Title

THE BEHAVIOR OF THE MARKET FOR ENERGY EFFICIENCY IN RESIDENTIAL APPLIANCES INCLUDING HEATING AND COOLING EQUIPMENT

Authors
Ruderman, H.
Levine, M.D.
McMahon, J.E.

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H. Ruderman, M.D. Levine, and J.E. McMahon

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THE BEHAVIOR OF THE MARKET FOR ENERGY EFFICIENCY IN RESIDENTIAL APPLIANCES INCLUDING HEATING AND COOLING EQUIPMENT

Henry Ruderman, Mark D. Levine and James E. McMahon

Energy Analysis Program
Applied Science Division
Lawrence Berkeley Laboratory
Berkeley, California 94720

September 1984

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ABSTRACT

This paper provides a quantitative analysis of the behavior of the market for the purchase of energy efficiency in residential appliances including heating and cooling equipment. We examine the historical efficiency choices during the period 1972-80 for eight consumer products. We characterize the behavior of the market for these products by an aggregate market discount rate. The major finding of this study is that the overall market discount rates for major household appliances are high (ranging from about 20 to over 800 percent). They appear to be relatively constant, even though fuel prices escalated rapidly during this time. We conclude from these results that the market for energy efficiency is not performing well.

THE BEHAVIOR OF THE MARKET FOR ENERGY EFFICIENCY IN RESIDENTIAL APPLIANCES INCLUDING HEATING AND COOLING EQUIPMENT

INTRODUCTION

This paper provides a quantitative analysis of the behavior of the market for the purchase of energy efficiency in residential appliances and heating and cooling equipment. Accurate forecasts of residential energy use require quantitative assessments of market decisions about energy efficiency. The results of our investigation of market behavior can lead to a better understanding of the barriers to investment in energy conservation. Understanding market behavior over time is a prerequisite to an evaluation of the need for and the importance of policies to promote energy efficiency.

The results of this work are particularly important to an assessment of the desirability of federal policies such as appliance efficiency standards. To the extent that the market place is performing effectively in the purchase of energy efficiency in household appliances, there is little need for federal policies to modify market forces. To the extent that the market for energy efficiency is not performing effectively, the justification for policy intervention is supported.

The major finding of this study is that the payback periods for investment in increasing the energy efficiency of most household appliances are less than three years. Except for air conditioners, the discount rates corresponding to these payback periods are much higher than real interest rates or the discount rates commonly used in life-cycle cost analysis of consumer choice. We conclude from this that the market for energy efficiency is not performing well. Several explanations of the under investment in efficiency are proposed and discussed: 1) lack of information about the costs and benefits of energy efficiency; 2) lack of access to capital markets; 3) expected savings are too small to be of interest to purchasers; 4) prevalence of third party purchasers; 5) unavailability of highly efficient equipment without other features; 6) long manufacturing lead times; and 7) other marketing strategies.

Considerable discussion of appliance efficiency choice can be found in the public testimony on the proposed U.S. Department of Energy's Consumer Products Efficiency Standards (DOE, 1982a) and in the comments by the Regulatory Analysis Review Group of the Council on Wage and Price Stability (1980). McFadden (1977) has done theoretical work on discrete choice models to study consumer decision making. McFadden and Goett (Goett, 1981) have applied these models to the assessment of appliance efficiency and fuel choice decisions. Hartman (1979) has applied discrete choice models to the choice of fuels for residential appliances. Hausman (1979) estimated individual discount rates for room air conditioners in an article in the Bell Journal of Economics.

In addition to research on discrete consumer choice models, several authors have studied aspects of overall market behavior as they relate to energy efficiency. Corum and O'Neal (1982) and Levine and Scott (in preparation) have estimated discount rates that apply to aggregate market decisions on thermal integrity of new houses, using approaches that we adopt in this paper to the study of appliance efficiency. Considerable background and preliminary analysis of this subject done by two of the authors (Levine and McMahon) is reported in the U.S. Department of Energy's Consumer Products Efficiency Standards Economic Analysis Document (1982a). Reid (1980) presented an overview of data pertinent to the evaluation of market decisions (especially in different market segments) on investing in more efficient residential equipment. Geller (1983) provides a valuable overview of the importance of energy efficiency in residential appliances and heating and cooling equipment.

In spite of the literature on the subject, no prior paper has treated all (or even more than a few) of the major appliances, air conditioners, and heating equipment using a single approach to characterize the behavior of the market for energy efficiency. Nor has any previous paper studied the behavior of the market for energy efficiency over time. Finally, most previous work has not attempted to characterize the national market but rather has analyzed relatively small data sets in the hope that they might help shed light on the overall market. This paper extends previous work in all of these areas.

In this study, we examine the historical efficiency choices for eight consumer products: gas central space heaters, oil central space heaters, room air conditioners, central air conditioners, electric water heaters, gas water heaters, refrigerators, and freezers. Central space heaters include boilers and furnaces. These products were selected because they account for a major part of residential energy consumption, data on efficiency and costs are readily available, and they have been under consideration by DOE for efficiency standards. Electric central and room heaters were not included because no significant improvement in their efficiencies are possible. Data on the efficiency of heat pumps and gas or oil room heaters were not available.

We characterize the behavior of the market for these eight products by two related quantities: a simple payback period and an aggregate market discount rate. The simple payback period is the time it takes to recover the additional cost of more efficient equipment through lower expenditures on fuel. The aggregate market discount rate quantifies the behavior of the market as a whole: the manufacturers of appliances, the wholesalers and retailers who distribute them, the third party appliance installers such as builders or plumbers, and the individual purchasers. We determined it empirically from data on the efficiency and cost of appliances purchased between 1972 and 1981.

Market discount rates differ from consumer discount rates both conceptually and in terms of the data required to evaluate them. Consumer discount rates characterize the life-cycle cost decision made by the consumer given the array of appliance prices and design options available in the marketplace. To calculate these discount rates, we need to know the price and efficiency of each model available to the consumer. In contrast, the market discount rate characterizes the decisions of the market as a whole. Although different segments of the market do not necessarily make their decisions on the basis of minimum life-cycle cost, we can calculate the discount rates associated with a market that is assumed in aggregate to behave as if it optimizes efficiency purchase decisions. In other words, we ask the question: if we treat the market conceptually as if the sum of all appliance efficiency choices could be characterized by a type of life-cycle cost decisions, what is the discount rate that would characterize the overall market? Decisions by manufacturers on which design options to produce, decisions by retailers and wholesalers on which models to advertise or discount, as well as the consumer purchase decision affect the market discount rate.

Distortions in the market place will show up as differences between the market discount rates and real interest rates for purchasing consumer goods. The calculation of market discount rates requires knowledge of which design options could possibly be manufactured and the costs (including profit margins) to deliver them to the ultimate user. Because consumer discount rates are based on prices, they tend to reflect short-term market conditions, such as sudden price increases or shortages of high-efficiency models. Market discount rates, on the other hand, reflect decisions made over a longer period of time; hence they tend to indicate long-term distortions in the market. In a long-term equilibrium in which prices reflect costs, market and consumer discount rates will be the same. For the analysis of policies directed at improving the energy efficiency of appliances, the market discount rate is the one that is more appropriate.

We note several limitations to the present work. First, our analysis is performed at a high level of aggregation. While it would be useful to divide the market into small segments that either exhibit relatively homogeneous behavior (e.g., renters; high socioeconomic groups owning homes; etc.) or exert similar influences on market response (e.g., consumers; manufacturers; retailers), this work does not carry the analysis into market segments in this way because of serious data limitations. Such an analysis could help in identifying where the market failures occur. The last section of the paper describes future work that could be done if the data were available. A second limitation of this work has to do with aggregation errors that are introduced as a result of using national data. As better data become available and as the studies are done at a more disaggregate level (including different market segments), the effect of aggregation errors will be better understood and possibly eliminated. As it is, we believe that our numerical results reflect in a meaningful way the behavior of the U.S. market with respect to investing in energy efficiency improvements in residential equipment.

