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SUBJECT:	Energy Consumption in Residential Gas and Electric Water Heaters and Ranges	
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ABSTRACT

Mathematical models of energy consumption derived from energy balances for ranges and water heaters are formulated to relate variations in design for upgrading efficiency to the total energy consumption. The water heater model predicts major energy savings when insulation is added around the storage tank and when tank water temperature is reduced. Results also show significant reduction in energy consumption when reducing the flue gas exit temperature and excess air flow, and when reducing or eliminating pilot usage in gas water heaters. The range model shows substantial reduction in energy consumption when adding oven wall insulation and when reducing the excess air flow through the oven in gas ranges.

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Contents

1. SUMMARY

Models relating energy consumption to key design parameters were developed for residential water heaters and ranges. This was accomplished by performing energy balances to determine the components of the general equations describing water heater and range performance. Each term of the energy balance was then formulated to predict consumption as a function of design options.

To evaluate the impact on energy consumption for each option, a baseline of energy utilization for each device was established. Background information was more readily available for water heaters than for ranges. Several recent studies have evaluated the effect of several design options on total energy consumption for gas and electric* water heaters. With this information, an energy consumption model describing water heater operation was developed which enabled evaluation of the impact of different design options on total energy consumption. The results obtained agreed favorably with those given from other sources based on both theoretical and experimental methods.

For water heaters, added jacket insulation and decreased tank water temperature offer means of greatly reducing total energy consumption at little or no change in cost. Substantial savings may also be obtained in gas water heaters by reducing or eliminating the pilot, reducing the flue temperature, and lowering the amount of excess air provided for combustion. It is recommended that detailed cost analyses be performed to determine which design options are cost effective at the present time.

Data describing energy use in ranges were not readily available. Calculations based on information from many different sources were performed to define the components of present energy utilization in ranges. The range model accurately reflects baseline energy consumption and utilization in gas and electric ranges.

Although no basis for comparison is available, the range model appears to allow reasonable estimations of the impact of the design options on energy consumption. Since the baseline data showed high inefficiencies in gas compared to electric ranges, future research on range efficiency should focus on gas ranges. The greatest reduction in energy consumption will occur when ventilation losses are reduced by installing a damper to reduce excess air flow through the oven. Oven wall losses in gas and electric ranges constitute another important area where energy conservation measures can be effective. The cost effectiveness of these design options, which have a large energy savings potential, cannot be established before experimental studies and cost analyses are complete.

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*Electric energy consumption in this report is calculated at the point of use.

2. INTRODUCTION

As an outgrowth of the recent energy shortage, FEA and ERDA must establish effective energy conservation measures and determine areas which require experimental investigation before planning research and developing a national energy policy. The Energy Division of ORNL is currently developing a comprehensive engineering-econometric model of energy consumption which will function as a major source of information necessary for making these decisions. The model predicts residential energy consumption according to supply and demand for the nation for the years 1970-2000.

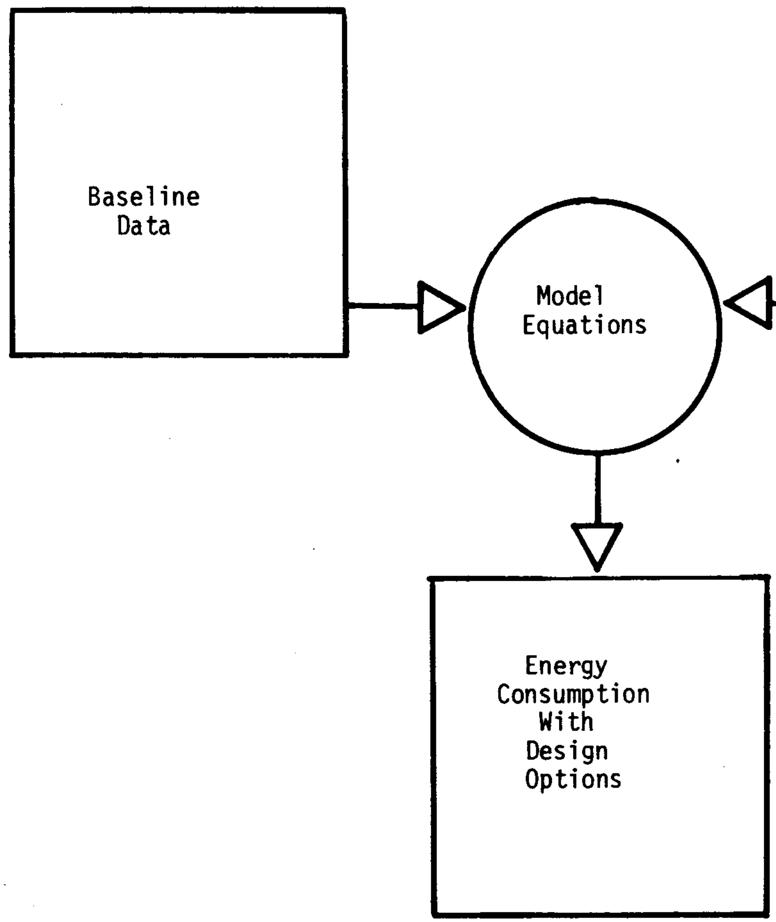
One section of this comprehensive model, the engineering cost model, will be the source of algorithms relating the energy efficiency and consumption for residential energy consuming devices to the design and retail cost for these devices. The algorithms for two major groups of home appliances, water heaters and ranges, are presented here for use in the engineering cost model.

The algorithms are equations which model the energy utilization for each appliance. Each equation was formulated to predict the energy consumption for an appliance with various design options to upgrade efficiency. The parametric constants in the algorithm for each appliance were calculated from baseline data on energy consumption and utilization. A list of design options most effective in reducing energy consumption was also compiled.

A review of prior results was performed and telephone contacts with appliance manufacturers, manufacturing associations, government agencies, and authors of related studies were established to determine each algorithm and to obtain the most recent information available. With these data, a baseline of energy utilization was constructed from which a list of design options was compiled.

3. PROCEDURE

The approach for determining energy consumption of water heaters and ranges, shown schematically in Fig. 1, consists of listing baseline data, compiling design options, and then constructing a model for calculating energy consumption for the various design options. The baseline is a set of variables which characterize the energy consumption of each appliance for a reference year. Design options are changes which can be incorporated into the design or operation of an appliance with a resultant decrease in energy consumption. The models, derived in Sects. 4.2 and 4.6, are algebraic equations which determine energy consumption of each appliance as a function of design option parameters and information established from the baseline.



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INFLUENCE OF DESIGN OPTIONS
ON ENERGY CONSUMPTION

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The information needed for establishing a baseline consists of the national energy consumption, the number of appliances in use, the areas of energy utilization, and the national distribution of appliances by size or capacity. All this information except for energy utilization was found in reports by the U.S. Bureau of the Census.

The results of prior studies were reviewed and appliance manufacturers, manufacturing associations, and authors of related studies were contacted for the correct data needed to obtain an accurate description of energy utilization. Extensive research is currently being conducted by range manufacturing associations to establish data required as a result of a recent federal order for the efficiency labeling of new appliances. The presently unpublished results of such work are regarded as proprietary information by manufacturers, hesitant to reveal such information to competitors. Baseline information concerning energy utilization incorporated into the range model represents an evaluation of pieces of information from a wide variety of sources.

To obtain an accurate concept of effective design options, the energy utilization was determined by performing an energy balance for each appliance. The individual terms in the energy balance were expressed as functions of existing operating parameters and additional design option parameters. These design options were evaluated to ensure the net result of each option would not have a major impact on cost, safety of operation, and change of the function of the appliance. The model parameters were left in a form allowing flexibility so that new and better values could be substituted for future improvement as more data become available.

4. BASELINE DATA AND MODEL DEVELOPMENT

4.1 Water Heater Description

Residential water heaters consist of a water storage section and a heat source. Electric water heaters rely on either one or two submerged heating elements to heat the water to the desired level. Hot water is drawn from the top of the water heater while cold water enters the water storage section near the bottom of the tank. The thermostat activates the heating elements when the water temperature falls below the desired level.

In gas water heaters, methane is burned with excess air producing hot flue gases. These gases travel up the flue transferring heat through the flue wall to the water. When the tank water temperature drops sufficiently, the pilot which is on continuously, ignites the main burner. Like the electric water heater, hot water is drawn from the top and cold water enters the storage section near the bottom.

4.2 Baseline Model of Water Heater Energy Consumption

Energy consumption by residential water heaters may be divided into two components. The first of these, withdrawal consumption, E_{wa}, is the energy required to raise the inlet water to the desired temperature level. Standby consumption, the second component, is the energy consumed in maintaining the tank water at this level. The standby losses are due to energy transferred from the water to the air through the water heater jacket, E_{jt}, the energy lost when gases at high temperatures leave the stack, E_{fl}, and the energy transferred from the water to the air through the walls of the water distribution system, E_{ln}. Performing energy balances on the control volumes shown in Figs. 2 and 3 yields

$$E = E_{wa} + E_{jt} + E_{fl} + E_{ln} \tag{1}$$

where E_{fl} is zero for electric water heaters. Furthermore,

$$E_{wa} = MC_p(T_w - T_{wi})(t) \tag{2}$$

The jacket losses are found by using the following equation:

$$E_{jt} = UA(T_w - T_a)(t) \tag{3}$$

The energy lost in the form of hot gases leaving the flue is the loss during main burner operation plus the loss during pilot operation, or

