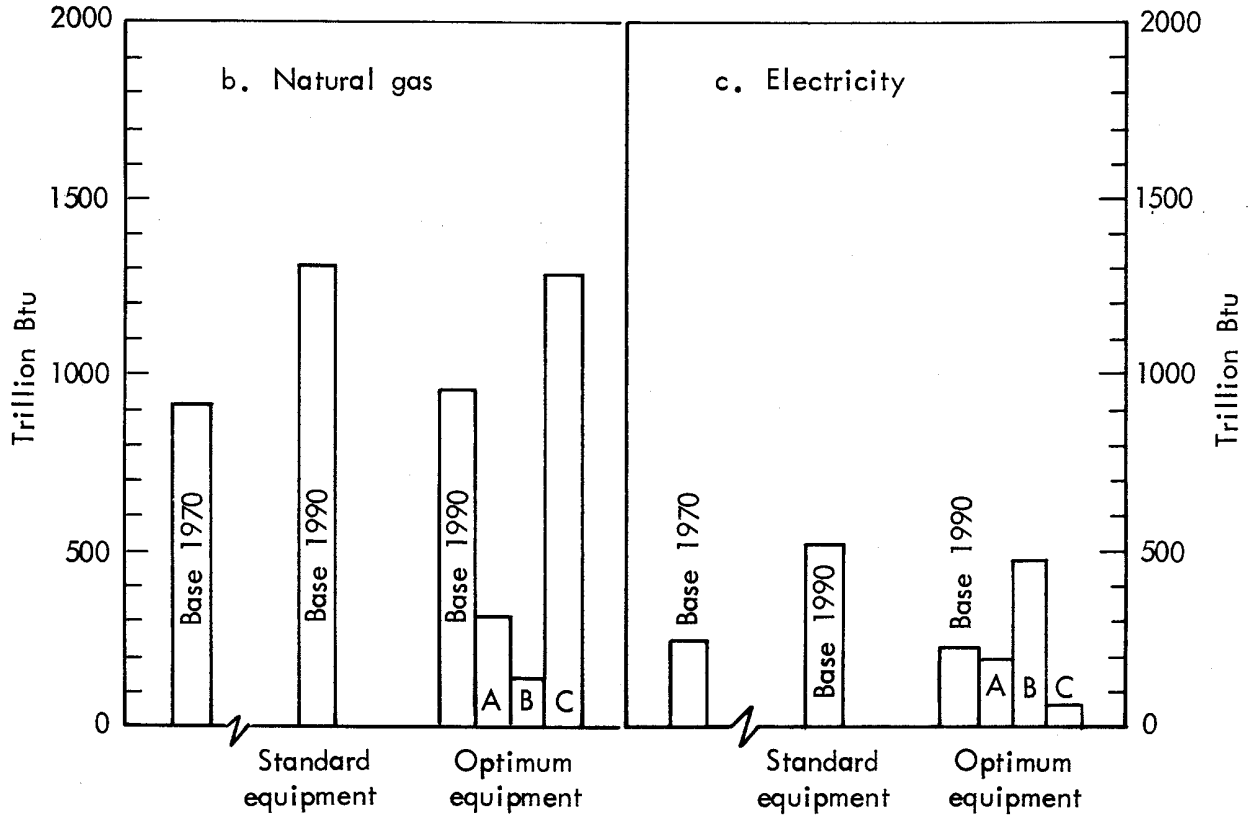


Fig. 7— (Continued)

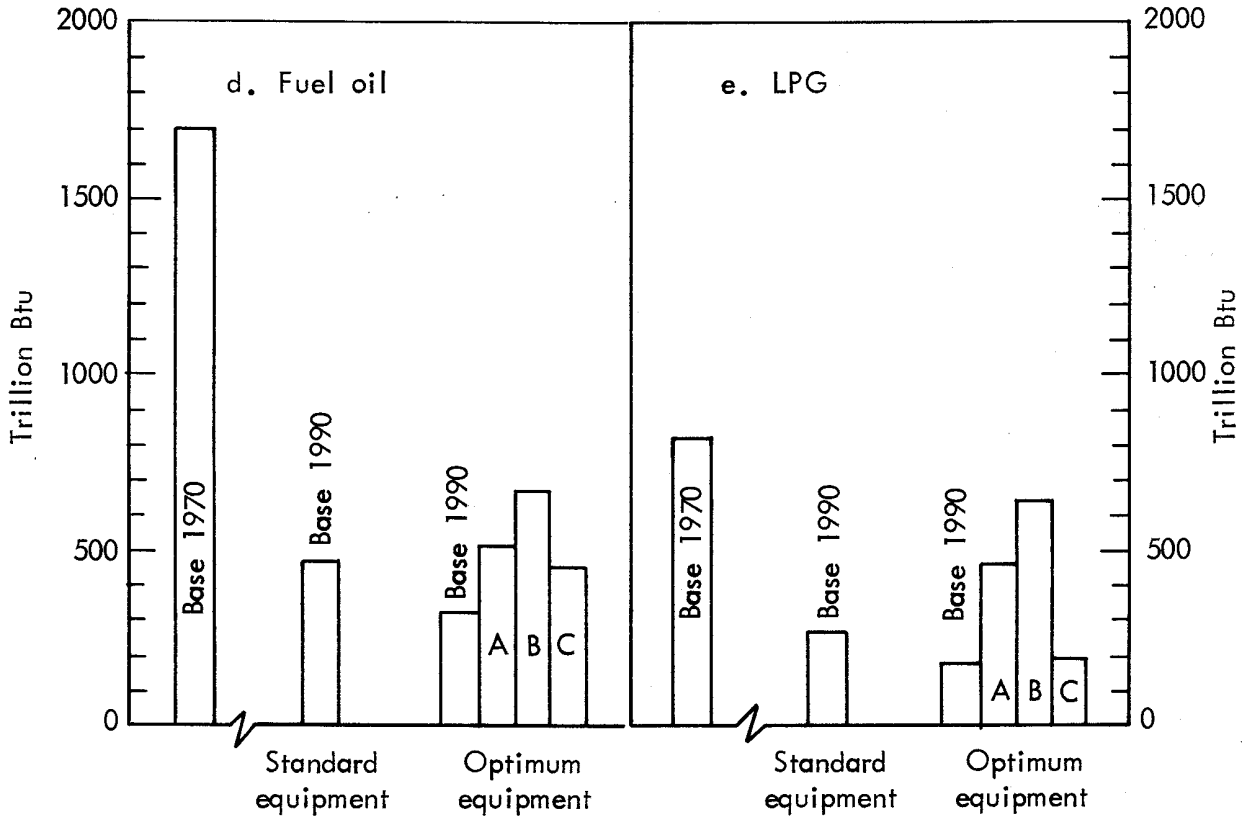


Fig. 7— (Continued)

Table 13

ESTIMATED EFFECT OF CONSERVATION POLICIES ON U.S. RESIDENTIAL WATER HEATING ENERGY CONSUMPTION, 1990

Fuel Price Case	Total End Use Energy		Total Raw Input Energy[a]	
	Trillion Btu	Percent of Base Case (W/O Policies)	Trillion Btu	Percent of Base Case (W/O Policies)
Without Policies (standard equipment)				
Base	1888	100	3093	100
With Policies (optimum equipment)				
Base	1223	65	1730	57
A	598	32	1000	32
B	733	39	1860	60
C	1411	74	1530	50

[a]Assuming 30 percent efficiency for generation and distribution of electricity.