The organization of this paper is as follows. The theoretical background and equations used to calculate the market discount rate are presented in the second section. It also contains discussions of the sensitivity of the results to the parameters of the model and aggregation bias. The following section discusses the data used and their limitations. Section four presents the results of the calculation of market discount rates and payback periods. Next, we interpret these results in terms of the behavior of various segments of the market. The final section contains our conclusions and recommendations for additional research.

We would like to thank the many people who reviewed drafts of this paper and who offered their suggestions and comments. Dr. Michael Rothkopf's clarification of the distinction between consumer and market discount rates was especially valuable. The continued support and interest by Michael McCabe and Fred Abel of the U.S. Department of Energy are especially appreciated. The conclusions and opinions expressed in this paper do not necessarily reflect those of the Department of Energy or the Lawrence Berkeley Laboratory.

THEORETICAL BACKGROUND

Discount Rates and Life-Cycle Costs

A discount rate is a measure of the present value of money received or spent in the future. For example, if someone values an income of $110 received a year from today the same as an income of $100 received today, that person has a discount rate of 10 percent per year. Given the discount rate r, one can calculate the present value of a stream of income (or expenditures) using the formula

$$PV = \sum_{t=1}^{N} \frac{X_t}{(1+r)^t}, \tag{1}$$

where

X_t = Income in time period t

and

N = Duration of income stream.

For a constant stream of income, this formula becomes

$$PV = PWF \cdot X_t,$$

where we have defined the present worth factor PWF by

$$PWF = \sum_{t=1}^{N} \frac{1}{(1+r)^t} = \frac{1}{r}\left(1 - \frac{1}{(1+r)^N}\right). \tag{2}$$

In chosing an appliance, the consumer makes a tradeoff, among other things, between its purchase price and its future operating costs. How the consumer weights these factors depends on his or her discount rate. A high discount rate implies that the operating costs are weighted less heavily because their present value is less. Thus, a consumer with a high discount rate would prefer a lower cost, less efficient product to a higher cost, more efficient one.

Because the discount rates of consumers are not known, they must be inferred from the behavior of the market. An aggregate market discount rate is one that has been determined from historical data on market behavior. The behavior of the market, however, is not determined solely by consumers: other participants such as manufacturers, distributors, retailers, government agencies, utilities, and third parties also play a role. We must therefore be careful in attributing an observed market discount rate to consumer choice without considering the effects of other participants in the market. This point is discussed in greater detail in the section on interpretation of the results.

Next, we discuss how aggregate market discount rates are determined from the average efficiency of appliances purchased given that appliance prices, efficiencies, and other attributes are determined by other segments of the market. It is necessary to work with average values because there is no data on appliance purchase choices by individuals. We assume the purchaser is faced with a set of cost-efficiency choices that are characterized by a continuous curve that is convex toward the origin, that is, higher efficiency is associated with higher prices. We further assume that on the average the consumer minimizes the life-cycle cost of purchasing and operating the appliance. The point on the cost-efficiency curve that minimizes the sum of the average purchase cost plus the average operating cost discounted at the market rate give the efficiency chosen. At this point, the market makes a tradeoff between purchase and operating costs such that an additional dollar spent in purchasing a more efficient appliance returns one dollar in discounted operating costs over the lifetime of the product.

Figure 1 illustrates the effect of different discount rates on the position of the minimum of the life-cycle cost curve for central air conditioners. At higher discount rates, the slope of the operating cost component is lower, and the the minimum is at higher annual energy consumption and lower appliance efficiency. A discount rate of 20 percent puts the minimum of the LCC curve at 34 million Btu, corresponding to the annual energy consumption during 1980. This point is marked on all three curves. Rather than using the discount rate to locate the minimum of the life-cycle cost curve, we reverse the process and determine the market discount rate from the position of the minimum, which is assumed to occur at the average energy use.

Calculation of Aggregate Market Discount Rates and Payback Periods

The life-cycle cost for owning and operating an appliance is the sum of the purchase cost and the discounted operating cost. Assuming that the only operating cost is for energy, the life-cycle cost is given by

$$LCC = PC + \sum_{t=1}^{N} \frac{FC_t}{(1+r)^t}. \qquad (3)$$

In this equation, PC is the purchase cost, FC_t is the fuel cost in period t, and N is the lifetime of the appliance. Maintenance costs are assumed to be independent of efficiency choice, hence they can be ignored in calculating market discount rates. For constant fuel costs, Equation 3 becomes

$$LCC = PC + PWF \cdot FP \cdot E, \qquad (4)$$

where PWF is the present worth factor defined above, FP is the average fuel price (assumed constant over time, i.e., the consumer expects no price escalation*), and E is the average energy consumption by the appliance. The market selects an energy use (or efficiency) that minimizes the average life-cycle cost of the appliance. Mathematically, this is equivalent to finding the

* This assumption will yield lower discount rates than if increases in fuel prices are anticipated by the market. If the anticipated rate of energy price escalation is e, the market discount rate would be approximately $r' = r + e$.

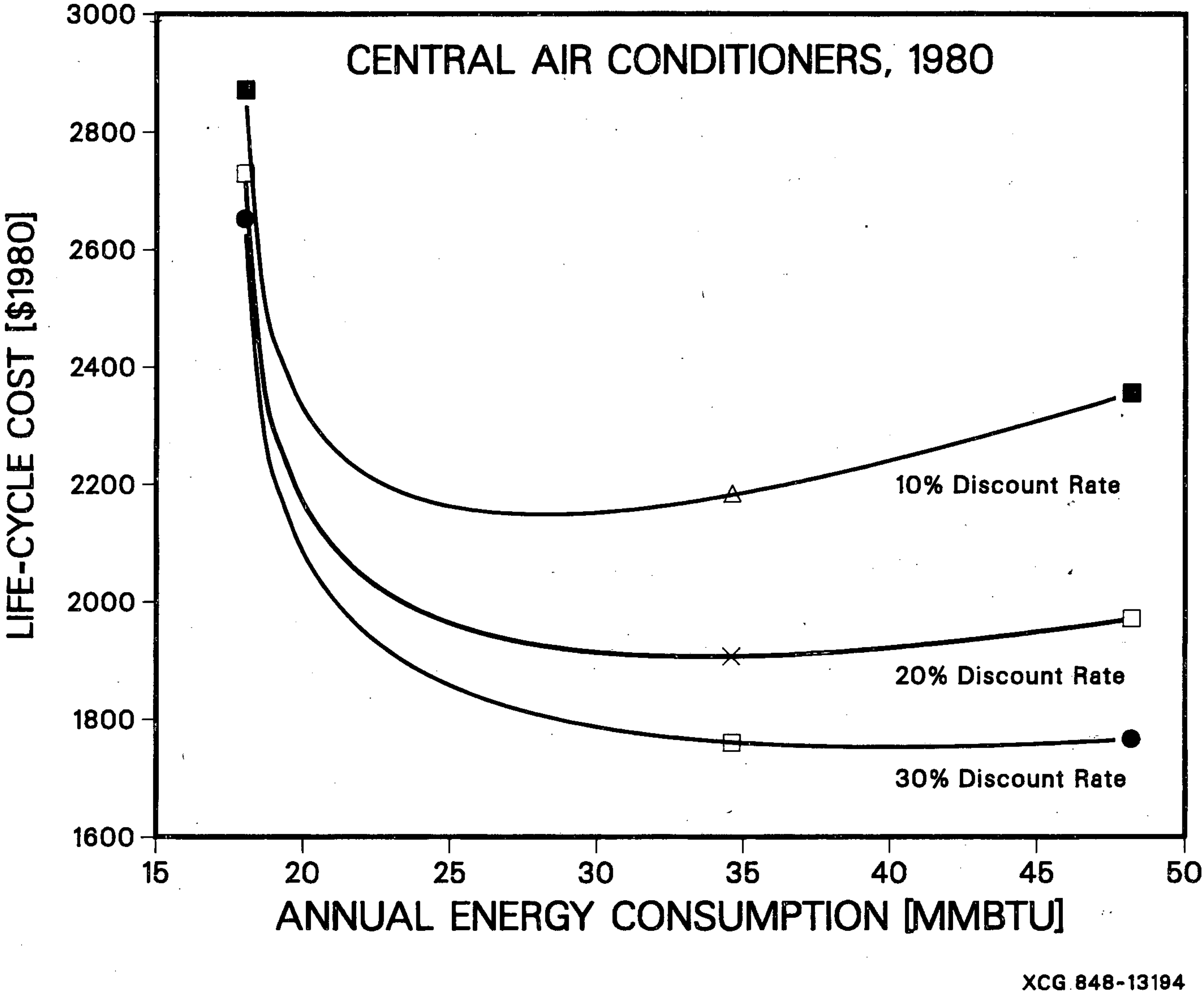

Figure 1. -- Life-Cycle Cost Curves as a Function of Discount Rate

energy use E_s such that

$$\left.\frac{dLCC}{dE}\right|_{E_s} = \left.\frac{dPC}{dE}\right|_{E_s} + PWF{\cdot}FP = 0. \tag{5}$$