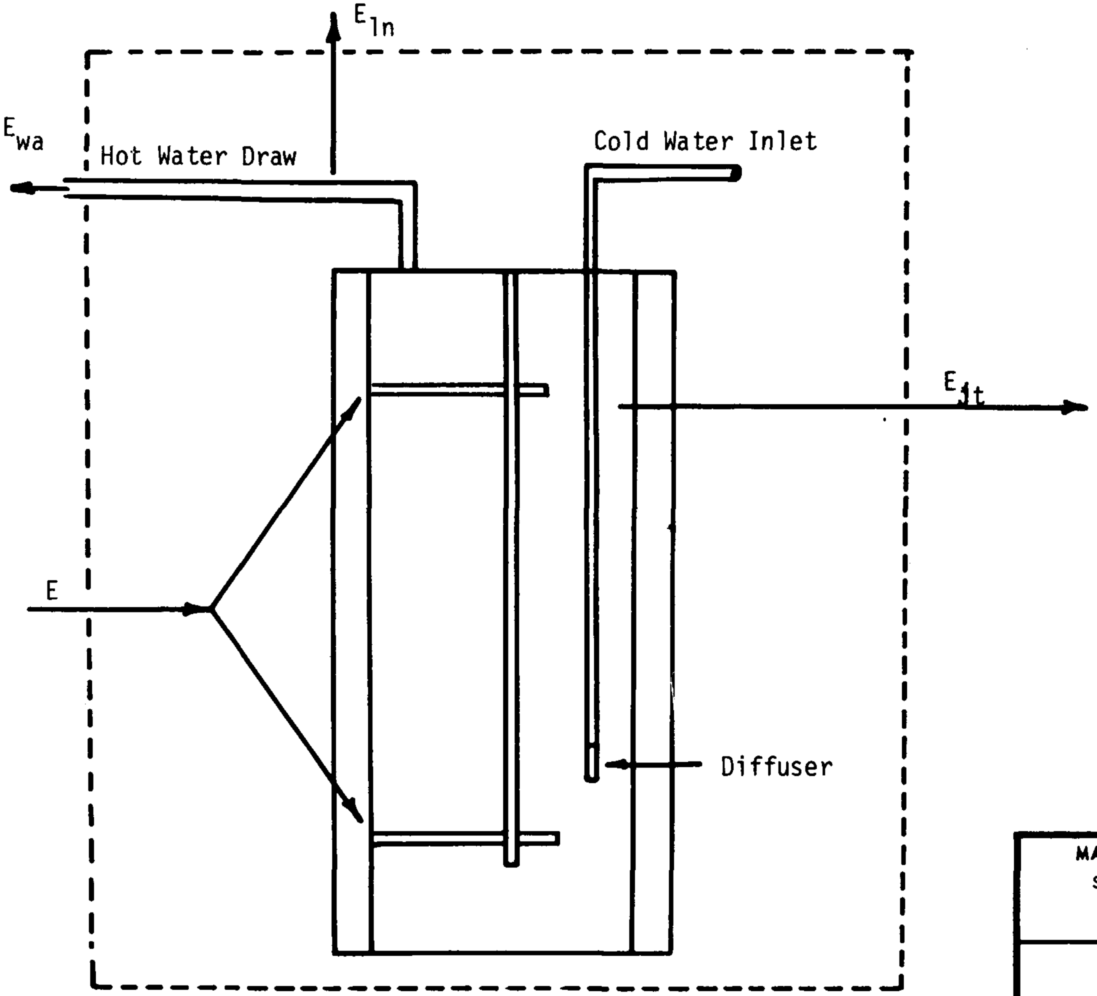
$$E_{fl} = E_{main\ burner} + E_{pilot} \tag{4}$$

where:

$E_{main\ burner}$ = (standard main burner firing rate)(capacity) (fraction of energy lost through the flue during main burner operation)(main burner operating time) (5)

and

E_{pilot} = (pilot consumption)(pilot operating time)(fraction of energy lost through the flue during pilot operation) (6)



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CONTROL VOLUME FOR ELECTRIC
WATER HEATER ENERGY BALANCE

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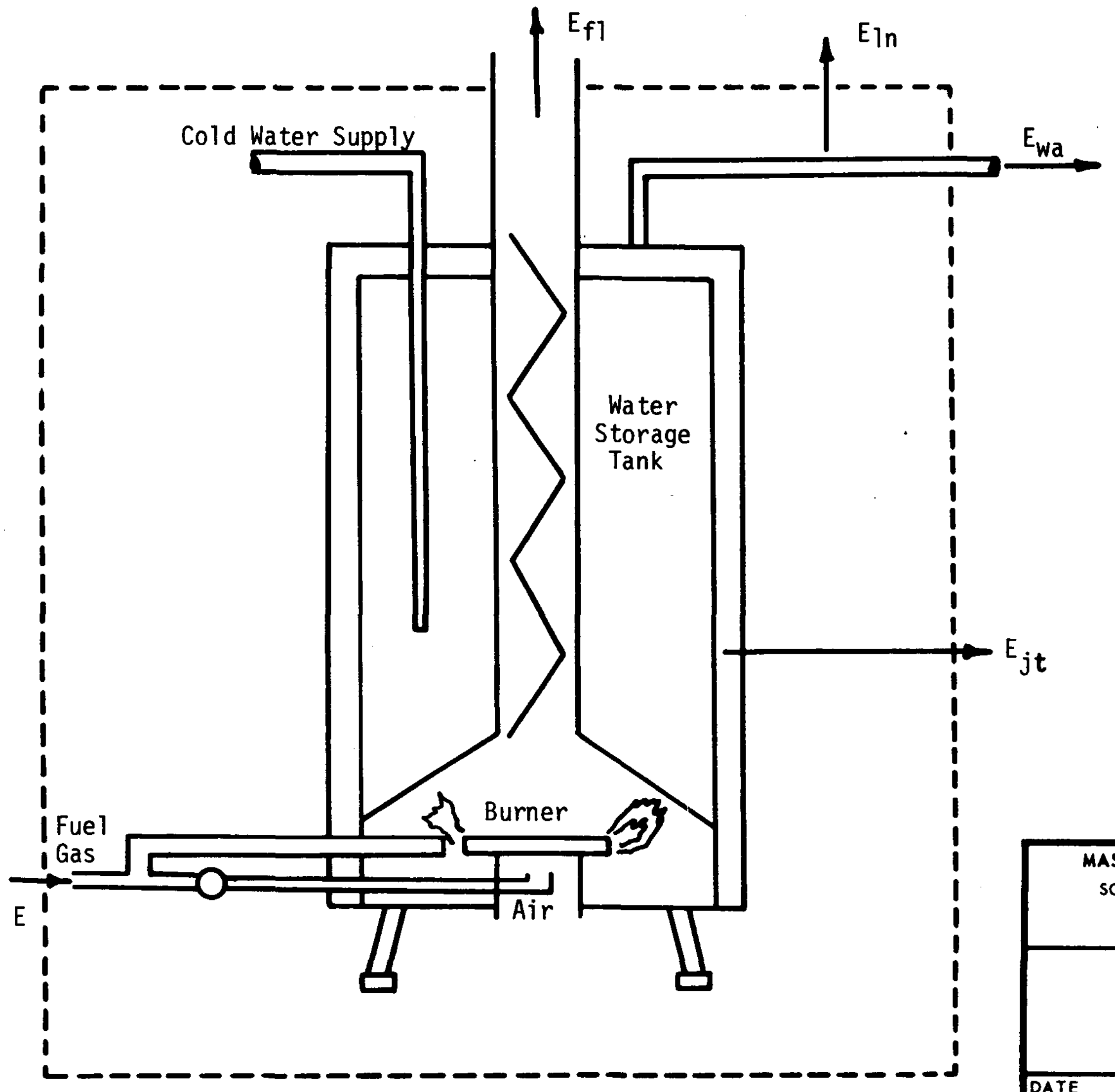

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CONTROL VOLUME FOR GAS
WATER HEATER ENERGY BALANCE

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The line losses are based on calculations performed by Quinn (34), who determined line loss based on a typical daily consumption schedule for bare, one-half-inch copper tubing. The consumption schedule is for a family where the father works, leaving the mother and children home most of the day. The schedule considers all activities in a typical home including showers, personal toilet, miscellaneous cleaning, laundry, and dishwasher operation. The line losses are then given by:

$$E_{ln} = (Q_w') (L) [(T_w - T_a)/70°F] \qquad (7)$$

where Q_w' is a variable whose value is determined by Quinn's calculations.

The total energy consumption for a given water heater is found by evaluating Eqs. (2) through (7) and substituting the results into Eq. (1).

4.3 Water Heater Baseline Data

To obtain the energy consumption and energy utilization for present water heaters, baseline values for the parameters in the water heater energy consumption model must be established. The desired hot water temperature of 140°F is based on the assumption that most water heater thermostats are on the "medium" setting. This setting corresponds to a water temperature of 140°F (26). Reports by Rand (26) and Arthur D. Little (ADL) (22) on water heaters also chose 140°F as the desired water temperature.

The inlet water temperature of 55°F is chosen in agreement with a draft report written by D.E. Spann of ORNL (37). The jacket losses are functions of the overall heat transfer coefficient, U, of the water heater walls and the tank surface area, A. Mutch (33) calculated the overall heat transfer coefficient for several different insulation thicknesses by setting it equal to the inverse of the sum of the resistances in the tank wall. He also calculated the surface area based on the increase in tank radius when insulation is added. For standard 40-gal-capacity gas water heaters with a thickness of one inch of jacket insulation, the overall heat transfer coefficient, U, is equal to 0.3835 Btu/ft^2-hr-°F and the outside surface area, A, is equal to 27.1 ft^2. Standard 50-gal electric water heaters are equipped with 2-in. insulation which corresponds to an overall heat transfer coefficient equal to 0.1713 Btu/ft^2-hr-°F and a surface area equal to 30.2 ft^2.

The temperature of the air surrounding the water heater and the water distribution system was assumed to be 70°F by several other reports on water heaters (30), and therefore was chosen for use in the ORNL model. A.O. Smith, one of the major suppliers of water heaters, specifies a main burner rate of approximately 1000 Btu/gal capacity/hr for its gas water heaters (36). A recent draft report by ADL (14) agrees with this value. The average capacities of 50 gal for electric and 40 gal for gas water heaters established by Mutch (25) were used in the ORNL model.

Based on experimental results, ADL sets main burner operation time at 1.5 to 2 hr/day (15). Two hours per day is chosen since it results in greater flue losses and is therefore conservative in predicting gas water heater efficiency. The pilot operation time in the model is 24 hr/day.

Based on experimentation performed by AGA in 1937, the fraction of energy lost through the flue during main burner operation is set at 0.26 (18). Recent reports (28) and manufacturer's data give values of pilot consumption between 700 and 778 Btu/hr. Seven-hundred-fifty Btu/hr was chosen for use in the water heater energy consumption model. Based on energy balances performed on experimental equipment, Spann states that the fraction of energy lost through the flue during pilot operation is 0.78 (37). By the method previously described, Quinn (34) calculated a loss of 41,347 Btu/yr per lineal foot of pipe for bare copper tubing. This value is then used for determining baseline line losses.