- In the Base Case with constant fuel prices, policies that elicit consumer response without changing prices may reduce end use energy needs to 65 percent of projected consumption without such policies; raw energy requirements could be reduced to 57 percent. As shown in Table 11, only 2 percent of U.S. homes would be without hot water.
- In Case A, the highest expected prices of all fuels (whether or not a result of government pricing policies) in combination with conservation policies would be expected to cause the lowest fuel consumption, 32 percent of the Base Case for both end use and raw input energy. However, this is largely a result of an increase in water heater vacancies to 14 percent caused by high fuel prices and would likely be regressive on low-income families.
- Of the four price cases, Case B yields the second lowest end use energy consumption, but requires the highest input of raw energy, although still less than without policies. This is because the doubling of natural gas prices would produce a strong shift to electric water heaters which, though more efficient than gas units at the point of end use, rely on the relatively inefficient generation and distribution of electricity. Water heater vacancies would be about 5 percent in this situation.
- Case C is the converse of Case B in that a heavy shift to natural gas units results from a doubling of electricity prices. As a result, end use energy is the highest of the four conservation cases, while raw energy inputs are the second lowest. Vacancy rates are projected at about 4 percent.

In postulating energy conservation policies, ultimate requirements for raw input energy must be determined and the impacts of providing it evaluated. The rationale for turning to electrical appliances in the future to conserve scarce fuels will depend on the abundance of other fuels and the development of renewable sources of electricity.

V. CONCLUSION

Much attention is paid these days to energy consumption. Officials at all levels of government as well as industry, commerce, the general public, and of course the news media are all devoting substantial time and thought to the problems of energy supply and demand, current and future. Conservation has become a household word. Household uses of energy such as space heating and cooling, lighting, cooking, and refrigeration are frequently-suggested targets for residential conservation. Although water heating is the second largest use of energy in the home and represents 3 percent of U.S. energy consumption for all uses, it has somehow escaped the mainstream of discussion on energy conservation.

In the course of this analysis, we have discovered that, like many other uses, residential water heating systems offer several opportunities for reducing energy requirements without suffering a loss in capability to generate hot water. Furthermore, many of these conservation opportunities result in lower total life cycle costs to the consumer, even at recent energy prices. Table 14 summarizes the effectiveness of several conservation measures that reduce thermal losses from conventional residential water heaters.

From our analysis of system-oriented conservation measures, the following conclusions can be drawn about fuel conservation in residential water heating:

Reducing Thermal Losses

- Thicker tank insulation is perhaps the most effective means of reducing heat losses and overall energy consumption of conventional water heaters. Depending on residential fuel prices, which determine the lowest cost insulation thickness, potential fuel savings range from 5 to 11 percent of total annual consumption for electric units and 21 to 26 percent for fossil-fuel units. If insulation is factory-installed, the lowest life cycle cost is achieved with 5 inches on electric units, 3 inches on natural gas units, and 4 inches on LPG and fuel oil units. If insulation is retrofitted, current fuel

Table 14

INCREMENTAL ENERGY SAVING POSSIBLE IN CONVENTIONAL RESIDENTIAL WATER HEATERS BY MEASURES THAT REDUCE THERMAL LOSSES

Conservation Measure	Percent Reduction		Remarks
	Electric	Fossil-Fired	
Tank insulation *total thickness:*			
3 in.	5.6	21.6	Reduction as a percent of total use with standard tank insulation (2-in. for electric, 1-in. for fossil-fired)
4 in.	8.2	23.8	
5 in.	9.6	25.0	
6 in.	10.5	25.8	
7 in.	11.0	26.2	
Water temperature *per 10°F reduction:*			
Standard tank insulation	4.5	5.8	Reduction as a percent of total use with indicated tank insulation and water at 140°F
4-in. tank insulation	2.0	2.1	
6-in. tank insulation	1.9	1.8	
Hot water plumbing *insulation:*	1.6	1.6	Reduction as a percent of total consumption for any level of tank insulation and water at 140°F

NOTE: The percentage reductions are not directly additive; cumulative reductions may be computed from

$$P_c = 1 - (1-P_i) \cdot (1-P_t) \cdot (1-P_p)$$

P_c is the cumulative reduction, P_i is the reduction due to additional insulation, P_t is the reduction from reducing the water temperature, and P_p is the reduction from plumbing insulation, all figures being decimals. For example, compared to a standard electric unit, one with 4 inches of tank insulation, water at 130°F, and pipe insulation:

$$P_c = 1 - (1 - .082) \cdot (1 - .02) \cdot (1 - .016) = .115$$

or 11.5 percent reduction in electricity use.

prices justify 3 inches on LPG and fuel oil units, but only standard insulation on electric and natural gas units.

- Lowering the hot water temperature is capable of saving about 5 percent of fuel annually per 10°F reduction with standard tank insulation and about 2 percent per 10°F reduction with thicker insulation. To the extent that it does not interfere with the availability of suitably hot water in the home, temperature reduction yields a cost saving to the consumer at any fuel price since it requires no additional investment.
- Insulating exposed hot water plumbing may reduce annual fuel use by 1.6 percent, assuming 25 feet of exposed tubing. This may be economically justified if residential electricity prices surpass 3.5 cents/kWh and fossil-fuel prices surpass 70 cents/therm.
- Altering the heating cycle by automatic shutdown during periods of little or no use may save about 0.2 percent annually for electric units and 0.6 percent for fossil units with standard tank insulation. However, this investment would not be economically justified until residential fuel prices surpassed 15 cents/kWh for electricity and 90 cents/therm for fossil fuels.

Reducing Nonrenewable Energy Requirements

- Combination solar-electric hot water systems are capable of greatly reducing requirements for fossil-fuel-based energy. The extent of reduction justified economically is basically a function of the solar environment in which the water heater is located and the prices of competing fuels. Solar-electric systems appear to be marginally competitive with all-electric systems in areas of the southern states where electricity prices are above 2 cents/kWh, in the central states above 2.5 cents/kWh, and in the northern states above 3.5 cents/kWh. Competition with fossil-fuels requires fuel prices above 32, 35, and 37 cents/therm in the southern, central, and northern states, respectively.

Widespread implementation of fuel-conserving measures in the residential sector may require formulation and promulgation of appropriate public policies, even when the measures are to the economic benefit of consumers. Both price and non-price policies are suitable, although some combination of both may be required to elicit widespread public response and effect the maximum possible reduction in energy consumption. The potential long-run effectiveness of conservation policies by 1990 under various cases of residential fuel prices has been shown in Table 13. Non-price policies would encourage consumers to install optimum equipment while price policies affect the life cycle costs of various systems and thereby also influence equipment choices.

The potential effects of conservation policies on residential water heating may be summarized as follows:

- Policies which encourage consumers to install economically optimum equipment may, in the long run, result in end use water heating energy reductions of 26 to 68 percent, depending on fuel prices.
- In terms of raw energy inputs, long-run savings could amount to 40 to 68 percent of Base Case energy requirements. This could equate to a savings of between 580,000 and 980,000 equivalent barrels of oil per day by 1990.
- Both price and non-price policies can be effective in encouraging manufacture, marketing, and installation of more efficient residential water heaters.
- Policies that cause drastic increases in the costs of heating water with all fuels may result in substantial water heater vacancies, which probably would be concentrated in low-income families.