Solving this for the present worth factor gives

$$PWF = \frac{-1}{FP}\left.\frac{dPC}{dE}\right|_{E_s}. \tag{6}$$

Hence, given the analytic form of the cost-efficiency curve, we can evaluate the derivative $\frac{dPC}{dE}$ at the average efficiency purchased during any year and, using Equations 6 and 2, determine the aggregate market discount rate. We use the manufacturers' shipment-weighted energy factor (SWEF) for the average efficiency purchased.

The simple payback period is defined as the time needed to recoup an initial investment in energy efficiency. Numerically, the payback period is equal to the increase in purchase cost divided by the decrease in annual operating cost. Assuming the operating costs change only because fuel use decreases, we have

$$Payback = \frac{\Delta PC}{FP{\cdot}\Delta E} = \frac{-1}{FP}\frac{dPC}{dE} = PWF. \tag{7}$$

Thus for a continuous cost-efficiency curve the payback period is just the present worth factor.

To calculate the aggregate market discount rate or the payback period, we need an analytic expression for the cost-efficiency curve with the right convexity properties and showing diminishing returns to scale. The original ORNL Residential Energy Use Model (Hirst and Carney, 1978) used an expression of the form

$$E = E_\infty + \left(\frac{B+1}{B+C}\right)^A (E_0 - E_\infty), \tag{8}$$

where

E = unit energy consumption (UEC)

E_0 = base year UEC

E_∞ = minimum UEC attainable at infinite purchase cost

$C = PC / PC_0$

PC = purchase cost corresponding to E

PC_0 = purchase cost corresponding to E_0

and A and B are parameters. In attempting to estimate these parameters, we observed that they are highly correlated because they both determine the shape of the curve once E_0 and E_∞ are known. This leads to a greater uncertainty in the estimate of these two parameters and thus the slope of the cost-efficiency curve.

We replaced this curve by an exponential curve of the form

$$E = E_\infty + (E_0 - E_\infty)\exp[-A(C - 1)]. \quad (9)$$

The curve specified by this equation has the same general shape as the original one, but it is simpler because it has one less parameter. The multicolinearity problem in estimating the parameters is thus eliminated. Using this form, the slope of the cost-efficiency curve becomes

$$\frac{dPC}{dE} = -\frac{PC_0}{A}\frac{1}{(E - E_\infty)}, \quad (10)$$

and the present worth factor or payback period is given by

$$PWF = \frac{PC_0}{A \cdot FP \cdot TI}\frac{1}{(E - E_\infty)}. \quad (11)$$

In the latter equation, we have included a factor TI to account for the possibility that the thermal integrity of the structure may change with time.*

The most common method for evaluating discount rates is to take the time period as one year. However, this will underestimate the discount rate when the payback period is shorter than one year. Since fuel and electricity bills are paid monthly, we chose a one month time period for evaluating the market discount rate. Thus the appliance lifetime N in Equation 2 is expressed in months. An exact calculation would take into account the monthly variation in energy use by each appliance and the month in which it was bought. Since these data are not available, we average over one year, so that the monthly energy use is one-twelfth of the annual. In presenting our results, we calculate an annualized discount rate $\overline{r}$ from the monthly discount rate r using the relationship

$$1 + \overline{r} = (1 + r)^{12}.$$

Sensitivity Analysis

Next, we examine how sensitive the estimates of the payback period and the aggregate market discount rate are to uncertainties in the location of the minimum of the life-cycle cost curve E_s. The sensitivity depends on the appliance characteristics embodied in the cost-efficiency curve. We define the sensitivities by dPWF/dE and dr/dE, respectively.

Differentiating Equation 11 gives

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* This factor is defined as the relative energy use at different levels of thermal integrity, hence TI decreases with better insulation and lower air infiltration.

$$\frac{dPWF}{dE} = -\frac{PWF}{E_s - E_\infty} = \frac{-PC_0}{A \cdot FP \cdot TI} \frac{1}{(E_s - E_\infty)^2}. \tag{12}$$

Clearly, the payback period is much less sensitive to uncertainties in average energy use at high energy consumption. From Equation 6 we note that, at a given energy consumption, the sensitivity is proportional to the slope of the cost-efficiency curve.

For typical appliance lifetimes and market discount rates, the discount rate is essentially inversely proportional to the present worth factor (see Equation 2):

$$r = \frac{1}{PWF}.$$

Then,

$$\frac{dr}{dE} = \frac{-1}{(PWF)^2} \frac{dPWF}{dE}$$

$$= \frac{A \cdot FP \cdot TI}{PC_0}. \tag{13}$$

This equation shows that the market discount rate is approximately linear in average energy use. Its sensitivity is independent of E_s.

Aggregation Bias

In calculating the payback period and market discount rate, we assume that all consumers will have an average energy use corresponding to the SWEF. If, in fact, there is a distribution of energy consumption, due to differences in efficiency choice or usage, the average market payback period of these users may be different from that calculated from the average energy use. We investigate this aggregation bias in two cases: one in which there is a distribution in energy use and a second in which there is a distribution in appliance efficiency. In the first case, the average payback period is greater than that calculated from the average energy use (and the discount rate is less). In the second case, the direction of the aggregation bias depends on the ratio of average efficiency to the maximum efficiency corresponding to E_∞. The amount of bias depends on the width of the energy and efficiency distributions.

The market payback period is the incremental capital cost of improving the average efficiency of all appliances sold divided by the resulting decrease in their operating cost:

$$PWF = -\frac{\Delta PC}{\Delta OC}. \tag{14}$$

To calculate an "average" market payback period, we first average the numerator and denominator separately over the distribution in energy or efficiency before taking their ratio. To investigate the effect of a distribution in energy use, we assume that E is uniformly distributed between $E_s - \Delta E/2$ and $E_s + \Delta E/2$, where $E = E_s$, the energy use corresponding to the

SWEF.

$$P(E) = \frac{1}{\Delta E}, \qquad E_s - \Delta E/2 \leqslant E \leqslant E_s + \Delta E/2.$$

We also assume a uniform distribution in efficiency η for $\eta_s - \Delta\eta/2 \leqslant \eta \leqslant \eta_s + \Delta\eta/2$. Since ΔPC and ΔOC are proportional to the slope of the purchase cost and operating cost curves, e.g., dPC/dE or $dPC/d\eta$, averaging them over these distributions gives

$$<\Delta PC> = \frac{1}{\Delta E}\Big[PC(E_s + \Delta E/2) - PC(E_s - \Delta E/2)\Big]$$

or

$$<\Delta PC> = \frac{1}{\Delta\eta}\Big[PC(\eta_s + \Delta\eta/2) - PC(\eta_s - \Delta\eta/2)\Big],$$

with similar expressions for $<\Delta OC>$.