If all the parameters are specified and if it is known that the average per unit consumption of electric water heaters is about 150 x 10^5 Btu/yr (7), the average daily consumption of hot water may be derived. The average daily consumption of 41.6 gal/day found by this method is low compared to the 50 gal/day used by Mutch (27), the 75 gal/day given by Spann (37), and the 71.4 gal/day suggested by ADL (16).

4.4 Design Options

Design options considered for electric water heaters include addition of fiberglass insulation to the walls of the tank, lowering the thermostat setting, and adding 85% magnesia pipe insulation to the water distribution system. In addition to those above, design options considered for gas water heaters included programmed off periods, reducing flow of excess air during main burner operation, reducing pilot rate or replacing pilot with electric ignition, and reducing flue exit temperature during main burner operation.

The energy lost through a water heater jacket, E_{jt}, can be reduced by installing thicker fiberglass insulation. This imposes a greater resistance to heat flow through the tank walls. Using this increase in resistance to find the overall heat transfer coefficients, Mutch (33) has obtained the results found in Table 1. These results, based on theoretical calculations only, are the basis for evaluating increases in jacket insulation.

Table 1. Heat Transfer Parameters for Water Heaters (33)

Insulation Thickness (in.)	U ($\mathrm{Btu/ft^2\text{-}hr\text{-}°F}$)	A ($\mathrm{ft^2}$)	
		Gas	Electric
1	0.3835	27.1	26.1
2	0.1713	31.4	30.2
3	0.1103	36.0	34.6
4	0.0813	40.8	39.1
5	0.0644	45.9	44.0
6	0.0533	51.3	49.1
7	0.0455	56.9	54.4

Decreasing the tank water temperature for hot water heaters will reduce the energy consumed to heat the water and decrease the wall losses by decreasing T_W in Eqs. (2) and (3). In estimating the effect on total energy consumption by dropping the tank water temperature, several assumptions are made:

1. The volume of hot water consumed is independent of water temperature, or

2. The total energy content of the hot water delivered to the average family is constant (i.e., E_{wa} is constant).

3. Line losses are linearly proportional to the temperature difference between tank water and air.

4. The driving force for heat transfer between the flue gases and the water is the temperature difference between the two. Since dropping the tank water temperature from 140 to 110°F results in only a 2% change in this driving force at the bottom of the stack, it is assumed that flue losses are independent of tank water temperature.

The energy lost from the water distribution system to the ambient can be reduced by adding 0.5-in. 85% magnesia pipe insulation. This imposes a greater resistance to heat flow through the pipe walls. To make the model simpler it is assumed that the consumption values of 41,347 Btu/ft-yr for bare pipe and 33,787 Btu/ft-yr for insulated pipe calculated by Quinn based on an average usage schedule are correct.

Programmed off-periods for water heating may be effective in reducing energy consumption by decreasing the temperature difference driving force for wall and line energy losses. By shutting the heating system down during periods when water is not used, the temperature within the water heater decays exponentially. Since the rate of temperature change is slow, it was assumed that the drop in temperature was linear for the time periods. Values for the average water temperature found in Table 2, during various shutdown periods were calculated for each period by equating the heat loss through the jacket from Eq. (3) to the heat lost by the water from Eq. (2). The temperature driving force in Eq. (3) was calculated from the average water temperature for a given off-period. Another assumption made was that jacket and line losses are directly proportional to the temperature difference driving force for each loss. Finally, when calculating E_{jt}, it was assumed that the water is heated to 140°F instantaneously when the main burner ignites.

Table 2. Average Tank Water Temperature* During Programmed Off-Periods

Off Period (hours)	T_W final (°F)	T_W average during off-period (°F)
0	140	
1	138.1	139.1
2	136.3	138.2
3	134.6	137.3
4	133.0	136.5
5	131.5	135.8
6	130.0	135.0
7	128.7	134.4
8	127.4	133.7
9	126.1	133.1
10	124.9	132.5

*Calculated for a 40-gal gas water heater with 1 in. of insulation ($U = 0.3835$ Btu/hr-ft^2-°F) and a tank surface area of 27.1 ft^2.

The savings resulting from decreasing the excess air flow rate during main burner operation are reflected in the E_{fl} term in the model equation. It is assumed that the fraction of energy lost through the stack during main burner operation drops to 0.20 when decreasing the excess air from 60 to 20% based on experiments performed by AGA (17).

When evaluating the option of replacing the pilot light by an intermittent ignition device (IID), it was assumed that the fraction of energy lost during pilot operation was 78% based on experiments by Hise (37). Thus, the total consumption of energy predicted by the model is reduced by 78% of pilot consumption when the pilot light is replaced.

Reducing the flue gas exit temperature in gas water heaters may effectively reduce total energy consumption. By adding finned tubes in the flue, the stack temperature can be reduced from 550 to 370°F, as indicated by experimental results from AGA (20). The test results also show that the fraction of energy lost during main burner operation drops 62% to 0.16; this value is used in the ORNL model to evaluate the option of reducing flue gas temperature.

4.5 Range Description

Electric ranges provide a heat source for cooking food by passing a current through a calrod resistance heater. Heat transfer on surface burners is by conduction from the heating element and by radiation from the reflective base plate. The major modes of heat transfer in electric ovens are radiation and convection.

Surface burners consist of a heating element controlled either manually or automatically by means of a thermostat switch. With manual control the temperature level for cooking is maintained by a constant current flow through the resistor. With a thermostatically controlled burner the temperature of the food container is monitored and maintained by an electromechanical thermostat which opens and closes a switch to pass current through the resistor when needed to maintain the container at the desired temperature.

All oven heating elements are controlled by an automatic thermostat. A small air flow into the bottom of the oven door and through the cooking cavity is necessary to obtain good cooking results in electric ovens.

Gas ranges provide the heat for cooking food by the controlled combustion of gas. The major means of heat transfer in the oven and on surface burners is convection and radiation. On most existing gas ranges combustion of gas at a pilot light provides a continuous source of ignition. The four surface burners are usually furnished with two pilot lights while the oven utilizes one.

Control of food temperature with gas burners is manual on most ranges in use, while automatic controls are manufactured for use on some models.

The manual control maintains a pre-set cooking rate by providing a continuous flow of gas to the burner. An automatic control maintains a cooking temperature by the regulation of gas flow to the burner when needed. A mechanical thermostat in contact with the food container senses the cooking temperature and adjusts the gas flow to the burner to maintain a desired cooking temperature.

Combustion of gas for oven cooking occurs at one main burner which is usually controlled by a thermostat switch. Heat transfer to the food cooking in gas ovens is mainly convection with some radiation (1). Air flows through the base of the range passing into the cooking cavity where it transfers energy to the food and walls before passing out through a vent under one of the surface burners.

4.6 Baseline Model for Range Energy Consumption

A cooking range utilizes energy in both the surface cooking area and the oven. By performing an energy balance for a range the total energy consumed is equal to the sum of the amounts consumed in the surface and oven.

$$E = E_s + E_o \tag{8}$$

The amount of energy consumed in each section can be further divided into cooking and waste energy. Let E_{cs} and E_{co} be the energy which can be attributed to cooking food on the surface and in the oven. Surface waste energy arises from pilot losses, E_{ps}, plus burner inefficiencies, E_{bi}. An overall energy balance for the hypothetical control volume around the surface gives

$$E_s = E_{ps} + E_{bi} + E_{cs} \tag{9}$$

Oven waste energy is attributed to pilot losses, E_{po}, wall losses, E_w, and ventilation losses, E_v. An overall energy balance for a hypothetical control volume around the oven results in

$$E_o = E_{po} + E_w + E_v + E_{co} \tag{10}$$

If there is a total of three pilot lights on a standard gas range, suppose a number, p, are not operating. By grouping the surface and oven pilot loss terms in Eqs. (9) and (10), the total annual pilot loss for a range is equal to the number of pilots in use multiplied by the average annual energy consumption of a pilot light, P:

$$E_{ps} + E_{po} = (3 - p)P \tag{11}$$

Assume a total of four surface burners on the average range and also assume that over a long period all burners are used for the same total amount of time. Suppose that one replaces a number, n, of standard burners with efficiency, ε_b, by more efficient burners with efficiency, ε_t. A factor relating the surface burner inefficiencies to the cooking energy is a function of n, ε_b and ε_t. The annual energy lost due to surface inefficiencies is equal to this factor multiplied by the total annual energy used to cook food on range tops, E_{cs}:

$$E_{bi} = E_{cs}\left[\frac{n}{4}\left(\frac{1}{\varepsilon_t} - 1\right) + \left(\frac{4 - n}{4}\right)\left(\frac{1}{\varepsilon_b} - 1\right)\right] \tag{12}$$

The energy loss from an oven during cooking time is equal to the rate of loss multiplied by the average equivalent cooking time for oven losses. The total annual energy due to wall and ventilation losses can be approximated as the sum of the hourly rates of heat loss through the wall, Q_w, and by air ventilation, Q_v, multiplied by the average equivalent cooking time for wall and venting losses, t_c.

$$E_w + E_v = (Q_w + Q_v)t_c \tag{13}$$

The heat loss across an oven wall can be calculated by an equation relating the overall heat transfer coefficient for the wall, U, the total surface area for heat transfer, A_o, and the temperature driving force between the oven temperature near the walls, T_o, and the room temperature, T_a.

$$Q_w = UA_o(T_o - T_a) \tag{14}$$

An oven wall contains a series of resistances including the air films next to the inner and outer walls, the fiberglass insulation, and any other added insulators. The variables related to heat transfer for each insulator are thickness, ℓ, and thermal conductivity, k. For air films the associated heat transfer coefficients are h_o and h_i. The overall heat transfer coefficient is related to the design of the oven wall as

$$U = \left[\frac{1}{h_o} + \sum_i \frac{\ell_i}{k_i} + \frac{1}{h_i}\right]^{-1} \tag{15}$$

The heat loss due to ventilation through an oven is the enthalpy of the exit gases in excess of the enthalpy of the entering gases. The rate of heat loss due to ventilation through an oven is equal to the mass flow rate of air through the oven multiplied by the average heat capacity of air in the oven and the temperature difference between the exiting gases, T_e, and the entering air, T_a, as

$$Q_v = \dot{m}\, Cp_a(T_e - T_a) \tag{16}$$

If Eqs. (9) and (10) are added and substituted into Eq. (8),

$$E = (E_{ps} + E_{po}) + (E_{cs} + E_{co}) + E_{bi} + (E_w + E_v) \tag{17}$$

Assume that the total energy consumed in cooking food annually, E_c, is constant. The sum of annual surface and oven cooking energy is then

$$E_c = E_{cs} + E_{co} \tag{18}$$

If Eq. (18) is substituted into Eq. (17),

$$E = E_c + (E_{ps} + E_{po}) + (E_w + E_v) + E_{bi} \tag{19}$$

Rearranging Eq. (11) and Substituting Eqs. (11), (12), and (13) into Eq. (19) gives

$$E = E_c + (3 - p)P + \frac{E_{cs}}{4}\left[\left(\frac{4 - n}{\varepsilon_b}\right) + \left(\frac{n}{\varepsilon_t}\right) - 4\right] + (Q_w + Q_v)t_c \tag{20}$$

4.7 Range Baseline Data

Values for annual consumption of energy for gas and electric ranges are found in Table 3. Because six out of seven values from reliable sources for electric range consumption are close to 4.1 x 10^6 Btu/unit-yr, this value was selected for the baseline. The value of the annual consumption for gas ranges is not as well established. The value 13.8 x 10^6 Btu/unit-yr for gas ranges was chosen because AHAM is the more reliable source of information.