Appendix A

RESIDENTIAL WATER HEATING: SOME TECHNICAL ASPECTS

A residential water heater is a fairly simple appliance, composed of a hot water storage tank (normally between 30- and 80-gallon capacity) with appropriate cold inlet and hot outlet water connections and fitted with one or more heating elements that are controlled by a thermostat located in the tank.* In this work, we make the following simplifying assumptions about water heaters:

- The mean size of the existing stock of residential water heaters is 50 gallons for electric units and 40 gallons for other types.**
- The mean thermostat setting in the existing appliance stock is to maintain hot water at 140°F and this temperature is uniform throughout the tank.
- The mean temperature of the air surrounding installed units is 70°F*** and behaves as an infinite heat sink.
- During normal operation, the temperature of water in the tank remains constant at the thermostat setting.****

Several sources have published estimates of the annual energy use of a residential electric water heater in normal use [4, 5, 12, 15-17], and there seems to be a fair consensus about the magnitude as Table A-1 shows. It seems a reasonable approach to use as a base the mean

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*A more complete description of water heating systems is given in Section II of this report.

**Based on conversations with manufacturers. See the Introduction.

***This is not an unreasonable assumption since water heaters are normally located indoors in colder climes and in garages or other protective structures in more temperate regions.

****Although the temperature may fluctuate during periods of water usage as cold water replaces the hot water drawn off, most water heaters have heat input rates large enough to recover from normal withdrawals (e.g., shower or washing machine) in a half-hour or less. Large withdrawals normally occur infrequently during the day.

value of 4400 kWh/year, or 150.3 therms/year. Quinn [8] has estimated the heat loss through the walls of a 50-gallon electric water heater with 2 inches of insulation as 8700 Btu/day (31.8 therm/year) for hot water at 140°F, with average 70°F ambient air. Since this figure is based on experimental evidence, we use it in this work.

Table A-1

ESTIMATES OF ANNUAL ENERGY USE OF A RESIDENTIAL ELECTRIC WATER HEATER

Source	kWh	Therms
Edison Electric Institute	4219	144.0
San Diego Gas & Electric	4308	147.0
Pacific Gas & Electric	4811	164.2
Hittman Assoc.	4400	150
Federal Power Commission	4280	146.1
Mean	4400	150.3

Thermal Tank Insulation

If the conduction of heat is steady, the rate of heat transfer through a *flat body* is equal to

$$q = \frac{kA(t_1 - t_2)}{L} \qquad (1)$$

where q = rate of heat transfer by conduction, Btu/hr

k = thermal conductivity of the material, Btu/ft-hr-°F

A = cross-sectional area of the body taken normal to the direction of heat flow

t_1, t_2 = temperature at the two faces of the body, °F

L = thickness of the body, ft.

Equation (1) is also approximately true for cylindrical bodies provided the ratio of outside to inside diameters is not greater than 2 [18]. Although the precise inside diameter of the water heater tanks is not known here (which is why we cannot use the precise heat transfer relationship), simple geometry dictates that this ratio must be less than 2 for insulation thicknesses less than half the inside diameter (about 16-18 inches).

In Eq. (1), the quantity k/L can be denoted by U, the thermal transmittance or overall coefficient of heat transfer through the wall, and has units of Btu/hr-ft^2-°F. Making this substitution and solving for U gives

$$U = \frac{q}{A(t_1 - t_2)} \tag{2}$$

We have specified q as 8700 Btu/day, or 362.5 Btu/hr. The surface area A of a 50-gallon electric water heater (height = 52 in, diameter = 22 in) is 30.23 ft^2. If we assume medium hot water temperature of 140°F and surrounding air temperature of 70°F, then from Eq. (2), U = 0.1713 Btu/hr-ft^2-°F for a unit with 2 inches of insulation.

A useful way to think of U is in terms of the thermal resistance, R, where $R = 1/U$, the reason being that values of R are additive for changing insulation levels while values of U are not. For a composite wall such as in a water heater, the total wall R value is equal to the sum of the R values for the individual wall components:

$$R_T = R_g + R_t + R_j + R_i \tag{3}$$

where the subscripts g, t, j, and i refer to the fiberglass tank lining, the tank shell, the jacket surrounding the entire unit, and the insulation, respectively. For changing insulation levels, R_i will change while the first three terms will remain a constant, R_k

$$R_k = R_g + R_t + R_j \tag{4}$$

Recalling that $R = 1/U$, we can write

$$U = \frac{1}{R_k + R_i} \qquad (5)$$

or, since $U = k/L$,

$$U = \frac{1}{R_k + L_i/k_i} \qquad (6)$$

where L_i and k_i are the thickness and thermal conductivity, respectively, of the insulation. The thermal conductivity of fiberglass or mineral wool insulation will vary with its density, cell size, diameter and arrangement of fibers, degree and extent of bonding material and transparency to thermal radiation. A nominal value of 0.0258 Btu/hr-ft-°F was chosen from the literature [19].*

By using Eq. (6), we can now estimate the effect of changing insulation on the thermal transmittance, U. Solving Eq. (2) for q allows us to estimate the effect of U on heat loss through the walls of a water heater.** Table A-2 shows estimated values of U, the annual heat loss, and total energy use for electric, natural gas/LPG and fuel oil water heaters with varying levels of insulation. The total energy use was estimated as follows.

First, the amount of net usable heat, H_u, in the hot water must equal the total energy consumption, H_t, minus all losses, H_ℓ. Hence, taking the direct burner efficiency, e, into account,

$$\frac{H_u}{e} = H_t - \frac{H_\ell}{e} \qquad (7a)$$

---

*If one solves Eq. (6) for R_k using $U = 0.1713$, $L_i = 2/12$ (for 2 inches of insulation), and $k_i = 0.0258$, the result is $R_k = -0.622$. The explanation for this implausible result lies in uncertainties in the heat loss rate from which U was determined and in the choice of an appropriate value for k_i, which was selected as the mean of a fairly wide range of acceptable values quoted in the literature.

**Although based on a 50-gallon electric unit with 2-inch insulation, these estimates should apply equally well to other types and sizes of water heaters since the composition of the tank wall, upon which U depends, is similar for all types and sizes.

Table A-2

EFFECT OF THERMAL INSULATION ON THE ANNUAL ENERGY USE OF RESIDENTIAL WATER HEATERS

Insulation Thickness (inches)	U (Btu/hr-ft^2-°F)	50-Gallon Electric			40-Gallon Gas/LPG			40-Gallon Oil	
		Surface Area (ft^2)	Heat Lost (Therms/yr)	Total Energy Use (Therms/yr)	Surface Area (ft^2)[a]	Heat Lost[b] (Therms/yr)	Total Energy Use (Therms/yr)	Heat Lost[b] (Therms/yr)	Total Energy Use (Therms/yr)
1	0.3835	--	--	--	*27.1*	*91.0*	*260.3*	*95.0*	*271.9*
2	0.1713	*30.2*	*31.8*	*150.3*	31.4	47.1	216.4	49.2	226.1
3	0.1103	34.6	23.4	141.9	36.0	34.7	204.0	36.2	213.1
4	0.0813	39.1	19.5	138.0	40.8	29.1	198.4	30.4	207.3
5	0.0644	44.0	17.4	135.9	45.9	25.8	195.1	27.0	203.9
6	0.0533	49.1	16.0	134.5	51.3	24.0	193.2	25.1	201.9
7	0.0455	54.4	15.2	133.7	56.9	22.7	192.0	23.7	200.6
8	0.0397	60.1	14.6	133.1	62.8	21.8	191.1	22.8	199.7
9	0.0352	66.0	14.2	132.7	69.0	21.3	190.6	22.2	199.1
10	0.0316	72.1	14.0	132.5	75.4	20.8	190.1	21.8	198.6

NOTE: Values are based on a hot water-air temperature differential of 70°F. Italicized figures indicate the current standard level of insulation offered.