Since the operating cost is simply $OC = FP \cdot TI \cdot E$, the expected value of the denominator given a uniform distribution of energy use is

$$<\Delta OC> = FP \cdot TI. \tag{15}$$

To calculate the average value of the numerator, we begin with the expression for the two-parameter cost-efficiency curve

$$PC = PC_0\left[1 - \frac{1}{A}\ln\frac{E - E_\infty}{E_0 - E_\infty}\right]. \tag{16}$$

Then,

$$<\Delta PC> = \frac{-PC_0}{A\Delta E}\ln\frac{E_s - E_\infty + \Delta E/2}{E_s - E_\infty - \Delta E/2} = \frac{-PC_0}{A\Delta E}\ln\frac{1+\epsilon}{1-\epsilon}. \tag{17}$$

where

$$\epsilon = \frac{\Delta E}{2(E_s - E_\infty)}.$$

For $\epsilon < 1$,

$$\ln\frac{1+\epsilon}{1-\epsilon} = 2\epsilon(1 + \epsilon^2/3 \ldots).$$

Taking the ratio of $<\Delta PC>$ to $<\Delta OC>$ gives for small ϵ the "average" market payback period

$$<PWF> = PWF \cdot (1 + \epsilon^2/3) \tag{18}$$

$$\geqslant PWF.$$

In terms of efficiency the purchase cost is

$$PC = PC_0 \left[1 - \frac{1}{A} \ln \frac{\eta - \eta_\infty}{\eta_0 - \eta_\infty} \frac{\eta_0}{\eta} \right]. \tag{19}$$

$$<\Delta PC> = \frac{-PC_0}{A\,\Delta\eta} \ln \left[\frac{\eta_s - \eta_\infty + \Delta\eta/2}{\eta_s - \eta_\infty - \Delta\eta/2} \frac{\eta_s - \Delta\eta/2}{\eta_s + \Delta\eta/2} \right]$$

$$= \frac{-PC_0}{A\,\Delta\eta} \ln \left[\frac{1+\epsilon}{1-\epsilon} \frac{1-\delta}{1+\delta} \right], \tag{20}$$

where

$$\epsilon = \frac{\Delta\eta}{2(\eta_s - \eta_\infty)}$$

and

$$\delta = \frac{\Delta\eta}{2\eta_s} = \frac{\eta_\infty - \eta_s}{\eta_s} \epsilon.$$

Similarly,

$$<\Delta OC> = -FP \cdot TI \cdot E_s \frac{\eta_s}{(\eta_s)^2 - (\Delta\eta/2)^2}$$

$$= \frac{-FP \cdot TI \cdot E_s}{\eta_s} \frac{1}{1 - \delta^2}. \tag{21}$$

Taking the ratio of $<\Delta PC>$ to $<\Delta OC>$ and assuming that $\epsilon << 1$, gives

$$<PWF> = PWF \cdot (1 - \delta^2) \cdot \left[1 + \frac{\eta_s}{\eta_\infty} \frac{\epsilon^2}{3} + \frac{\eta_\infty - \eta_s}{\eta_\infty} \frac{\delta^2}{3} \right]. \tag{22}$$

The last two factors in Equation 22 tend to cancel each other, so the aggregation bias calculated in this way will tend to be less than that calculated by averaging the payback period. Whether $<PWF>$ is smaller or larger than PWF depends on the ratio of η_s to η_∞: if this ratio is larger that two-thirds, $<PWF>$ is larger than PWF, otherwise it is smaller. Of the appliances we have studied, only gas and oil furnaces and electric water heaters have efficiencies greater than two-thirds of the maximum efficiency. These will show a positive aggregation biases for their market payback periods, whereas the rest will show negative aggregation biases.

Note that for a uniform distribution, the variance $\sigma^2 = \Delta^2/12$, where Δ is the full width of the distribution. From the results for uniform distributions in E and η, we surmise that, in general, the aggregation bias is proportional to the the variance of the distribution. If we know the distribution of energy use or efficiency, we can estimate the aggregation bias from its variance using Equation 18 or 22. Alternatively, we can put an upper limit on the bias from the range of the distribution.

To estimate the magnitude of the aggregation bias, we used data on the distribution of efficiency of central air conditioners in 1980 published by the Air-Conditioning and Refrigeration Institute (1983). The average efficiency (SEER) was $\eta_s = 7.76$, with a variance $\sigma^2 = 0.51$. The aggregation bias is of order of magnitude $\epsilon^2 = 0.01$, or about one percent. Biases of this size are small compared to the uncertainties caused by measurement error in the SWEF and other data used to calculate the payback period.

DATA REQUIREMENTS

The data required to perform an analysis of aggregate market behavior include:

- purchase cost and unit energy consumption of alternative design options for each product;
- average efficiency purchased;
- energy prices;
- thermal characteristics of houses; and
- average appliance lifetimes.

Data Sources

Relationship of energy use to equipment purchase cost

The major sources of data are the engineering cost analyses performed for the U.S. Department of Energy's analysis of Consumer Product Efficiency Standards (DOE, 1980 and 1982b). These reports provided estimates of the purchase costs (manufacturing plus distribution costs) of individual appliances with different efficiencies. Supplemental data were obtained from Arthur D. Little, Inc. (ADL, 1982) to extend the cost and efficiency data back in time to 1972, and forward to 1981 from the original data sets for 1978 (and 1980 for some products).

Each product type, i.e. refrigerators, was divided into classes, such as manual defrost, partial automatic defrost, automatic defrost top-mount, etc. Classes were defined within each end use for two reasons: 1) to separate models with a different primary energy source; and 2) to separate products having a different capacity or other performance-related feature which affects efficiency and utility. The engineering analyses provided different design options for each class. Purchase costs were estimated by applying a constant percentage markup to the manufacturer's cost of each design option. A computer program (McMahon, 1984) was used to aggregate the data from the various classes into a single set of data points representing the product type -- refrigerators. This aggregation involves weighting the data points for each class by the shipments of that class in 1978. Finally, a least squares fit was performed to the functional form specified above (Equation 9), to obtain the two parameters of the curve (A and E_{∞}).

The engineering analyses provided estimates of energy use and efficiency related to purchase cost for 1978 (for all products) and 1980 (for refrigerators and freezers only). The supplemental data set for 1972 is weak, consisting of fewer data points, representing only one class, and only efficiencies were provided. These were converted to unit energy consumption by assuming an inverse relationship to efficiency and scaling to the 1978 baseline unit.

Efficiency measurements were not made in 1972. However, manufacturers have records of the design options used at that time. Manufacturers responded to the DOE CS-179 Survey in 1979, in which they estimated the efficiencies of products manufactured in 1972 (DOE, 1982a Table 3-12). These estimates are presumed to be less reliable than efficiencies based on measurements on appliances built more recently. The range of efficiencies available in 1972 was defined as the range of values provided by individual manufacturers' answers to the DOE survey. The incremental cost between the average 1972 efficiency and the extreme (high and low) efficiencies was estimated by assigning design options to each that might reasonably account for the differences in efficiency, then estimating the difference in cost between those designs.

A typical energy use vs. purchase cost curve is shown in Figure 2. The points correspond to aggregated design options for the product type. The curve is a fit to Equation 8 forced through the highest energy use point (at E_0). The lowest energy use (highest efficiency) is determined by the maximum efficiency available at the time of the enginering analysis (1979). This low energy use point is heavily weighted in the fitting, effectively defining the value of E_∞. Because of the uncertainty in its value, we perform a sensitivity analysis on this parameter. It is also important to realize that the points and the fitted curve represent averages of appliance types that could have been available in the market during the period 1972 to 1980. The parameters of the fitted curves and the values of other quantities used in calculating the market discount rates are displayed in Table 1.