Table 3. Annual Energy Consumption for Cooking Ranges

	Consumption in Millions of Btu/yr				
	Source (8)				
	AHAM	USDA	USA*	Dole	This Study
Gas	13.8	-	-	9.5	13.8
Electric	4.0	4.5	3.4	4.1	4.1

*Hearings before certain Subcommittees on Governmental Operations and Science and Astronautics, House of Representatives, 93rd Congress, July 12, 1973.

The values obtained for gas and electric range energy utilization in our model are presented in Table 4. General Electric, the largest electric range manufacturer, provided the values in the table for electric ranges (9). The values for gas ranges were obtained with the assumption that the energy attributed to cooking is the same for gas and electric ranges. Since gas surface burner efficiency is standardized (5), the energy consumed on the surface and in the oven of gas ranges was then derived. Finally calculations of energy losses in gas ovens based on experimental data (11) were used to complete the list of energy utilization for gas ranges in Table 4.

Table 4. Energy Utilization in Ranges

Breakdown of Utilization	Electric Range[1]	Gas Range[2]
Surface cooking	0.350	0.104
Surface loss	0.150	0.113
Oven cooking	0.285	0.084
Oven wall loss	0.172	0.223
Oven vent loss	0.043	0.146
Pilot loss	-	0.330

[1] Total consumption = 4.1 x 10^6 Btu/yr-unit.

[2] Total consumption = 13.8 x 10^6 Btu/yr-unit.

General Electric furnished a complete list of electric range energy utilization which agreed with the information obtained from other range manufacturers. Overall cooking energy utilization from Table 4 is 63.5%, while Dole reports 65% (7). The approximate values derived from Tables 3 and 4, 1.4 x 10^6 and 1.2 x 10^6 Btu/yr, for surface and oven cooking, respectively, were used as tie elements to obtain energy utilization for gas ranges from the data for electric ranges. Since it was known that the standard for gas surface burner efficiencies set by ANSI was 48%, the surface and oven energy utilization in gas ranges was calculated. Calculations based on experimental results from the Hardwick Stove Co. (11) showed that the ratio of energy lost by conduction through the oven walls to the energy lost due to convection of hot gases out of the oven cooking cavity is approximately 1.50. The values in Table 4 for energy utilization in gas ranges were calculated from this information. The values of energy consumed in cooking with gas and electric ranges in the range model are found by combining Tables 3 and 4. For example, the total cooking energy in a gas range, 2.59 x 10^6 Btu/yr, is equal to 13.8 x 10^6 Btu/yr from Table 3 multiplied by 0.104 plus 0.084 from Table 4.

The ratio of wall loss to ventilation loss during cooking in gas ranges, 1.50, was derived from our calculations of Hardwick Stove Co. experimental results which showed 60 and 40% of gas oven losses were due to wall and ventilation losses respectively. The American Gas Assn., AGA, published a comprehensive study in 1952 (2), which may be outdated, showing these values to be 27 and 73%. The difference between the two sets of values is partly due to the different amounts of air flowing through the cooking cavity. The results from Hardwick Stove Co. are equivalent to approximately 65% more air flow than that reported by AGA.

The annual consumption for the three pilot lights in a range is based on the value reported by AGA, 400 Btu/hr. The value of P was calculated to be 1,170,000 Btu/yr for each pilot light assuming continuous pilot usage. The term (3 - p)P in the model is based on the assumption that all pilot energy is lost. Although the pilot flame is in the same location as the main oven burner, the amount of pilot energy utilized for cooking food was assumed to be negligible when compared to the total consumption, and no allowances were made for space heating by pilot lights in ranges.

Surface burner efficiency for gas ranges has been standardized by ANSI (5) at 48%. Although the standard from the Association of Home Appliance Mfrs., AHAM, for electric heating element efficiency is 55% (6), manufacturers indicated values ranging from 55 to 80%; 70% was chosen because it was an average of the values obtained. Thus, burner efficiency values, ε_b, used in the model are 0.48 for gas and 0.70 for electric burners.

The wall and insulation losses for the baseline were based on new calculations of previous experimental results. The most common gas and electric range currently in use has a width between 24 and 32 in. according to the U.S. Bureau of the Census (39). Since the only experimental results (11) showing wall and insulation losses were for a 30-in.-wide oven, this size was chosen as the baseline.

The value of Q_v for gas ranges was calculated from Eq. (16) using the operating parameters for oven vent temperature, T_e, and air flow rate given by Hardwick Stove Co. (11). With an inside oven temperature, T_o, equal to the cooking temperature setting in the oven, the value Q_w calculated from Eqs. (14) and (15) was 75% less than that reported by Hardwick (11). From experimental measurements of overall heat loss (11) and calculated values of U and A, the apparent temperature driving force, $T_o - T_a$, was derived from Eq. (14). This result corresponds to an inside oven air temperature, T_o, equal to 1471°F which is slightly less than the theoretical flame temperature.*

In summary, the Q_v and Q_w values represented in the baseline energy utilization and the parameters in the baseline model equation for gas ranges were obtained from calculations based on experimental results supplied by Hardwick Stove Co. (11). The calculations are shown in Appendix 9.1. The values in the baseline model equation for Q_w and Q_v are 2660 and 1740 Btu/hr, respectively.

For electric ranges the value for the flow of air through the oven, $\dot{m}$, was not reported with the experimental results. However, the approximate value for air flow through electric ovens was obtained from Tappan (38), a major manufacturer. This value, in conjunction with the experimental results, enabled calculation of the Q_v value for electric ranges.

Since complete experimental results were not available for electric ranges, the value of Q_w was derived by taking the ratio of Q_w/Q_v from Table 4. The resulting value for Q_w enabled calculation of the apparent inside air temperature, 1743°F,* from Eq. (14). This value was used in all calculations for Q_w when evaluating design options in the model.

The equivalent cooking time used to calculate wall and venting losses in the model was obtained by combining the baseline values of hourly energy loss from the oven, Q_v and Q_w, with the total annual consumption of energy for oven ventilation and wall losses for the baseline from Tables 3 and 4. These values were 244 hr/yr for electric ranges and 1273 hr/yr for gas ranges.*

4.8 Design Options

The most direct method to reduce wall losses in ovens is to decrease the overall heat transfer coefficient, U, for the oven wall. The area for heat transfer cannot be reduced without making radical design changes in the oven, and the temperature driving force for heat transfer can only be lowered by major variations in cooking conditions within the oven. The most direct method of lowering U is by increasing the insulation thickness. Electric oven manufacturers have been building and selling self-cleaning ovens designed with twice as much insulation. The insulation thickness values, ℓ, in Eq. (15) were chosen as 3.5, 4.5, and 5.5 in. corresponding to a 40 to 120% increase. These values were chosen so that the impact on cost would not override the impact on energy savings within this range,

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*The values for T_o and t are not realistic; see p. 34 for discussion.

since self-cleaning ovens are marketable. The design options of gas ranges were evaluated for the same values of insulation thickness.

Gas range manufacturers indicated that excess air in ranges varies between 200 and 300%. ADL (17) indicates that the minimum safe value for excess air is 20%. Values for excess air as design options for the gas range model were 25% reductions from the baseline level of approximately 200% to a minimum value of 50%, which are within safe limits (17). The excess air values corresponding to the design options for reducing vent losses in the model were from 240 to 60 ft^3/hr.

Surface cooking losses in gas ranges can be reduced safely by installing thermostat control burners. Thermostat burners have shown an efficiency, ε_t, of 0.58 based on experimental results of a major burner manufacturer (12), while the ANSI standard for standard burners, ε_b, is 0.48 (3). No comparable tests were made for electric burners, and it was assumed that the standard burner efficiency, ε_b, could be increased from 0.70 to an efficiency, ε_t, of 0.80 by replacing the standard burner by a thermostatically controlled type burner.

Most manufacturers have replaced only the oven pilot light by an electrical ignition device which is most likely due to the cost of such devices. The number of pilots, p, eliminated in our model was 1, 2, and 3.

5. RESULTS AND DISCUSSION

5.1 Water Heaters

Baseline values were substituted into the water heater energy consumption model to find the annual energy consumption per unit for gas water heaters and the energy utilization breakdown of present gas and electric water heaters. The results, along with those predicted by several other sources, are presented in Tables 5 and 6.