[a]Surface area figures apply to both gas/LPG and oil units.

[b]Heat loss figures include the direct burner efficiency of 70 percent for gas/LPG and 67 percent for oil, i.e., they represent the energy consumed to replace the heat lost by conduction through the tank walls.

For a 50-gallon electric unit, H_t and H_ℓ have been identified as 150.3 therm/year and 8700 Btu/day (31.8 therm/year), and e is about 100 percent.* Thus, H_u = 118.5 therms which equates to about 50 gallons per day at 140°F.** Conversely, the total use must equal the net usable heat plus all losses:

$$H_t = \frac{H_u}{e} + \frac{H_\ell}{e} \tag{7b}$$

Values of e were determined as 70 percent for gas/LPG units and 67 percent for oil units;* their total energy use is therefore 260.3 therms/year for natural gas/LPG units and 271.9 therms/year for oil units, each with one inch of insulation.

The Heating Cycle

Normally, the thermostat is in sole charge of controlling the heat element(s) in a water heater. Whenever water in the tank falls below a preset temperature, because of either withdrawals or heat losses, the thermostat turns on the heating element until the water again reaches the preset temperature. During the night and other periods of low water usage, fuel is consumed mainly to compensate for heat losses. This fuel is wasted in the sense that it is used to keep the water hot during a period when little or no hot water is needed. The best way to eliminate this waste and still maintain acceptably hot water might be to employ a low-temperature cut-in thermostat to activate the heating element when the water reached a preset minimum temperature. The additional cost would be about $15 or $20.

The cooling of a tank of hot water can be estimated as follows. For any two water temperatures, t_o and t_f with $t_o > t_f$, the amount of heat, ΔH, given up in cooling from t_o to t_f is,

*These were determined from manufacturers' ratings for gross heat input (Btu/hour) and recovery rates (gallons/hour at 100°F rise).

**We assume that average hot water usage does not depend on the type of water heater.

$$\Delta H = \rho \cdot C_P \cdot V \cdot (t_o - t_f) \tag{8}$$

where ρ is the density of water (8.3 lb/gallon), C_P is the heat capacity of water at constant pressure (1.0 Btu/lb-°F), and V is the quantity of water (gallons). If $t_o - t_f$ is small, the heat loss rate, q, will be nearly constant and the time, $\Delta\tau$, to cool from t_o to t_f will be

$$\Delta\tau = \frac{\Delta H}{q} \tag{9}$$

Also, if $t_o - t_f$ is small, the mean temperature during the cooling period, $\bar{t}$, will be

$$\bar{t} = \frac{t_o + t_f}{2} \tag{10}$$

Making the appropriate substitutions for ΔH and q in Eq. (9), we have

$$\Delta\tau = \frac{\rho \cdot C_P \cdot V \cdot (t_o - t_f)}{U \cdot A \cdot (\bar{t} - t_a)} \tag{11}$$

where t_a is the air temperature. Equation (11) is accurate as long as $t_o - t_f$ is kept small (not larger than 1°F). To estimate $\Delta\tau$ for larger temperature changes, one must pace through the range in small steps using Eq. (11), then sum the $\Delta\tau$ values to give the total cooling time. This procedure was programmed on JOSS* and resulted in the cooling curves shown in Fig. A-1.

The next step was to estimate the amount of energy to be saved by allowing the hot water to cool to some minimum temperature before heating it back up. To do this, the daily hot water usage schedule shown in Table A-3 was used in conjunction with the cooling curves to determine the temperature profile in the water tank during the day.**

*JOSS is the trademark and service mark of The Rand Corporation for its computer program and services using that program.

**We assume that cold water at 60°F replaces the hot water drawn from the tank.

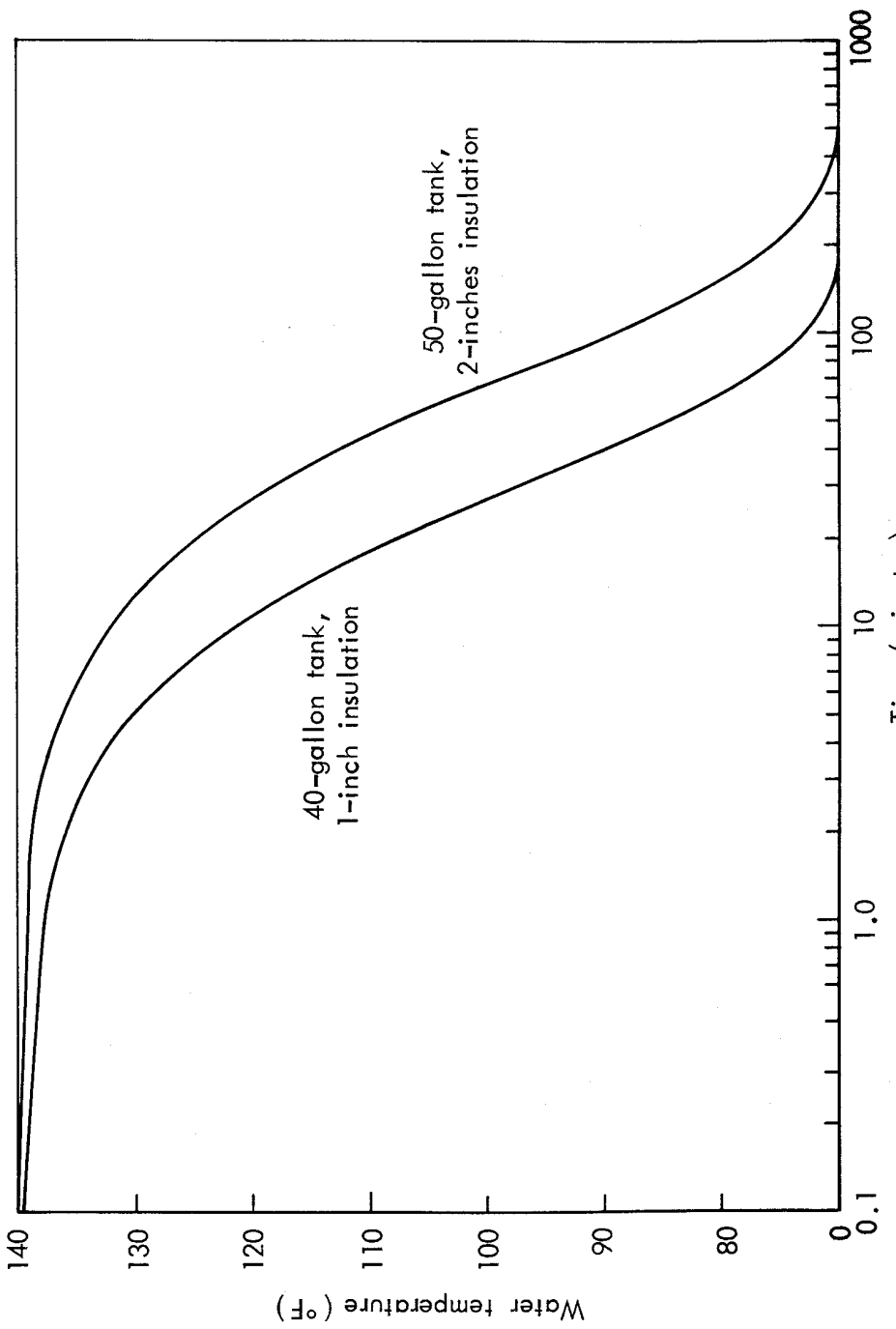


Fig. A.1 — Cooling curves for residential water heaters in 70° F ambient air

Table A-3

DAILY RESIDENTIAL HOT WATER USAGE SCHEDULE

Time	Hot Water Used		Time	Hot Water Used	
	Percent	Gallons		Percent	Gallons
12-1 a.m.	2.25	1.12	12-1 p.m.	3.60	1.80
1-2	--	--	1-2	5.10	2.55
2-3	--	--	2-3	2.70	1.35
3-4	--	--	3-4	2.40	1.20
4-5	--	--	4-5	2.10	1.05
5-6	--	--	5-6	3.75	1.88
6-7	1.50	0.75	6-7	6.75	3.38
7-8	4.65	2.32	7-8	11.60	5.80
8-9	7.25	3.62	8-9	9.60	4.80
9-10	8.49	4.20	9-10	6.90	3.45
10-11	6.90	3.45	10-11	5.46	2.73
11-12	4.50	2.25	11-12	4.65	2.32
			Total	100.0	50.0

Source: Ref. 8, p. 26.