Table 1. -- Parameters for Calculating Market Discount Rates

Appliance	N (Years)	E_∞/E_0	A	PC_0 ($ 1980)	E_0 (MMBtu)
Gas Central Space Heater	23	0.5357	10.533	1932.20	99.83
Oil Central Space Heater	23	0.7413	17.372	2958.01	134.47
Room Air Conditioner	15	0.4736	5.620	433.60	15.69
Central Air Conditioner	12	0.3667	5.272	1243.60	48.68
Electric Water Heater	13	0.7369	11.516	159.21	58.31
Gas Water Heater	13	0.4885	6.371	196.23	24.60
Refrigerator	19	0.2550	9.608	493.10	21.05
Freezer	21	0.2089	14.677	337.44	24.64

Note: The parameters are defined in Equations 3 - 9 in the text.

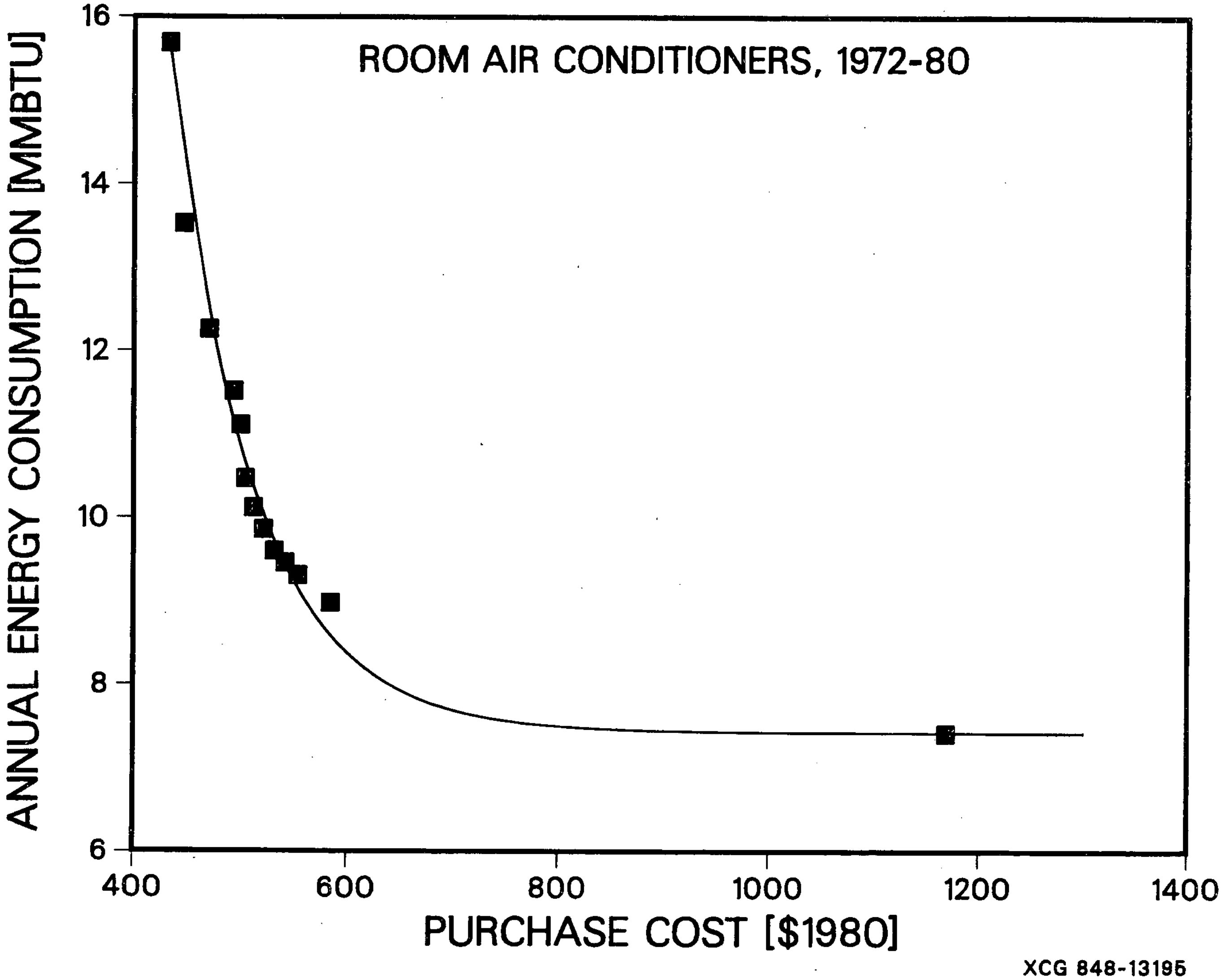

Figure 2. -- Annual Energy Consumption vs. Purchase Cost Room Air Conditioners

Shipment-weighted energy factors (SWEF)

Several sources were used to estimate the SWEFs. First, the Department of Energy's CS-179 Survey of Manufacturers provides historical data from the trade associations for 1972 and 1978 average efficiencies shipped. The same source provides projections for 1980 and 1985. Second, comments on the April 2, 1982 DOE Notice of Proposed Rulemaking for Consumer Product Efficiency Standards provide industry data for average efficiencies in the last ten years for some products. The Association of Home Appliance Manufacturers (AHAM, 1982) provided estimates for selected years in the period 1972-81 for refrigerators, freezers, room air conditioners, clothes dryers, clothes washers, and dishwashers. The Air-Conditioning and Refrigeration Institute (ARI, 1982) provided annual efficiencies of central air conditioners, as did Lennox for its products. Two manufacturers (Carrier, 1982 and Lennox, 1982) provided estimates of the efficiencies of their gas furnaces sold after 1975. While estimates from individual manufacturers represent only part of the industry, they serve as a check on the CS-179 industry-wide numbers. Table 2 lists the efficiencies, data sources, products, and years.

Fuel and electricity prices

The energy prices used in calculating market discount rates are shown in Table 3. Natural gas, fuel oil and average electricity prices for 1972 to 1980 were originally published by the Energy Information Administration (EIA) (DOE, 1979 and 1981a). These data were obtained by LBL in the form of tables in which DOE had converted the original prices to 1981 dollars using GNP deflators and assuming a 9.9 percent inflation rate from 1980 to 1981. The electricity prices had been converted to dollars per million Btu using a factor of 3412 Btu/kWh. At LBL, the prices were converted to 1980 dollars and the electricity prices were converted to dollars per million Btu of primary fuel assuming an average heat rate (including losses) of 11,500 Btu/kWh. Prices for 1981 and the first quarter of 1982 from the *Monthly Energy Review* (DOE, 1982c) were added.

Winter and summer marginal electricity rates are used for heating and cooling equipment, respectively. Marginal rates are calculated as the average rate for the 500 to 1000 kWh per month block. Winter rates are derived from EIA's *Monthly Electric Bills* (DOE, 1981b). Although EIA does not publish similar data for the summer bills, data for summer 1981 and winter 1982 are published by the Edison Electric Institute (1982). From these data we derived a figure of 0.865 for the ratio of summer to subsequent winter rates for the 500 to 1000 kWh block. This ratio was applied to the winter rates to calculate the rates for the previous summer. This method could not not be applied for 1982; the summer rate for 1982 was estimated by extrapolating the previous two years rates.