Table 5. Gas Water Heaters

	ORNL	Mutch (28)	Lee (16)
Total consumption (10^5 Btu/yr)	304.6	260.3	376.0
Useful heat to water	35.4%	45.5%	49.5%
Jacket loss	20.9%	35.0%	12.0%
Flue loss	40.3%	19.5%	38.0%
Line loss	3.4%		

Table 6. Electric Water Heaters

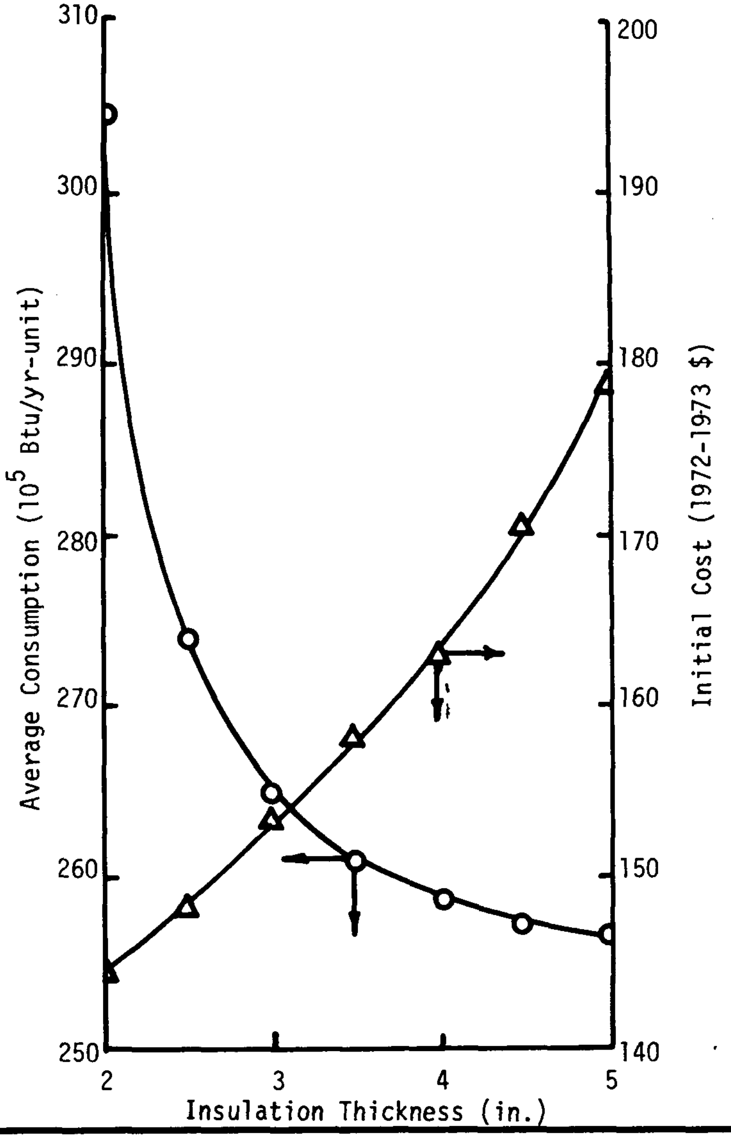
	ORNL	Mutch (28)	Spann (37)	Lee (16)
Total consumption (10^5 Btu/yr)	149.7	150.3	153.9	224.2
Useful heat to water	71.9%	78.8%	77.8%	83.0%
Jacket loss	21.2%	21.2%	22.2%	17.0%
Line loss	6.9%			

It appears that the ORNL model is conservative in predicting the amount of energy which is actually used for heating the water. This is not true for electric water heaters. Mutch (25), Spann (37), and Lee (14) chose the energy balance control volume in such a way as to eliminate line losses from consideration. On this basis the ORNL model predicts 78.8% of the total energy consumed is useful heat to the water. This value compares closely with those predicted by the other sources. Since the ORNL model agrees with the other sources presented, based on both experimental and theoretical results, it is concluded that the ORNL model accurately represents the energy consumption of electric water heaters.

The ORNL model is also conservative in predicting the amount of useful heat to the water in gas water heaters. This may be attributed to two sources. First as was the case for electric water heaters, the control volume for the energy balance performed by the other sources eliminates line losses from consideration. Second, the amount of energy required to heat the water is much lower for the ORNL model because daily consumption is set at 41.6 gal/day. Mutch and Lee set daily consumption at 50 and 71 gal/day, respectively. The energy required to heat the water is 107.7 x 10^5 Btu/yr for ORNL, 129.4 x 10^5 Btu/yr for Mutch, and 183.8 x 10^5 Btu/yr for Lee. These values represent the percentages given in Table 5.

Adding fiberglass insulation to the jacket of a water heater reduces wall losses and as a result reduces total energy consumption. The effect of increased jacket insulation on total energy consumption, as predicted by the ORNL model, is presented in Figs. 4 and 5 for gas and electric water heaters. The cost figures are taken from Mutch (27) and include water heater, piping, and all installation required.

The initial cost increases almost linearly with insulation thickness for both gas and electric water heaters. However, the energy saved when adding one inch of fiberglass insulation decreases almost exponentially with increasing insulation thickness. Therefore, it is concluded that the energy conserved per added dollar of investment is greatest when adding jacket insulation to units presently containing one or two inches of insulation. This is a very important conclusion since present gas water heaters contain one inch of jacket insulation and present electric water



Cost Data from Mutch (<u>29</u>)

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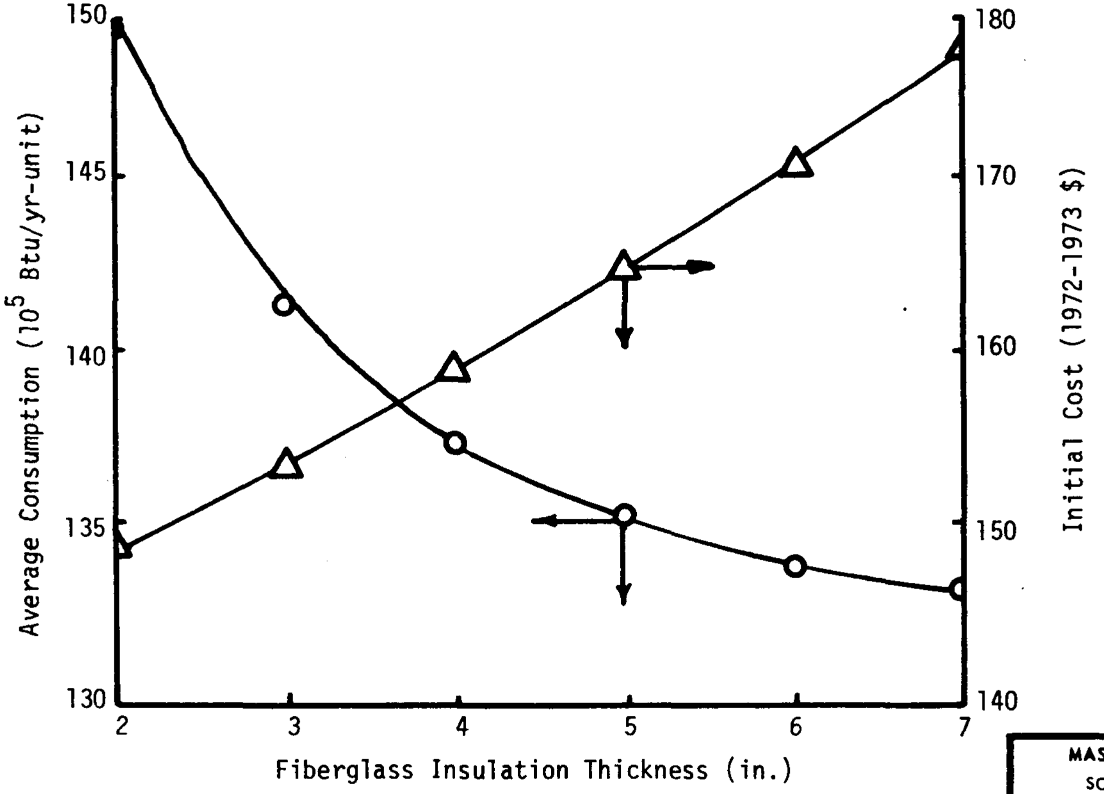
AVERAGE CONSUMPTION AND COST AS
FUNCTIONS OF INSULATION THICKNESS
FOR GAS WATER HEATERS

DATE	DRAWN BY	FILE NO.	FIG.
2-22-76	RJB	CEPS-X-226	4



Cost Data from Mutch (29)

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AVERAGE CONSUMPTION AND COST AS FUNCTIONS OF JACKET INSULATION THICKNESS FOR ELECTRIC WATER HEATERS

DATE	DRAWN BY	FILE NO.	FIG.
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heaters contain two inches. Since a water heater must be able to fit through a standard 32-in. doorway, a practical limit of four inches of jacket insulation is set.

It is important to compare the results obtained from the ORNL model to those given by other sources. The ORNL model predicts 8.1% savings in total consumption when two inches of fiberglass insulation is added to present electric water heaters. Lee (21) and Mutch (33) predict 8% energy savings. The ORNL model predicts 10.5% savings in total energy consumption compared to a 12% savings predicted by Spann (37) when adding four inches of insulation to an electric water heater.

If three inches of fiberglass insulation is added to the jacket of a gas water heater, total energy consumption is reduced by 14.2% according to the ORNL model, 8% according to Lee (21), and 23.7% according to Spann (37). This difference is easily explained by remembering that the ORNL model sets the jacket losses at 20.9% while Lee and Mutch set it at 12 and 35%, respectively. Spann predicts 14.4% savings in energy consumption when four inches of jacket insulation is added to a gas water heater. The ORNL model predicts 15%.

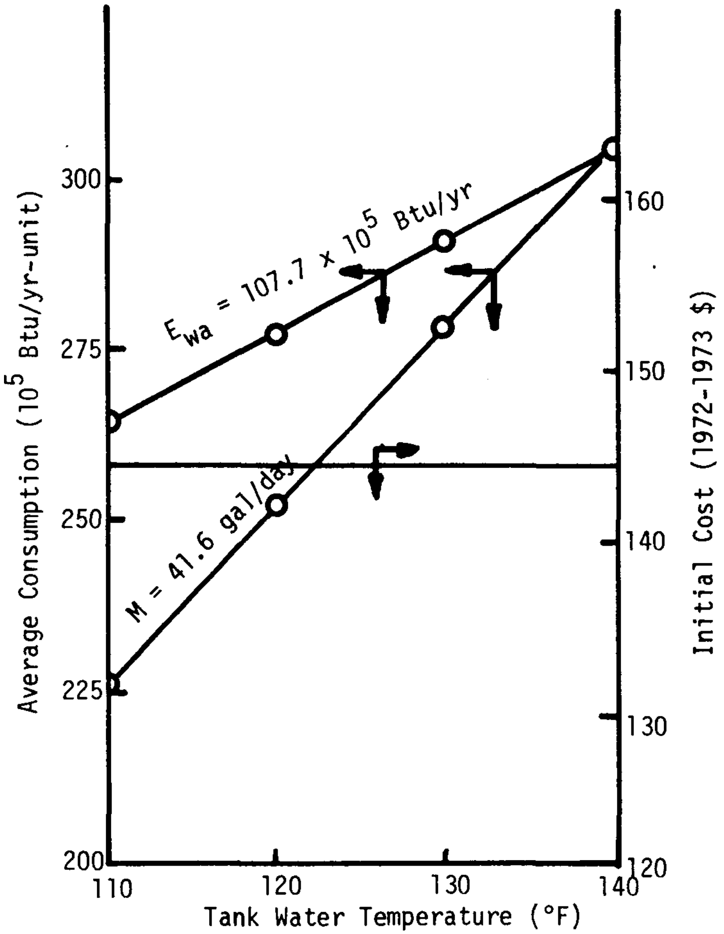
Hence, jacket insulation represents a means of obtaining large energy savings at low values of added initial cost. It is recommended that detailed cost analysis based on water heater lifetime and fuel prices be performed to find the optimum insulation thickness.