Using Eq. (1), the water temperature in the tank at the beginning and end of each hour is estimated and the average hourly temperature is assumed to be their arithmetic mean. The heat lost during each hour is estimated as

$$\Delta H = \Delta\tau \cdot U \cdot A \cdot (\bar{t}-t_a) \qquad (12)$$

The total heat lost is the sum over all hours.

The results are shown in Table A-4. The energy saved is an inverse function of the minimum acceptable water temperature at which the heating element is activated to reheat the water to the maximum temperature. At a setting of 110°F, which is probably about the minimum acceptable temperature for household uses, the reduction in energy consumption would be 4.5 percent for electric units and 5.2 percent for other types. These figures are for standard levels of tank insulation. Thicker insulation would reduce these savings accordingly.

SOLAR ENERGY

A simple residential solar water heater consists of a collector, which absorbs solar radiation and transfers the heat to water, and a storage tank where the hot water is kept for use. The tank is connected to the hot and cold water plumbing system in the same manner as a conventional water heater. Through a separate piping system, cool water at the bottom of the tank flows to the solar collector where it is heated and returned to the top of the tank. The tank is elevated above the collector so that water flows naturally by thermosiphoning (convection) and a pump is not required.

The size of the solar collector needed is dependent upon the amount and temperature of hot water required, the temperature of the cold water, the intensity of solar radiation, the ambient air temperature, the efficiency of the solar collector, the length of the solar day, and the level of service desired from the solar water heater (i.e., the fraction of the total amount of hot water used during the year that is provided by solar energy). Obviously, the amount of solar

Table A-4

POTENTIAL ENERGY SAVINGS BY USING INTERMITTENT RATHER THAN CONTINUOUS STANDBY HEATING CYCLE

Minimum Water Temperature (°F)	Range of Water Temperature (°F)	Annual Energy Saved	
		Therms	Percent of Total Use
50-Gallon Electric			
110	30	6.7	4.5
120	20	4.2	2.8
130	10	1.6	1.1
40-Gallon Gas/LPG			
110	30	13.7	5.2
120	20	9.4	3.6
130	10	5.1	2.0
40-Gallon Fuel Oil			
110	30	14.3	5.2
120	20	9.9	3.6
130	10	5.3	2.0

NOTE: Minimum water temperature is the temperature at which the heating element turns on and reheats the water to the maximum temperature of 140°F.

energy available and the ambient air temperature also depend on the latitude and time of year.

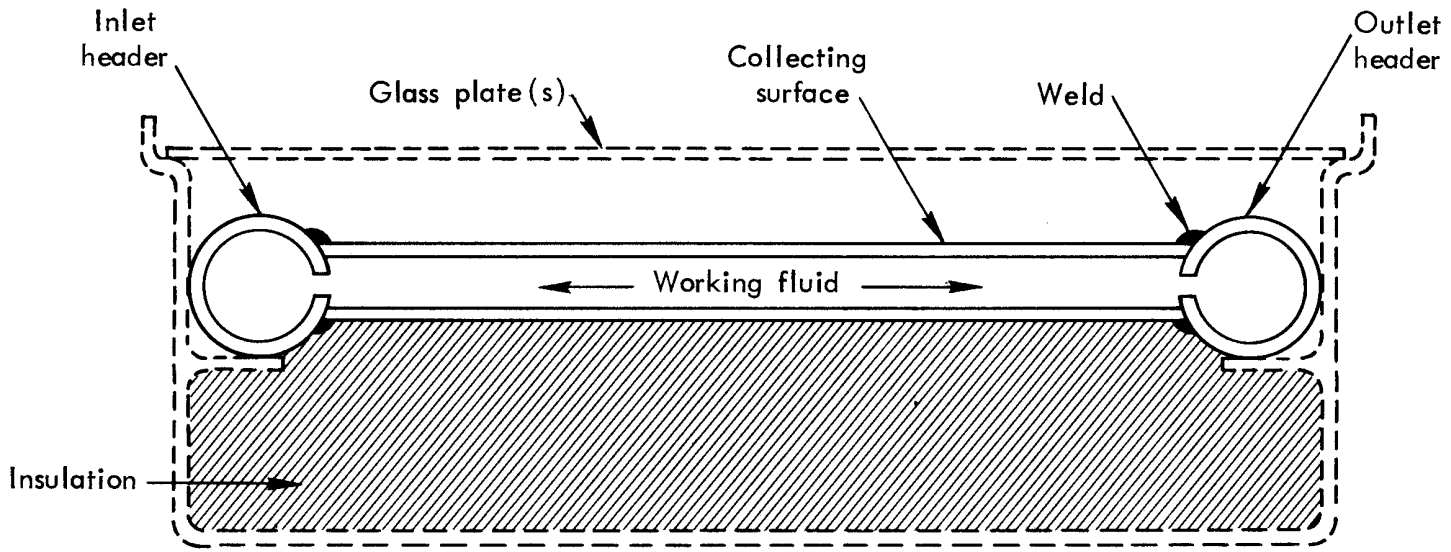
The design of the solar collector is critical because its efficiency determines the surface area required and because it is the most costly item in the system. The design chosen is a parallel-plate type based on the work of Stratton [20] and is shown in Fig. A-2. Water flows in a 1/2-inch thick layer between parallel aluminum plates (1/16-inch thick), being heated from the top plate, which is exposed to radiation. The top plate is painted with a selective coating to reduce re-radiation. Both plates are terminated by an aluminum header (1/2-inch inside diameter) at each end and are sealed together on the edges. Three inches of fiberglass or mineral wool insulation line the bottom plate to reduce conductive heat losses and the unit is housed in a 22-gauge sheet metal box. To reduce radiant losses, one or more glass covers are placed over the top of the housing.*

Ideally, the collector would be mounted on a tracking mechanism that would keep the collector surface oriented toward the sun as it moves across the sky. However, a tracking mechanism would be a very costly item in investment and maintenance. Satisfactory all-around performance can be gained with the collector permanently oriented due south (in the northern hemisphere) and inclined from the horizontal. The best angle of inclination depends on the period of the year during which the collector will operate and the latitude. If I_o is the radiation intensity (Btu/ft^2-day) on a horizontal surface, the intensity, I, on a surface inclined at an angle θ (degrees) from horizontal can be determined from

$$\frac{I}{I_o} = \frac{\sin(180 - \theta - \phi)}{\sin \phi} \tag{13}$$

where ϕ is the elevation (degrees) of the sun above the horizon. The ratio I/I_o is called β and, for any θ, depends on ϕ which varies with the latitude and time of year. The idea is to select the collector

*The optimum number of glass cover plates is discussed later.