Table 2. -- Shipment-Weighted Energy Factors (SWEF)

Appliance	Source	1972	1975	1976	1977	1978	1979	1980	1981	1982
Gas Central	CS-179	62.7	--	--	--	63.6	--	65.9	--	--
Space Heater	Lennox	--	65.0	65.0	65.1	65.5	66.3	66.6	67.0	--
(AFUE %)	Carrier	--	63.7	--	--	65.1	66.3	66.7	66.5	--
Oil Central Space Heater (AFUE %)	CS-179	73.6	--	--	--	75.0	--	76.0	--	--
Room Air	CS-179	6.22	--	--	--	6.75	--	7.03	--	--
Conditioner (EER)	AHAM	5.98	--	--	--	6.72	--	7.02	7.06	--
Central Air	CS-179	6.66	--	--	--	6.99	--	7.76	--	--
Conditioner	Lennox	--	6.19	6.94	7.02	7.00	7.05	7.14	7.73	8.18
(SEER)	ARI	6.66	--	7.08	7.18	7.39	7.54	7.60	7.63	7.87
Electric Water Heater (Percent)	CS-179	79.8	--	--	--	80.7	--	81.3	--	--
Gas Water Heater (Percent)	CS-179	47.4	--	--	--	48.2	--	51.2	--	--
Refrigerator	CS-179	4.22	--	--	--	5.09	--	5.72	--	--
(cu.ft./kWh/day)	AHAM	3.84	--	--	--	4.96	--	5.59	6.09	--
Freezer	CS-179	8.08	--	--	--	10.07	--	10.83	--	--
(cu.ft./kWh/day)	AHAM	7.29	--	--	--	9.92	--	10.85	11.27	--

Data Sources:
AHAM - Association of Home Appliance Manufacturers
ARI - Air-Conditioning and Refrigeration Institute
Carrier - Carrier Corporation
CS-179 - Department of Energy Survey of Manufacturers
Lennox - Lennox Corporation

Thermal characteristics of houses

Thermal integrity factors were defined as the relative annual energy consumption for space conditioning end uses, reflecting changes from the stock house in existence in 1977 in terms of thermal characteristics (including insulation, window glazings, infiltration, etc.). The thermal integrity values for historical years were estimated from survey data (NAHB, 1979 and DOE, 1980). For years before 1977, thermal integrity values were found by extrapolating the 1978-79 trends. After 1977, they were taken from the ORNL/LBL Residential Energy Model outputs

(DOE, 1982a). The values used here were weighted averages to capture the relative sales of each product to new and existing houses (with different thermal integrity factors) each year. Table 4 contains the values used.

Appliance lifetimes

The appliance lifetimes (Fechtel, 1980) are the same as used in the Consumer Product Efficiency Standards analysis (DOE, 1982b). While other sources are available, sensitivity analysis indicates that selection of a different set of values would not affect the results very much.

Data Limitations

First, the necessity to treat the market at an aggregate level tends to introduce aggregation bias. That is, the individual decisions by the participants in the market are obscured, and only the average result can be observed. The only available data on efficiencies of products are the shipment-weighted average for selected years, provided by manufacturers directly or through trade associations. These data dictate the level of aggregation. If data were available for individual purchasers, including the efficiencies of the product purchased and the expected usage level in that household, then analysis could address the issues of different classes of purchasers (landlords, home owners, builders) and different income levels of consumers.

Second, the actual prices of products sold are not known. Although prices are needed to calculate consumer discount rates, purchase costs are needed for market discount rates. The engineering estimates used for the cost-efficiency relationship assume a constant percentage markup from the ex-factory cost, independent of the design option. That is, the pricing policy is assumed to be uniform, with no special treatment for high or low efficiency products. In a rational market, overheads and markups should not depend on efficiency.

Cost-efficiency relationship

In 1972, no measurements were made of appliance efficiencies. The supplemental engineering analysis involved estimating the cost of products with efficiencies corresponding to the highest, average, and lowest efficiencies reported in the CS-179 survey of manufacturers. The reported efficiencies were based on manufacturer's judgment. In some cases, the least efficient 1972 units were so much less efficient than the 1978 models that there were no obvious design changes that could account for the large differences. Costs of 1972 products were inferred by working backwards from the 1978 baseline product. (Usually, the 1978 baseline unit had an efficiency close to the more efficient product reported for 1972.) Thus, the 1972 prices were calculated from design options inferred from estimated efficiencies.

Table 3. -- Residential Fuel and Electricity Prices
[1980 Dollars per Million Btu]

Year	Electricity Rates[a] Average	Winter	Summer	Gas	Oil
1972	3.533	2.986	2.593	2.092	2.465
1975	3.940	3.827	3.398	2.387	3.969
1976	4.024	3.928	3.540	2.577	
1977	4.172	4.092	3.575	2.891	
1978	4.428	4.133	3.426	3.049	4.207
1979	4.393	3.980	3.158	3.452	
1980	4.658	3.650	3.486	3.847	7.039
1981	4.901	4.031	3.644	4.038	
1982[b]	4.851	4.060	3.800	4.429	

(a) Electricity rates are calculated per million Btu of primary energy assuming an average heat rate of 11,500 Btu/kWh. Winter and summer rates are for the 500-1000 kWh block.

(b) First quarter data.

Source:
1972-77 DOE/EIA "State Energy Fuel Prices by Major Economic Sector from 1960 through 1977" (DOE, 1979)
1978-82 DOE/EIA *Monthly Energy Review.* (DOE, 1982c)

See text for discussion of winter and summer electricity rates

Table 4. -- Average Thermal Integrity Values Corresponding To the Purchase of New Furnaces and Air Conditioners

Appliance	1972	1975	1976	1977	1978	1979	1980	1981	1982
Furnace - Electric	.950	.923	.914	.905	.896	.887	.866	.847	.829
Furnace - Gas	1.014	.960	.942	.924	.906	.888	.860	.829	.795
Furnace - Oil	1.032	.969	.948	.927	.906	.885	.833	.789	.751
Central Air Conditioner	.993	.990	.989	.988	.987	.986	.980	.975	.968
Room Air Conditioner	1.001	.995	.993	.991	.989	.987	.983	.977	.973

Source: ORNL/LBL Base Case of March 1982

Notes: All values are weighted averages for purchases in new and existing houses. They are relative to the 1977 stock building characteristics.

The data for the engineering analyses for products manufactured after 1978 are much more complete. The efficiencies and incremental costs have been reviewed by manufacturers. The prices, as noted above, assume a constant percentage markup from ex-factory costs. No attempt has been made to model the pricing policies of manufacturers and retailers. The average efficiency factors shown in Table 2 are consistent with estimates of aggregate national energy usage.

The cost-efficiency curves represent the purchase costs of various design options under long-run equilibrium conditions. During a period of rapidly rising energy prices, the price-efficiency curve could have a different slope from the cost-efficiency curve. Purchasers would demand fewer low efficiency models and more high efficiency ones. Since manufacturers can not change product lines rapidly, the price of low efficiency models would decrease while that of high efficiency models would increase. In terms of Equation 9, the A parameter would be smaller, resulting in longer payback periods and consumer discount rates lower than market discount rates. Data on the average purchase cost of different efficiency models do not exist, so we can not test this hypothesis.

Energy prices and maintenance costs

The energy prices used are based on observed national averages as reported by the Energy Information Administration. Regional variation in energy prices were not considered, although they might be correlated with appliance saturation and usage. Summer and winter marginal prices were used for space conditioning end uses to take into account tail block rate structures. However, only crude estimates on the national level were available to assign these prices.

In calculating life-cycle costs, we have omitted the contribution of maintenance costs to the operating costs because of a lack of data for individual appliances. We do not know the magnitude or direction of the effect, but we believe it to be small. If maintenance costs are proportional to energy use, e.g. to hours of operation, then the market discount rates would be higher. If, on the other hand, more efficient products need more maintenance, the effect would be in the opposite direction giving lower discount rates. Whatever the direction of the effect, it should be small because maintenance costs in general are small relative to fuel costs.

Thermal characteristics of houses

Survey data has provided some insight into the difference in thermal characteristics between existing and new houses in recent years. However, these surveys are based on limited samples, introducing some uncertainty into the national averages used here. Furthermore, the weighting of appliance installations into new versus existing homes is taken from the

ORNL/LBL Residential Energy Model outputs. There is no independent confirmation of this distribution of installations by house vintage.

RESULTS

We calculated aggregate market discount rates and simple payback periods for years between 1972 and 1981 using cost and efficiency data from several sources. Our first step was to estimate the parameters of the energy use vs. purchase cost curve (Equation 9) for each appliance. Evaluating Equation 11 at the energy use corresponding to the SWEF gave the present worth factor (payback period) from which we calculated to a monthly discount rate by solving Equation 2. This was then converted to an annualized rate. We examined uncertainties in the discount rate by two methods. First, we analyzed sensitivity by varying the values of the fitted parameters and the SWEF. Second, we compared the discount rates derived from different data sources.