Average consumption predicted by the ORNL model as a function of tank water temperature is presented for gas and electric water heaters in Figs. 6 and 7. The cost figures presented are again based on Mutch (29). The two assumptions made relating water consumption to water temperature provide approximately upper and lower limits for the energy consumption model. It is unrealistic to assume that water consumption remains constant with varying water temperature. This assumption predicts too large an energy savings. It seems also unrealistic to predict a constant Btu/day rate to a family. This assumption predicts too little energy savings. It is recommended that a study be conducted to determine water consumption as a function of water temperature.

There is no increase in the initial cost when the thermostat setting is lowered. It is therefore concluded that the tank water temperature should be set as low as possible while remaining hot enough to satisfy residential requirements.

The ORNL model predicts a 37.4% savings assuming fixed water demand for a drop in tank water temperature from 140 to 110°F. Lee predicts a 31% drop for the same conditions. The ORNL model predicts 4% savings in total energy consumption for every 10° drop in water temperature for electric water heaters while Lee and Mutch predict 5%.

Adding 0.5-in. 85% magnesia pipe insulation results in a savings in total consumption of 1.3% for electric and 0.7% for gas water heaters. Mutch estimates an added cost of $1/lineal foot of pipe (32). Mutch



Cost Data from Mutch (29)

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AVERAGE CONSUMPTION AND COST AS A FUNCTION OF TANK WATER TEMPERATURE FOR GAS WATER HEATERS

DATE	DRAWN BY	FILE NO.	FIG.
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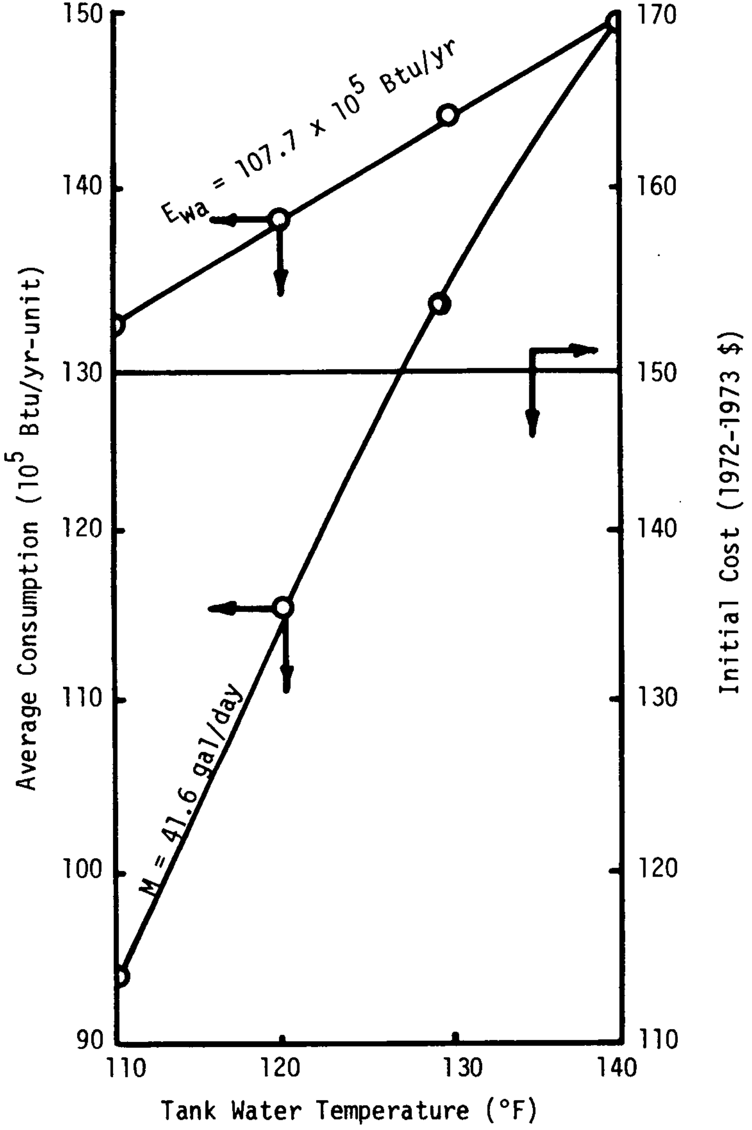

Cost Data from Mutch (<u>29</u>)

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AVERAGE CONSUMPTION AND COST AS A
FUNCTION OF TANK WATER TEMPERATURE
FOR ELECTRIC WATER HEATERS

DATE	DRAWN BY	FILE NO.	FIG.
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predicts a savings in total energy consumption of 1.6% for both gas and electric water heaters. Lee predicts a possible 5% savings for both gas and electric water heaters (23).

The difference between the ORNL model prediction and that by Lee is due to the length of pipe considered. The ORNL model uses 25 ft of exposed copper tubing, the same value used by Spann (37), as its baseline value, while Lee uses 200 ft. On this basis the ORNL model predicts savings of 10.4% for electric water heaters and 5.6% for gas water heaters.

It is impossible to draw a conclusion on the accuracy of the ORNL model for calculating line losses at this time. It is, however, concluded that the addition of insulation to the water distribution system does not have the energy savings potential of adding jacket insulation or decreasing the water temperature.

Shutting down the heating unit completely during the nighttime period when there is no demand for hot water saves the fuel normally used to balance standby losses. The ORNL model predicts a 0.3% savings for a 6-hr shutdown period for gas water heaters. It also predicts a 1.8% savings in energy consumption for two 10-hr shutdown periods daily. Mutch (31) predicts savings of 0.5% for a 6-hr shutdown period while Lee predicts 10% for the two 10-hr shutdown periods (24). This 10% prediction represents the maximum savings possible, and as a result is not a realistic figure. Spann states that the savings obtained for programmed off periods less than 24 hr is negligible.

The cost of the timer required to totally shutdown the heating unit is between 25 and 40 1975 dollars (24). It is concluded that programmed off periods represent very little potential for energy savings in residential gas water heaters.

Reducing the excess air level from 60 to 20% during main burner operation results in an energy savings of 27.8 x 10^5 Btu/yr or 9.1% for gas water heaters. Twenty percent excess air corresponds to a carbon dioxide level of 9.9% which is unsafe for human inhalation. Therefore, it is necessary to install a forced draft mechanism costing between ten and twenty dollars (17). The energy consumed by this mechanism is assumed to be negligible. Lee estimates a savings of 8% in energy consumption in gas water heaters for a reduction in excess air level from 60 to 20%. The model and the assumptions used in evaluating the effect of reducing excess air are based on experimental results published by AGA (18).

It is concluded that reducing excess air levels in gas water heaters is a viable design option. It is recommended that a detailed cost study be performed to see if this and the remaining options are feasible at current fuel prices.

Reducing the pilot consumption to 330 Btu/hr instead of the baseline value of 750 Btu/hr results in a savings of 26.6 x 10^5 Btu/yr. This represents 9% of the annual consumption for the typical gas water heater.

Since pilot consumption below 330 Btu/hr is not sufficient to balance standby losses and above 330 Btu/hr results in large flue losses, then 330 Btu/hr is the optimum pilot consumption rate (19). Lee predicts a savings of 13% for the same reduction in pilot consumption (19).

Eliminating the pilot completely by adding electric ignition and flue dampers results in a savings of 47.0×10^5 Btu/hr or 15.4%. This option adds 50 to 100 dollars (1975) to the initial investment (19). Lee predicts a savings of 14% based on experimentation performed by AGA (19).

An energy savings of 29.2×10^5 Btu/yr may be realized by lowering the exit flue temperature in gas water heaters from 550 to 375°F. This is accomplished by replacing the baffling in the flue with finned baffling. The 9.6% savings predicted by the ORNL model is in close agreement with the 10% predicted by ADL (21). Both of these predictions are based on the experimental results obtained by AGA (21).

5.2 Ranges

Baseline energy utilization shows that electric ranges are more efficient than gas ranges. Losses in electric ranges represent 36.5% of the input energy, while losses in gas ranges are 81.2%. Energy consumption as a function of different design options for both electric and gas ranges is found in Tables 7 and 8. Approximately 17% of total energy consumed by electric ranges is lost through the walls. To reduce this conductive loss, the thickness of fiberglass insulation can be increased from the standard 2.5 in. up to 5.5 in., and the resultant energy consumptions evaluated by the model are presented in Fig. 8. Changes in the amount of energy savings fall exponentially when greater levels of insulation are added. Hence, an optimum thickness can be computed from initial costs, fuel prices, and appliance life-expectancy.

The surface burner of the electric range is about 70% efficient (10). By replacing regular surface controls with thermostat controls at a hypothetical efficiency of 80%, a 1.54% energy savings is possible for each surface burner. Vent losses in electric ovens are 4.3%. If air flow rate is reduced from the typical value of 4 ft^3/min (38) to 1 ft^3/min, the energy consumption is reduced from 4.10×10^6 to 3.97×10^6 Btu/yr, corresponding to a 3.2% savings.

The largest energy losses in gas ranges occur in pilot lights. We assumed that the heat transferred to the surroundings is not significant enough to contribute to space heating. As a possible substitute for pilot lights, the intermittent ignition device has become the subject of many studies (35). Although the cost is about $40 each including installation (35), 8.82% energy savings is obtained for each IID installed.