Note: Not to scale

Source: Ref. 20

Fig. A-2 — Cross-sectional view of parallel-plate solar collector

inclination θ so that β does not fall below about 0.8 at high solar elevations (during the summer) and so that β is maximized at the lowest solar elevation expected when all hot water will be provided by the solar unit. The time of lowest solar elevation is the design month (i.e., the month in which solar conditions are poorest). These conditions will determine the collector surface area required to meet hot water demands at that time. Monthly solar elevation angles for various northern hemisphere latitudes have been published [19].

To size the collector for specific applications, we use the methodology and data of Farber et al. [13], which is described below.

The amount of heat collected daily on 1 ft^2 of a flat plate collector, h_c, is

$$h_c = I_o \cdot \beta \cdot c_i \tag{14}$$

where c_i is the combined solar transmission coefficient of i glass plates that cover the collector. The daily heat lost per ft^2 through the glass plates by re-radiation from the collector surface, h_ℓ, is

$$h_\ell = T \cdot U_i \cdot (t_w - t_a) \tag{15}$$

where U_i is the combined thermal transmittance of i glass plates (Btu/hr-ft^2-°F); t_w and t_a are the temperatures (°F) of the hot water and ambient air, respectively; and T is length of time (hours) hot water is passing through the collector, i.e., the length of the solar day.* The net heat transferred to the water per ft^2 of collector surface, h, is then, $h_c - h_\ell$:

$$h = \left(I_o \cdot \beta \cdot c_i\right) - \left(T \cdot U_i \cdot (t_w - t_a)\right) \tag{16}$$

The total amount of heat needed, H, can be determined using Eq. (8) with V being the daily usage of hot water, t_f the cold water temperature

*Water is not circulated through the collector from sunset to sunrise since it would cool off.

and $t_o = t_w$. The collector area needed to provide that heat is,

$$A = \frac{H}{h} \tag{17a}$$

or

$$A = \frac{\rho \cdot C_P \cdot V \cdot (t_w - t_f)}{(I_o \cdot \beta \cdot c_i) - (T \cdot U_i \cdot (t_w - t_a))} \tag{17b}$$

Farber's values for c_i and U_i are given in Table A-5.

Table A-5

VALUES OF SOLAR TRANSMISSION COEFFICIENT AND THERMAL TRANSMITTANCE FOR GLASS PLATES

Number of Glass Plates (i)	Solar Transmission Coefficient (c_i)	Thermal Transmittance (U_i, Btu/hr-ft^2-°F)
1	0.748	1.03
2	0.625	0.625
3	0.542	0.429
4	0.474	0.345

Source: Ref. 13, p. 78.

The investment associated with a solar water heater includes the following estimated cost parameters:

Solar collector* (less glass cover plates)	\$3.90/ft^2
Glass cover plates, each**	\$1.00/ft^2

*Based on the following prices obtained from manufacturers and dealers: fabricated aluminum, \$1.50/lb; sheet metal, \$0.35/lb plus 20 percent markup; insulation, \$0.05/ft^2-inch [7].

**Private communication with dealer.

80-gallon tank with 6-inch insulation and electric heater*	$116.50
Installation, plumbing, wiring**	$195.00

The feasibility and cost of solar water heating was analyzed for three latitudes in the United States: 32°N (southern tier of states), 40°N (central tier), and 48°N (northern tier). For each latitude, published information was employed on average daily solar radiation [22], length of the solar day [19], and average daily ambient temperatures [23]. All data were monthly means. The collector was sized to provide a maximum of 80 gallons per day of 130°F water with cold service water at 75°F for the southern region, 68°F for the central region, and 60°F for the northern region. At each latitude, several systems were designed, providing varying amounts of the total annual hot water usage, and the cost of each determined.***

The effect of the number of glass cover plates was also examined and, in each case, the number was chosen which resulted in the lowest total investment cost. The southern tier of states is the only region where a system of this design could operate year-round to generate all the hot water needed from solar energy. In the central and northern regions, air temperatures drop below freezing during part of the year, during which times the solar unit would be shut down and hot water provided by an auxiliary electric heater.

---

*An electric backup heater is included even in the 100 percent solar system because we presume that abnormal weather conditions or hot water demands may occasionally arise that would require a booster. The price of a tank without the heater would be about $50 less.

**From Ref. 21, p. 60.

***For each latitude, several systems were designed using the environmental parameters of various months. It was assumed that a system designed for 100 percent solar operation during a specific month would be capable of generating all hot water needed during less severe months and, weather permitting, would also generate a portion of hot water needed during more severe months. The actual portion generated by solar energy during the more severe months was estimated using Eq. (8) and Eq. (16); the remainder was taken to be generated by electricity. Average hot water usage was assumed to be 50 gallons per day.

The results of the design and cost analyses are given in Table A-6. As one moves from southerly to northerly latitudes, the collector area (and investment) necessary to produce a given level of solar performance increases because of the lower radiation densities and colder temperatures encountered at higher latitudes.

It should be noted that the solar and temperature data used in the analysis for each latitude are quite typical of that latitude in the climatic regime extending east of the Rocky Mountains to the Atlantic Coast. However, in the Rockies and regions to the west, solar radiation, cloud cover, and ambient temperature are strongly influenced by local topography, elevation, and proximity to the Pacific Ocean. Hence, the information in Table A-6 should be considered applicable only to the area east of the Rockies. In the Rockies and regions west, solar systems must be designed according to the prevailing local conditions.

Table A-6

ESTIMATED DESIGN, COST AND PERFORMANCE OF SEVERAL SOLAR WATER HEATING SYSTEMS AT THREE U.S. LATITUDES

Design Month	Collector Area (ft^2)/No. of Glass Cover Plates	Optimum Collector Inclination Above Horizontal	Investment Cost	Annual Percent Hot Water From		Annual Electricity Use (kWh)
				Solar	Electricity	
Southern Region (32°N Latitude)[a]						
December	80/2	46°	$782	100	--	--
November	74/1	45°	683	96.4	3.6	142
September	43/1	28°	521	83.5	16.5	650
August	40/1	14°	504	72.3	27.7	1092
June	39/1	7°	501	65.4	34.6	1364
Central Region (40°N Latitude)[b]						
November	93/2	56°	$863	83.3	16.7	658
September	55/1	39°	579	69.6	30.4	1198
August	51/1	23°	560	59.1	40.9	1612
Northern Region (48°N Latitude)[c]						
September	71/1	42°	$660	58.3	41.7	1643
June	63/1	23°	619	51.1	48.9	1927
August	58/1	32°	593	52.7	47.3	1864

[a]As far north as San Diego, Dallas, and Atlanta.

[b]As far north as Denver, St. Louis, and Philadelphia.

[c]As far north as Seattle, Fargo, and Bangor, Maine.

Appendix B

PRESENT VALUE AND THE DISCOUNT RATE

It is intuitively obvious that the value one places on money is time-dependent. Ten dollars in the hand today is worth more than the prospect of ten dollars at some time in the future. Some of the reasons for this should be apparent: the money can be invested to yield some additional return over time; because of inflation, future money will have less buying power than current money.

The discount rate is a measure of one's time preference for money. An annual discount rate of 10 percent means that money next year is worth 10 percent less than money this year. Another way of looking at it is that, if my personal discount rate is 10 percent, then I will be indifferent if offered a choice between some amount of money now or 10 percent more than that amount in one year.