Figures 3 and 4 show life-cycle cost curves for two of the appliances. We calculated the curves for each year using the estimated market discount rate. The annual energy consumption corresponding to the SWEF in that year is indicated at the minimum of each curve. Over time, as the efficiency of the appliance increases, the minimum shifts to the left and the life-cycle cost increases. The increase in cost between 1972 and 1980 is due mainly to an increase in fuel price.

The results presented in Tables 5 and 6 for the CS-179 data are based on a single cost-efficiency curve for each appliance covering the period 1972-80. The tabulated discount rates are expressed in percent per year. Changes in discount rates and payback periods over time for a single appliance are due to changes in SWEF, fuel prices, and, in the case of temperature sensitive appliances, thermal integrity. The observed discount rates range from less than 20 to more than 800 percent per year. Those for central space heating and water heating appear to be increasing over the time period, whereas the others either decrease or remain constant.

To understand these year-to-year differences, we performed a sensitivity analysis of the results for gas central space heaters. As shown in Table 7, we varied both the parameters of the cost-efficiency curve and the SWEF. The market discount rate vs. SWEF is plotted in Figure 5. These results show that the observed discount rate is most sensitive to the assumed SWEF. Of the parameters of the cost-efficiency curve, the greatest sensitivity is to the value of E_{∞}. Since the other three parameters each enter Equation 9 in a similar way, they have the same percentage effect on the discount rate.

The sensitivity analysis for the other appliances showed similar results. Central air conditioners show about the same percentage change in discount rate for the same percentage change in the cost-efficiency curve parameters or the SWEF. Refrigerators are relatively insensitive to changes in SWEF and E_{∞}, whereas oil central space heaters are more sensitive to these quantities.