Approximately 15% of the energy consumed in a gas oven is convected out the flue. By decreasing the percentage of excess air from 200 to 100%, a linear reduction from 13.8×10^6 Btu consumed per year to 11.6 x Btu/yr is

Table 7. Design Options for Electric Ranges

1. Wall Loss - add insulation

Thickness (in.)	Energy Consumption (10^6 Btu/yr)	Savings (%)
2.5	4.10	0
3.5	3.92	4.3
4.5	3.82	7.0
5.5	3.72	8.7

2. Surface Cooking Loss - improve surface burner efficiency from 70 to 80%

No. of New Burners	Energy Consumption (10^6 Btu/yr)	Savings (%)
0	4.10	0
1	4.04	1.54
2	3.97	3.10
3	3.91	4.66
4	3.85	6.22

3. Vent Loss - decrease ventilation

Air Flow Rate (ft^3/min)	Energy Consumption (10^6 Btu/yr)	Savings (%)
4	4.10	0
3	4.05	1.05
2	4.01	2.13
1	3.97	3.20

Table 8. Design Options for Gas Ranges

1. Pilot Loss - use electric ignition device

No. of New Pilots	Energy Consumption (10^6 Btu/yr)	Savings (%)
0	13.82	0
1	12.62	8.82
2	16.85	17.64
3	9.69	26.46

2. Vent Loss - decrease excess air

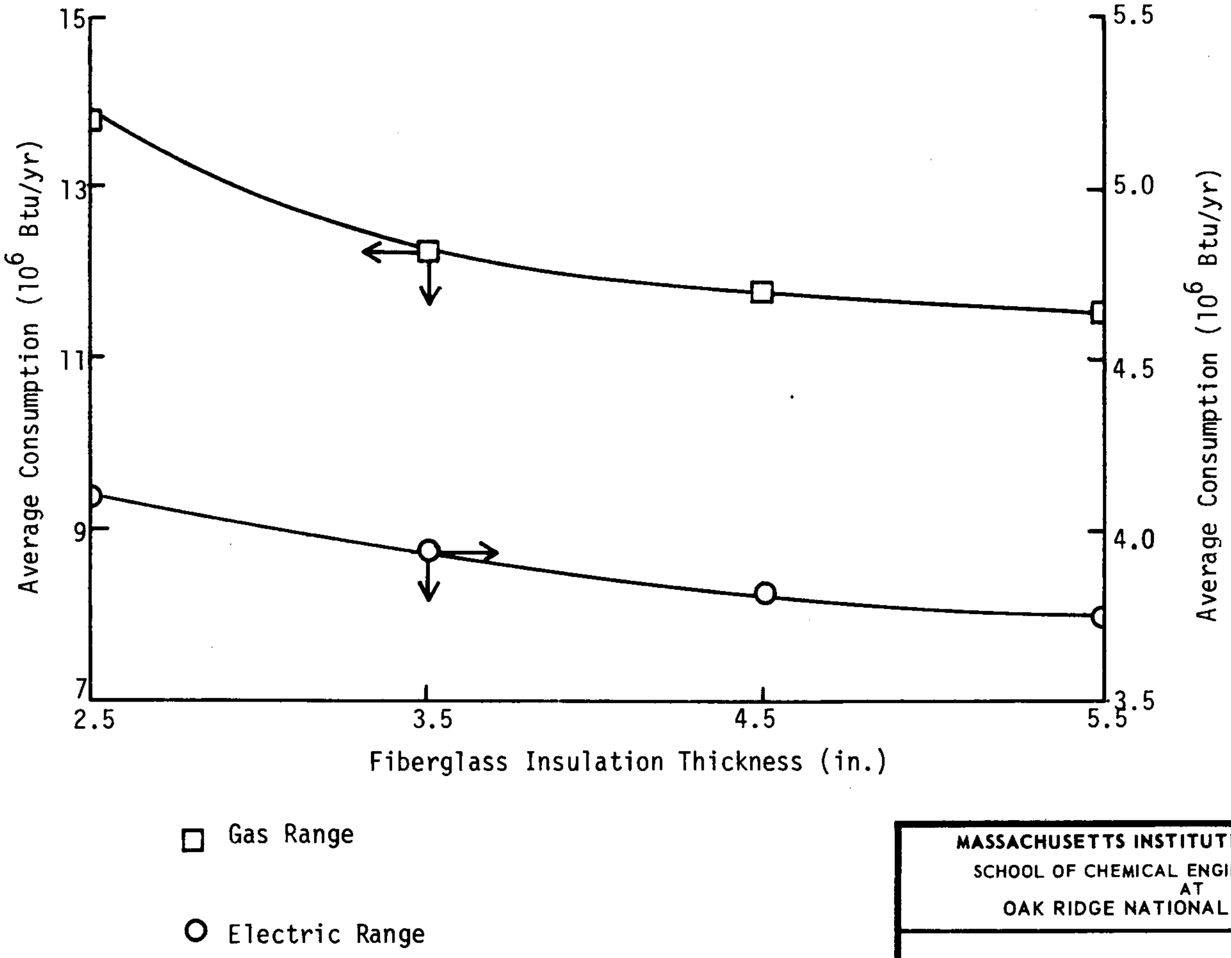
Excess Air (%)	Energy Consumption (10^6 Btu/yr)	Savings (%)
200	13.82	0
150	12.63	4.0
100	12.08	8.2
50	11.53	12.4

3. Wall Loss - add insulation

Thickness (in.)	Energy Consumption (10^6 Btu/yr)	Savings (%)
2.5	13.82	0
3.5	12.34	6.2
4.5	11.84	10.5
5.5	11.51	12.6

4. Surface Cooking Loss - use thermostat control with efficiency at 58.5%

No. of Controls	Energy Consumption (10^6 Btu/yr)	Savings (%)
0	13.82	0
1	13.05	1.0
2	12.92	2.0
3	12.78	3.0
4	12.65	4.0



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ENERGY CONSUMPTION AS A FUNCTION OF INSULATION THICKNESS FOR RANGES

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predicted by the model. Thus reducing excess air flow through gas ovens to cut ventilation losses offers a substantial energy savings potential. However, the feasibility cannot be ascertained fully until experimentation shows no detrimental side effects on oven performance when reducing air flow. Because of the 15% energy savings potential such experimental work is recommended.

Another loss in gas ovens is conduction through the walls, representing 60% of the oven losses (2). Table 7 shows the reduction in energy consumption when adding insulation. By varying the thickness from the standard 2.5 to 5.5 in., the energy consumption decreases by 12.6%.

More efficient thermostat controls can boost efficiency of the surface burner from 48 to 58.5% (12). These controls cost the range manufacturers about $6, more than ten times the price of a standard burner (12), and 4% of total energy can be saved if all four burners are replaced.

The accuracy of the results when modeling is strongly dependent on the baseline parameters adopted. Possible errors result from the difficulty in quantifying the design parameters that are statistically representative of the majority. Moreover, there are only scattered published results available for comparison. Some difficulties which arise when incorporating data into the range model will be discussed.

In the ORNL model, the vent and wall losses are equal to the number of equivalent hours for oven losses per year, t_c, multiplied by the hourly vent and wall loss, Q_V and Q_W. The annual energy loss in ovens is obtained by rearranging Eq. (17) to solve for the term $(E_W + E_V)$ using baseline energy consumption from Tables 3 and 4. The number of hours of equivalent cooking time for wall losses is determined by dividing the annual oven wall and ventilation energy loss by the hourly rate of loss, $Q_W + Q_V$, so that the model will show baseline energy consumption. The value of t_c is 244 hr for electric ranges and 1273 hr for gas ranges.

Because the cooking time for most foods in gas and electric ovens is approximately the same, one would expect that t_c should be equal for gas and electric ovens. The large difference in t_c values is an indication of error in the methodology in determining this value. When Q_V and Q_W were determined, the values for A, $\dot{m}$, and C_p in Eqs. (14) and (15) were well established, while U and ΔT were unrealistic. The U value was for the case of a uniformly insulated oven with no heat leaks from structural metal supports. The value of ΔT corresponded to an average inside oven wall air temperature close to the theoretical flame temperature. This value is high for gas ovens and extremely high for electric ovens when one considers the physical mode of operation. In a gas oven, hot combustion gases are introduced into the cooking compartment through two slits approximately 1-3/4 in. from the walls on two sides of the oven. From these slits, hot gases flow upward by convection near the walls which act as a heat sink at an average temperature of 25°F below cooking temperature setting, based on an oven set at 375°F (1). The gases mix with internal gases and leave through the vent pipe located at the top wall, at an average temperature of 42°F below cooking temperature (11), based on an oven set at 350°F. As a result of these errors the t_c values are not reasonable and the energy savings evaluated by the model for oven wall and ventilation design options may be in error.

6. CONCLUSIONS

1. The ORNL model accurately predicts energy utilization breakdown for electric water heaters.

2. The ORNL model accurately predicts average energy consumption and energy utilization breakdown for gas water heaters.

3. The energy conserved per added dollar of investment is greatest when adding jacket insulation to standard units.

4. Tank water temperature should be maintained at as low a value as possible, probably 110°F, while remaining hot enough to satisfy residential requirements.

5. Reducing pilot consumption, eliminating the pilot completely, reducing flue exit temperature, and reducing the excess air flow during main burner operation show high energy saving potential for gas water heaters.

6. The range model allows an approximate evaluation of design changes to improve energy utilization.

7. More energy savings will result from design changes to upgrade efficiency in gas ranges than in electric ranges.

8. The gas range model shows that gas ranges will consume 33% less energy when the pilot light is eliminated.

9. The range model shows that reduction of vent losses will result in 13% energy savings for gas ranges.

10. Addition of insulation is the most practical design change for both gas and electric ranges.

7. RECOMMENDATIONS

1. Detailed cost analysis should be performed to determine which of the water heater design options are feasible at present fuel prices.

2. A study should be conducted to determine water consumption as a function of water temperature.

3. Energy savings potential exists, but experimental work is needed to assess the feasibility of reducing excess air flow in gas ovens.

4. More experimentation is recommended to obtain information for a more accurate baseline energy utilization for gas and electric ranges.