Discount rates may be evaluated in many ways, all of which are highly subjective. In the case of purchases by a private individual, one might argue that his discount rate is reflected by the interest rate on savings deposit accounts, since that is what he could earn on his money if he did not spend it. Or, one could use the interest rate charged on signature loans as an estimate, arguing that consumer discount rates must be at least this high since no one would borrow money at an interest rate higher than his discount rate. This argument leads to higher discount rates than the first method. There are, no doubt, people whose discount rates are at both ends of this spectrum, as well as others whose rates fall outside. Our point is that the discount rate is a personal value judgment, depending on the individual's financial position and perception of the time value of money. It is doubtful that the average rate for a consumer group can be specified with any accuracy. At best, an indication of its magnitude can be gained by a logical consideration of the money market a typical consumer finds himself in.

For the purpose of our analysis and as an illustrative example, we assume that interest rates on consumer loans offer an indication

of the public's average discount rate. Rates on what may be called marginal loans (e.g., home improvement loans, credit cards, charge accounts) typically range from about 12 to 18 percent per year. These market rates include the projected rate of inflation since the lender must anticipate the effect inflation will have on the return he earns on his money. Since we deal with constant-value dollars in this study, inflation must be deducted from this rate. If b is the interest rate on borrowed money, i the rate of inflation, and d the inflation-free discount rate, then

$$(1+b) = (1+i)(1+d) \tag{1a}$$

or

$$d = \frac{1+b}{1+i} - 1 \tag{1b}$$

However, since interest paid on a loan is a tax-deductible item, the real rate of interest paid on a loan is

$$b = (1-t)r \tag{2}$$

where t is the consumer's combined state and federal income tax rate and r is the market loan rate. Equation (1b) then becomes

$$d = \frac{1 + (1-t)r}{1+i} - 1 \tag{3}$$

The value d is the inflation-free, after-tax discount rate indicated by the market interest rate on personal loans. The combined state-federal income tax rate for median-income families is currently about 15 percent.* Assuming nominal inflation of 4 percent per year,

*The 1972-73 federal income tax liability for a married couple with two dependents and $10,000 adjusted gross income was 9.1 percent. State income tax liabilities range from zero to 15 percent of adjusted gross income, for which a median of 6 percent was chosen. (Ref. 24, pp. 395 and 429.)

market loan rates of 12 to 18 percent equate to inflation-free, after-tax discount rates of from 6 to 11 percent, with a median of 8 percent.

In this study, we examine the economics of domestic water heating systems in terms of their life cycle costs. The life cycle cost of a system is the capital investment plus the discounted present value of the operating costs over the life of the system. In the case of water heating, the operating cost is the annual constant-dollar fuel cost, A; the discounted present value, P, of this stream of annual fuel costs is

$$P = A \cdot \left[\frac{(1+d)^n - 1}{d(1+d)^n} \right] \qquad (4)$$

where n is the expected lifetime of the system (years) and d, again, is the inflation-free, after-tax discount rate.

Appendix C

SELECTED REGIONAL ESTIMATES

This Appendix contains selected data pertaining to consumption of fuels for residential water heating on a regional basis. The regions are the nine geographic census divisions of the United States. The regional estimates herein form the basis for the national estimates presented in Section IV of this report.

Table C-1 contains regional estimates of fuel consumed in residential water heating in 1970. They are based on estimated per unit fuel consumption and information on occupied housing units and water heater saturations contained in the 1970 Census of Housing [2].

Contained in Table C-2 are projections to 1990 of regional water heater saturations under four fuel price cases (see Section IV, especially Table 12). Anderson's [3] stock elasticities were employed and 1970 Census saturations and fuel prices were used as a base. Future fuel prices were assumed to change uniformly over all regions, ignoring the effect of transportation costs, and mean household income was assumed to grow 1.75 percent per year in constant dollars. The projected saturations are long-run equilibrium values in that they assume fuel prices are constant for a prior length of time to allow the water heater stock to adjust.

Table C-3 presents estimated 1990 regional fuel consumption under the four fuel price cases with standard water heating equipment and with the economically optimum equipment justified by the fuel prices. Again, these estimates indicate long-run responses to changes in fuel prices and equipment; in this sense, they should not be considered as projections but indications of the long-run effects of fuel prices and policies to encourage utilization of optimum equipment under those prices.

Table C-1

ESTIMATED REGIONAL FUEL CONSUMPTION IN RESIDENTIAL WATER HEATING, 1970

Fuel	New England	Mid-Atlantic	East No. Central	West No. Central	South Atlantic	East So. Central	West So. Central	Mountain	Pacific	United States
Fuel oil[a]	7810	20,000	950	20	270	--	--	--	40	29,090
Natural gas[b]	29	149	219	82	76	37	116	44	156	908
LPG[a]	1000	1990	3240	3490	2990	1500	3740	1000	1490	20,440
Electricity[c]	3.5	6.7	12.3	5.3	20.8	7.3	2.3	2.6	10.0	70.9
Trillion Btu										
Fuel oil	41	105	5	1	14	--	--	--	2	168
Natural gas	29	149	219	82	76	37	116	44	156	908
LPG	4	8	13	14	12	6	15	4	6	82
Electricity	12	23	42	18	71	25	8	9	34	242
Total	86	285	274	114	159	68	139	57	196	1400

[a]Thousand barrels/year.

[b]Billion cubic feet/year.

[c]Billion kWh/year.

Table C-2

PROJECTED REGIONAL WATER HEATER SATURATION, 1990
(percent)

Fuel	Northeast[a]	Southeast[b]	West So. Central	North Central and West[c]	United States
Base Case					
Fuel oil	8	--	--	--	2
Natural gas	55	31	80	63	56
LPG	1	1	3	1	1
Electric	34	63	14	34	39
None	2	5	3	2	2
Case A					
Fuel oil	13	--	--	--	3
Natural gas	17	7	33	23	19
LPG	3	3	11	5	5
Electric	54	68	29	61	59
None	13	22	27	11	14
Case B					
Fuel oil	17	--	--	--	4
Natural gas	6	2	17	9	8
LPG	2	2	13	4	4
Electric	70	88	56	83	79
None	5	8	14	4	5
Case C					
Fuel oil	11	--	--	--	2
Natural gas	72	56	88	84	76
LPG	2	3	4	2	2
Electric	12	31	4	12	16
None	3	10	4	2	4

NOTE: Based on Anderson's stock elasticities, Ref. 3, pp. 33, 66.

[a] New England and Mid-Atlantic regions.

[b] South Atlantic and East South Central regions.

[c] East North Central, West North Central, Mountain, and Pacific regions.