8. ACKNOWLEDGMENT

The authors wish to thank Eric Hirst for his guidance.

9. APPENDIX

9.1 Sample Calculations

To calculate the baseline energy consumption for gas water heaters, the components of the total energy consumption must be calculated. The energy required to heat the water, E_{wa}, per year is,

$$E_{wa} = MC_p(T_w - T_{w_i})t$$

$$= (41.6\ \text{gal/day})(8.341\ \text{Btu/gal-°F})(85\text{°F})(365\ \text{day})$$

$$= 107.7 \times 10^5\ \text{Btu}$$

The energy lost through the water heater wall per year is,

$$E_{jt} = UA(T_w - T_a)t$$

$$= 0.3835\ \text{Btu/ft}^2\text{-hr-°F}(27.1\ \text{ft}^2)(70\text{°F})(8760\ \text{hr})$$

$$= 77.4 \times 10^5\ \text{Btu}$$

The energy attributed to flue loss per year is,

$$E_{fl} = (\text{main burner firing rate})(\text{capacity})(730\ \text{hr})\ (\text{fraction of energy lost through flue}) + (\text{pilot consumption})(8030\ \text{hr})\ (\text{fraction of energy lost through flue})$$

$$= (1000\ \text{Btu/hr-gal})(40\ \text{gal})(730\ \text{hr})\ (0.26) + (750\ \text{Btu/hr})\ (8030\ \text{hr})\ (0.78)$$

$$= 122.9 \times 10^5\ \text{Btu}$$

Finally, the line losses are

$$E_{ln} = (Q_w')\ (L)(\Delta T/70\text{°F}) = (41{,}347\ \text{Btu/ft})\ (25\ \text{ft})(70/70)$$

$$= 10.3 \times 10^5\ \text{Btu}$$

The total energy consumption is, then,

$$\begin{aligned} E &= E_{wa} + E_{jt} + E_{fl} + E_{ln} \\ &= 107.7 \times 10^5 \text{ Btu} + 77.4 \times 10^5 \text{ Btu} + 122.9 \times 10^5 \text{ Btu} \\ &\quad + 10.3 \times 10^5 \text{ Btu} \\ &= 304.6 \times 10^5 \text{ Btu} \end{aligned}$$

To establish the energy consumption of a gas range, the losses due to conduction through the walls and due to oven ventilation must be calculated. The ventilation term for the range energy balance is

$$Q_v = \dot{m}\, C_{p_a}(T_e - T_a) \tag{16}$$

Substituting in the baseline values for gas ranges from Hardwick Stove Co. (11) gives

$$\begin{aligned} Q_v &= (28.6 \text{ lb/hr})(0.255 \text{ Btu/lb-°F})(308 - 70\text{°F}) \\ &= 1740 \text{ Btu/hr} \end{aligned}$$

The baseline and design values for oven wall loss are calculated from experimental data (11). For an oven at steady state,

$$Q_{total} = Q_v + Q_w$$

and

$$Q_w = Q_{total} - Q_v = 4400 - 1740 = 2660 \text{ Btu/hr}$$

But Q_w can also be described as

$$Q_w = UA\Delta T$$

where

$$U = \left[\frac{1}{h_o} + \sum_i \frac{\ell_i}{k_i} + \frac{1}{h_i}\right]^{-1} \tag{15}$$

The average temperature of insulation is 445°F, and the inside film heat transfer coefficient is

$$h_i = h_c + h_r = 2.8 + 1.6 = 4.4 \text{ Btu/hr-ft}^2\text{-°F}$$

$$\frac{1}{h_i} = 0.23$$

$$U = \left[\frac{1}{1.29 \text{ Btu/hr-ft}^2\text{-°F}} + \frac{(0.0349/12)\text{ft}}{26 \text{ Btu/hr-ft}}(2) + \frac{2.5 \text{ in.}}{0.440 \text{ Btu/hr-ft}^2\text{/in.}} + \frac{1}{4.4 \text{ Btu/hr-ft}^2\text{-°F}}\right]^{-1}$$

$$= [0.775 + 0.002 + 5.68 + 0.23]^{-1}$$

$$= 0.150 \text{ Btu/ft}^2\text{-hr-°F}$$

As is evident in the above calculation, the effect of the conduction through the sheet metal walls and the effect of convection through the inside air film are negligible.

To allow for U as a design variable in the model, ΔT is required. Hence,

$$\Delta T = \frac{Q_W}{UA} = \frac{2660}{0.150(11.23)} = 1579 \text{ F°}$$

The model equation for ranges will satisfy the baseline energy consumption, E, for a gas range,

$$E = E_c + (3 - p)P + \frac{E_{cs}}{4}\left[\frac{4-n}{\varepsilon_b} + \frac{n}{\varepsilon_t} - 4\right] + (Q_W + Q_V)t_c \qquad (20)$$

$$= 2.6 \times 10^6 \text{ Btu} + (3 - 0)1.17 \times 10^6 \text{ Btu} + \frac{1.4 \times 10^6}{4} \text{ Btu}$$

$$\times \left[\frac{4 - 0}{0.48} + 0 - 4\right] + (2660 + 1740 \text{ Btu/hr})(1273 \text{ hr})$$

$$= 13.2 \times 10^6 \text{ Btu}$$

The model equation for ranges can be used to determine the energy consumption when adding four thermostat control burners instead of standard surface burners,

$$
\begin{aligned}
E &= 11.64\ \text{Btu} + \frac{1.4 \times 10^6}{4}\ \text{Btu}\ \left[\frac{4}{0.48} - 4 + \frac{4}{0.585} - 4\right] \\
&= 12.6 \times 10^6\ \text{Btu}
\end{aligned}
$$

For electric ranges the energy consumption can be established after the energy losses due to conduction through the walls and due to oven ventilation are determined.

$$Q_v = \dot{m}\, C_{p_a}(T_e - T_a) \tag{16}$$

Substituting the baseline value for $\dot{m}$ from Tappan (<u>38</u>) into Eq. (16) and assuming $T_e = 300°\text{F}$ gives

$$
\begin{aligned}
Q_v &= (12.3\ \text{lb/hr})(0.255\ \text{Btu/lb})(300 - 70) \\
&= 723\ \text{Btu/hr}
\end{aligned}
$$

The ratio of ventilation to wall losses in electric ovens can be found from Table 4.

$$\frac{Q_v}{Q_w} = \frac{0.043}{0.172}$$

Since experimental information for electric oven wall and ventilation losses is not available,

$$
\begin{aligned}
\text{oven wall loss} &= \frac{Q_v}{\left(\frac{Q_v}{Q_w}\right)} = \frac{723}{(0.043/0.172)}\ \text{Btu/hr} \\
&= 2892\ \text{Btu/hr}
\end{aligned}
$$

The model equation for ranges will satisfy the baseline energy consumption, E, for an electric range.

$$\begin{aligned} E &= E_c + \frac{E_{cs}}{4}\left[\frac{4-n}{\varepsilon_b} + \frac{n}{\varepsilon_t} - 4\right] + (Q_w + Q_v)t_c \\ &= 2.6 \times 10^6 \text{ Btu} + \frac{1.4 \times 10^6}{4} \text{ Btu} \left[\frac{4-n}{0.7} + \frac{n}{0.8} - 4\right] \\ &\quad + (2892 \text{ Btu/hr} + 723 \text{ Btu/hr})244 \text{ hr} \\ &= 4.1 \times 10^6 \text{ Btu} \end{aligned}$$

The model equation for ranges can be used to determine the energy consumption when replacing four standard burners with thermostat control burners.

$$\begin{aligned} E &= 3.48 \times 10^6 \text{ Btu} + \frac{1.4 \times 10^6}{4} \text{ Btu} \left[\frac{4-4}{0.7} + \frac{4}{0.8} - 4\right] \\ &= 3.8 \times 10^6 \text{ Btu} \end{aligned}$$

9.2 Nomenclature

A	water heater surface area, ft^2
A_o	inside oven wall surface area, ft^2
C_p	water heat capacity, Btu/gal-°F
C_{p_a}	air heat capacity, Btu/lb-°F
E^*	average energy consumption of a water heater, Btu
E_{bi}	energy lost as a result of surface inefficiencies, Btu
E_c	energy consumed in cooking, Btu
E_{cs},E_{co}	energy consumed in surface/oven of a range due to cooking, Btu
E_{fl}	energy lost through flue, Btu
E_{jt}	energy lost through water heater jacket, Btu
E_{ln}	energy lost through the walls of the water heater distribution system, Btu
E_{ps},E_{po}	energy consumed by surface/oven pilots, Btu
E_s,E_o	energy consumed in the surface/oven of a range, Btu

---

*All E notation refers to energy consumed per year per unit.

E_v	energy lost by oven ventilation, Btu
E_w	energy lost through oven walls, Btu
E_{wa}	energy required to heat water, Btu
h_c	heat transfer coefficient for convection, Btu/ft^2-hr-°F
h_i	inside heat transfer coefficient of oven wall, Btu/ft^2-hr-°F
h_o	outside heat transfer coefficient of oven wall, Btu/ft^2-hr-°F
h_r	heat transfer coefficient for radiation, Btu/ft^2-hr-°F
k	thermal conductivity, Btu/ft-°F
L	length of piping for water distribution system, ft
ℓ	thickness of resistance to heat flow, ft
M	hot water consumption, gal/day
$\dot{m}$	air flow rate through oven, lb/hr
n	number of surface burners with efficiency, ε_t
P	annual pilot consumption, Btu/pilot-yr
p	number of pilots eliminated
Q_{total}	total energy input to oven at equilibrium, Btu/hr
Q_v	heat lost by oven ventilation, Btu/hr
Q_w	heat lost through oven wall, Btu/hr
Q'_w	oven wall heat loss, Btu/ft
ΔT	temperature difference between tank water and the ambient, °F
T_a	ambient temperature, °F
T_e	temperature of oven exit gas, °F
T_o	average air temperature adjacent to oven walls, °F
T_w	desired water temperature, °F
T_{wi}	inlet water temperature, °F
t	time, hr or day
t_c	average equivalent cooking time for wall and ventilation losses in oven per year, hr

U	overall heat transfer coefficient, Btu/ft^2-hr-°F
ε_b	thermal utilization efficiency of standard burners
ε_t	thermal utilization efficiency of more efficient burners

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