Table C-3

ESTIMATED REGIONAL FUEL CONSUMPTION IN RESIDENTIAL WATER HEATING WITH STANDARD AND OPTIMUM[a] EQUIPMENT - 1990

Fuel Price Case	New England	Mid-Atlantic	East No. Central	West No. Central	South Atlantic	East So. Central	West So. Central	Mountain	Pacific	United States
Fuel Oil (thousand barrels/year) with standard equipment										
Base	2100	66290	--	--	--	--	--	--	--	8380
A	3240	10,290	--	--	--	--	--	--	--	13,530
B	4380	13,340	--	--	--	--	--	--	--	17,720
C	2860	8570	--	--	--	--	--	--	--	11,430
with optimum equipment										
Base	1520	4380	--	--	--	--	--	--	--	5910
A	2290	7240	--	--	--	--	--	--	--	9530
B	3050	9530	--	--	--	--	--	--	--	12,580
C	2100	6100	--	--	--	--	--	--	--	8190
Natural Gas (billion cubic feet/year) with standard equipment										
Base	70	217	290	106	116	41	175	66	220	1301
A	22	67	106	39	26	9	72	24	80	445
B	8	24	41	15	7	3	37	9	31	175
C	92	285	386	142	209	74	192	88	293	1761
with optimum equipment										
Base	51	158	212	77	85	30	128	48	161	950
A	16	48	75	28	18	6	51	17	57	316
B	6	17	29	11	5	2	26	6	22	124
C	67	208	282	104	152	54	140	64	214	1285
LPG (thousand barrels/year) with standard equipment										
Base	250	750	1250	500	1000	250	1500	250	750	6730
A	1000	2990	5730	1990	2740	1000	5980	1250	4240	26,900
B	750	1990	4490	1740	1740	750	6980	1000	3490	22,900
C	750	1990	2240	750	2740	1000	2240	500	1740	14,000
with optimum equipment										
Base	175	750	1000	250	750	175	1000	170	500	4770
A	750	1990	3990	1500	1000	250	*0*	750	1500	*11,7[illegible]*
B	500	1500	3240	1250	1250	500	4980	750	2490	16,500
C	500	1500	1500	500	1990	750	1500	250	1250	9740
Electricity (billion kWh/year) with standard equipment										
Base	7.3	22.8	26.4	9.7	39.8	14.1	5.3	5.8	19.9	151.2
A	11.7	36.0	47.5	17.3	43.1	15.2	10.5	10.8	36.0	228.2
B	15.2	46.9	64.4	23.7	55.7	19.6	20.5	14.6	48.9	309.7
C	2.6	7.9	9.4	3.5	19.6	7.0	1.5	2.0	7.0	60.6
with optimum equipment										
Base	6.2	19.3	*14.6*	*5.3*	*7.6*	*2.6*	*0.6*	*2.0*	*6.7*	*64.9*
A	*4.1*	*12.6*	*14.4*	*5.3*	*6.2*	*2.0*	*0.9*	*2.3*	*6.4*	*54.2*
B	12.9	39.3	*35.4*	*12.9*	*10.5*	*3.8*	*2.9*	*5.3*	*16.7*	*139.7*
C	*0.9*	*2.6*	*2.9*	*1.2*	*2.6*	*0.9*	*0 0*	*0.6*	*1.2*	*12.3*
Total (trillion Btu) with standard equipment										
Base	107	332	385	141	256	90	199	87	291	1888
A	83	256	291	106	184	65	132	66	220	1403
B	86	262	279	103	204	73	135	63	212	1417
C	119	365	427	157	287	102	206	97	324	2084
with optimum equipment										
Base	81	250	*200*	*96*	*114*	*40*	*134*	*56*	*186*	*1223*
A	*45*	*137*	*140*	*52*	*43*	*14*	*54*	*28*	*85*	*538*
B	68	207	*163*	*60*	*46*	*17*	*56*	*27*	*89*	*733*
C	*83*	*255*	*238*	*110*	*169*	*60*	*146*	*67*	*223*	*1411*

[a]Standard equipment means water heaters as currently available (i.e., current levels of tank insulation) and mean water temperature of 140°F. Optimum equipment refers to units with the economically optimum thickness of tank insulation, mean hot water temperature reduced 30°F, and solar collectors installed where justified by fuel prices. Italicized figures indicate use of solar-electric systems in those portions of regions where justified by prices of competing fuels. Hot water plumbing insulation is not included in any case because, even in situations where fuel prices are high enough to justify it on conventional units, solar-electric water heaters have already been substituted.

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● NEXT ACTIVITY CHOICE

```
|TYPE         TO                                  |
|                                                 |
|  !describe...EDIT THE SCHEMA                    |
|  !enter......ENTER STUDY DATA                   |
|  !retrieve...RETRIEVE STUDY DATA                |
|  !worksheet..MANIPULATE WORKSHEETS              |
|  !analyze....ANALYZE DATA                       |
|  !subset.....SUBSET PATIENTS                    |
|                                                 |
|  !review.....EXAMINE A DATA INPUT FILE          |
|  !comments...RECORD COMMENTS                    |
|  !goodbye....TERMINATE THIS SESSION             |
|  !files......EXAMINE FILE UTILIZATION           |
|                                                 |
|  !response...CREATE/USE A RESPONE FILE          |
```

● WORKSHEET OPTIONS

```
|TYPE TO                          |
|                                 |
|   0..SELECT A WORKSHEET         |
|   1..DISPLAY THIS WORKSHEET     |
|                                 |
|   2..LABEL WORKSHEET ROWS       |
|   3..LABEL WORKSHEET COLUMNS    |
|                                 |
|   4..ENTER DATA BY ROWS         |
|   5..ENTER DATA BY COLUMNS      |
|   6..ENTER DATA RANDOMLY        |
|                                 |
|   7..DISCARD THIS WORKSHEET     |
|   8..SORT THIS WORKSHEET        |
|   9..LIST YOUR WORKSHEETS       |
```

● ENTER OPTION

```
|TYPE TO                |
|                       |
|   1..ADD NEW DATA     |
|   2..CORRECT OLD DATA |
|   3..ADD A NEW PATIENT|
```

● ANALYZE OPTIONS

```
|TYPE TO                          |
|                                 |
|   0..SELECT A WORKSHEET         |
|   1..DESCRIPTIVE STATISTICS     |
|   2..T-TEST                     |
|   3..CHI-SQUARE TEST            |
|   4..LINEAR REGRESSION          |
|   5..ANOVA                      |
|   6..CROSS TABS                 |
|   7..SCATTER PLOT               |
|   8..HISTOGRAM                  |
|   9..ROW/COL CALCULATIONS       |
|  10..NORMALITY TEST             |
|  11..RANK CORRELATION           |
```

● RETRIEVE OPTIONS

```
|TYPE TO                                          |
|   0..SELECT A WORKSHEET                         |
|-------------------------------------------------|
|TYPE TO COPY DATA                                |
|      FROM                TO                     |
|                                                 |
|   1..Study Data File.....Panel/event display    |
|   2.....................Worksheet              |
|   3.....................Terminal/              |
|                          Communication File     |
|                                                 |
|   4..Worksheet...........Worksheet              |
|   5.....................Communication File     |
|                                                 |
|   6..Communication File..Worksheet              |
```

● RESPONSE FILE CHOICES

```
|TYPE    TO                       |
|                                 |
|  1..EXECUTE A RESPONSE FILE     |
|  2..CREATE A RESPONSE FILE      |
|  3..EDIT A RESPONSE FILE        |
|  4..DISCARD A RESPONSE FILE     |
```

● SUBSET CHOICES:

```
|TYPE      TO CREATE A SET OF PATIENTS FROM       |
|                                                 |
|  1..A LIST OF PATIENT ABBREVIATIONS             |
|  2..THOSE BELONGING TO ALL OF A LIST OF SETS    |
|  3..THOSE BELONGING TO AT LEAST ONE OF A LIST OF SETS |
|-------------------------------------------------|
|          THOSE WHOSE STUDY FILE DATA SATISFY    |
|                                                 |
|  4..ALL CONDITIONS IN A LIST                    |
|  5..AT LEAST ONE CONDITION IN A LIST            |
|-------------------------------------------------|
|          THOSE WHOSE WORKSHEET DATA SATISFY     |
|                                                 |
|  6..ALL CONDITIONS IN A LIST                    |
|  7..AT LEAST ONE CONDITION IN A LIST            |
```

```
|TYPE     TO                                      |
|                                                 |
|  8..LIST PATIENT ABBREVIATIONS FROM A SET       |
|  9..LIST ALL OF YOUR SET NAMES                  |
| 10..DISCARD A PARTICULAR SET                    |
```

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