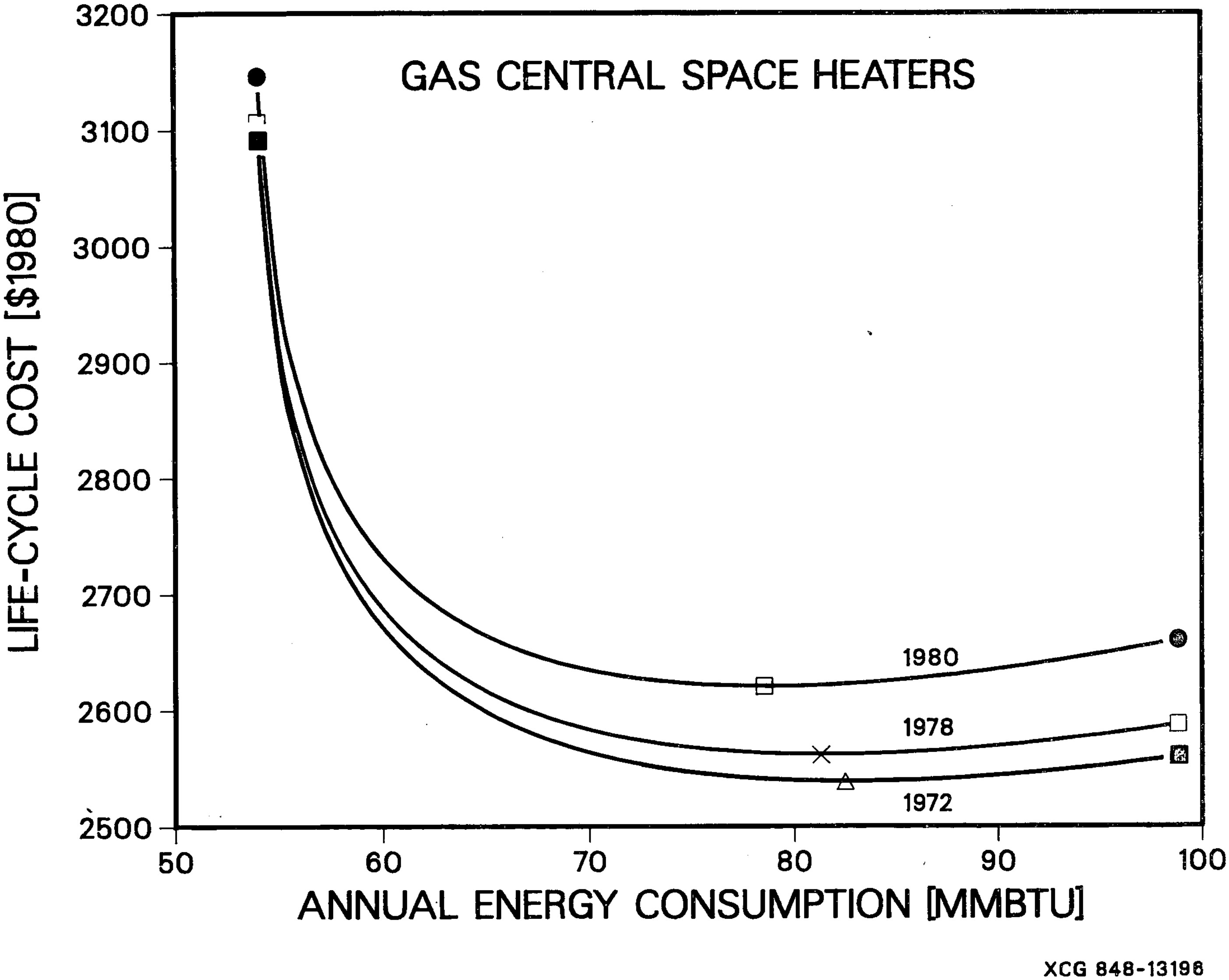

Figure 3. -- Life-Cycle Costs for Gas Central Space Heaters

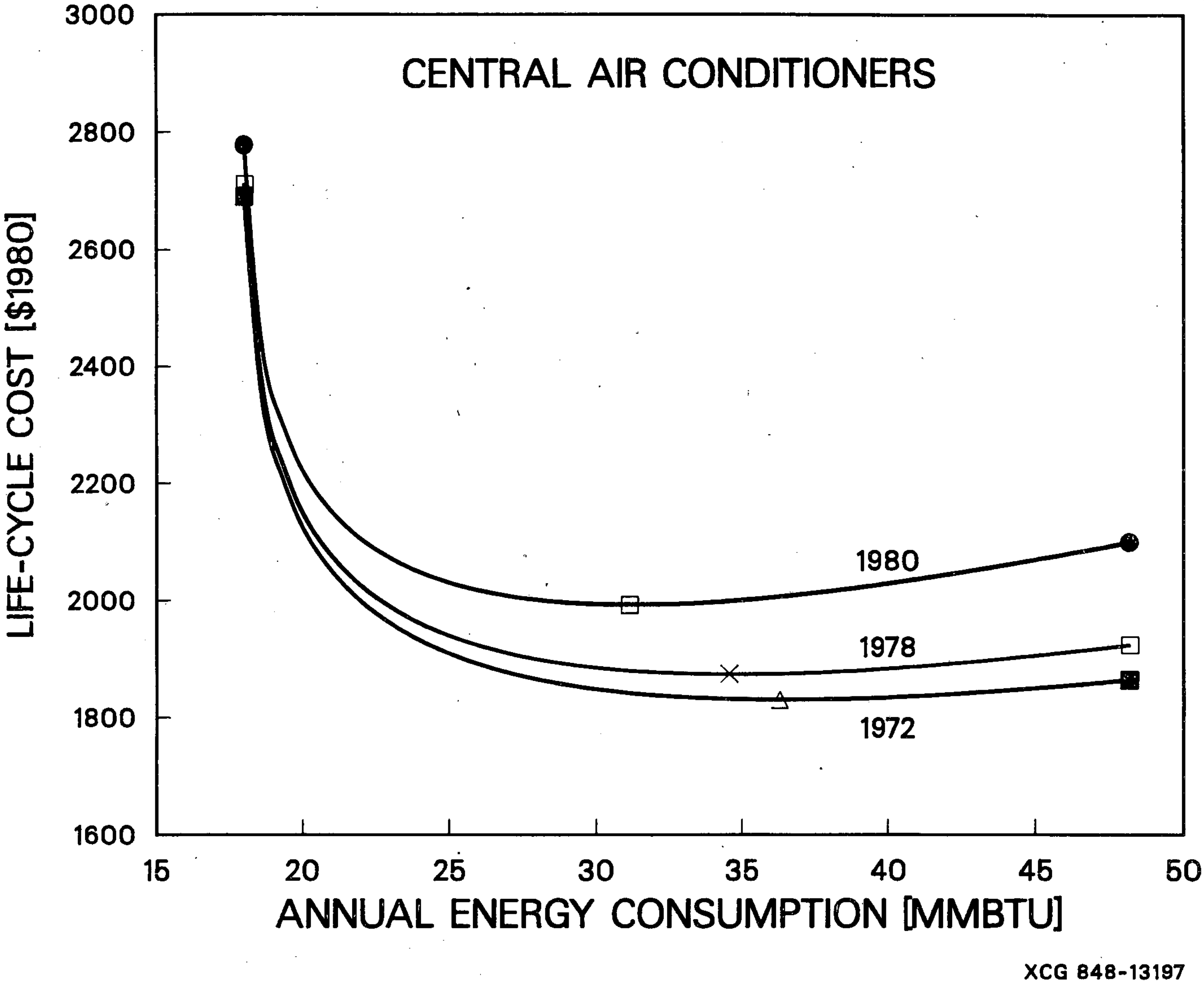

Figure 4. -- Life-Cycle Costs for Central Air Conditioners

Table 5. -- Aggregate Market Discount Rates for Appliances, 1972-80
Based on ADL Cost-Efficiency Curves

Appliance	1972	1978	1980
Gas Central Space Heater	39	51	56
Oil Central Space Heater	52	78	127
Room Air Conditioner	20	22	19
Central Air Conditioner	19	25	18
Electric Water Heater	587	825	816
Gas Water Heater	91	146	166
Refrigerator	105	96	78
Freezer	379	307	270

Table 6. -- Payback Period in Years for Appliances, 1972-80
Based on ADL Cost-Efficiency Curves

Appliance	1972	1978	1980
Gas Central Space Heater	2.98	2.38	2.21
Oil Central Space Heater	2.33	1.70	1.18
Room Air Conditioner	5.11	4.77	5.25
Central Air Conditioner	4.96	4.16	5.18
Electric Water Heater	.48	.41	.41
Gas Water Heater	1.50	1.07	.98
Refrigerator	1.35	1.45	1.69
Freezer	.60	.67	.72

The second way of examining uncertainties in the discount rates is to see how sensitive they are to changes in annual energy use. Table 8 presents the results of calculating $\frac{dr}{dE}$ using Equations 12 through 14. The figures show the change in market discount rate for an increase in energy use of one million Btu per year. They indicate that the sensitivity is larger at high discount rates. The sensitivity increases with time as fuel prices increase.

It is our judgment that the uncertainty in the SWEFs is five percent or less. This uncertainty is not expected to contribute much to the uncertainty in the discount rate. The parameters of the cost-efficiency curve are less well known, perhaps within ten percent. Because of the fitting procedure, E_∞ may be too low, leading to a high discount rate. Future work on the cost

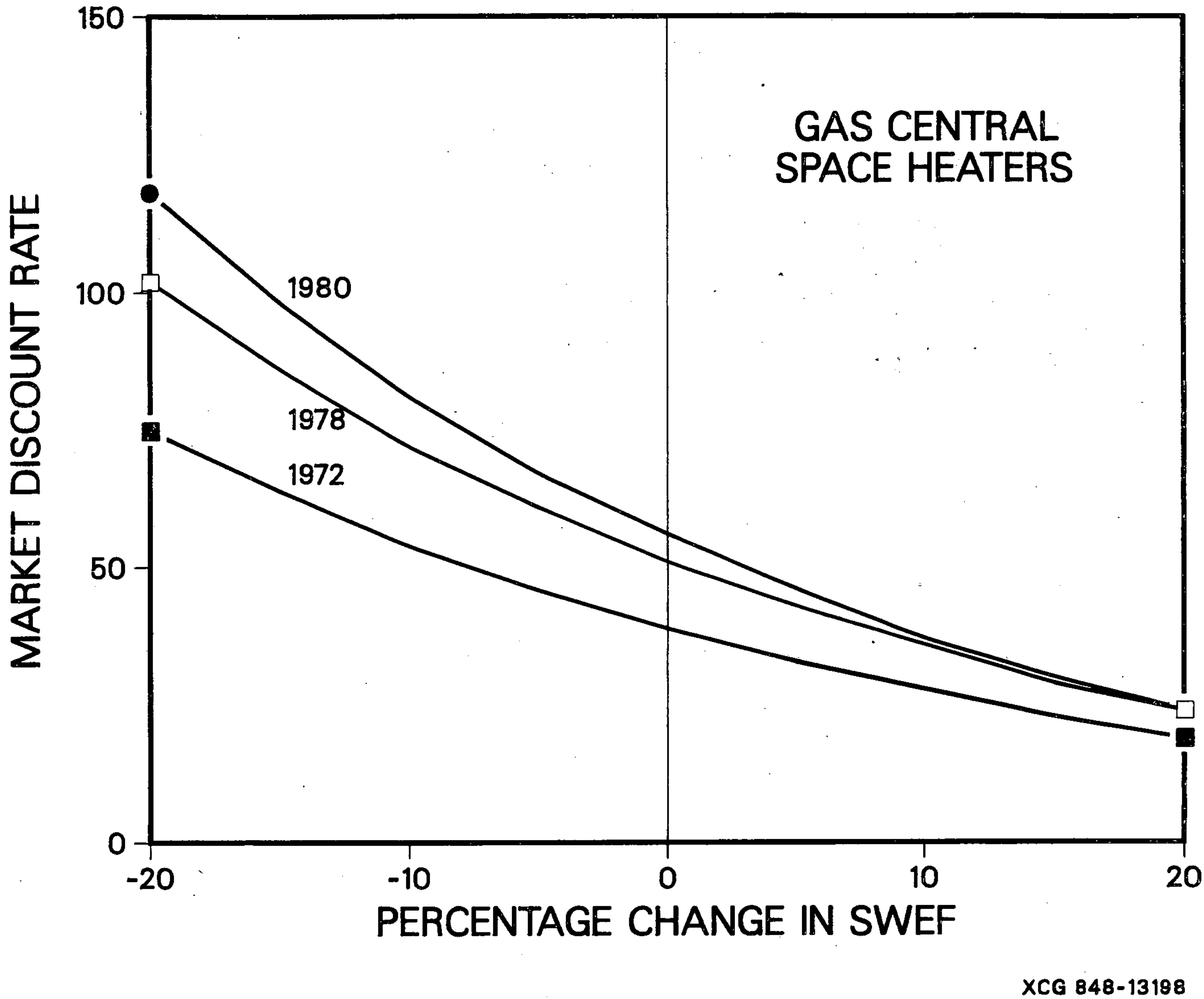

Figure 5. -- Effect of SWEF on Market Discount Rate Gas Central Space Heaters, 1972-80

Table 7. -- Sensitivity Analysis of Market Discount Rates
For Gas Central Space Heaters

Case	1972	1978	1980
Nominal Parameter Values	39	51	56
Increase E_∞ 10%	30	38	39
Decrease E_∞ 10%	47	62	69
Increase A 10%	44	57	63
Decrease A 10%	35	46	50
Increase PC 10%	35	46	50
Decrease PC 10%	44	57	63
Increase E_0 10%	44	57	63
Decrease E_0 10%	35	46	50
Increase SWEF 20%	19	24	24
Increase SWEF 15%	23	29	30
Increase SWEF 10%	28	36	37
Increase SWEF 5%	33	43	46
Decrease SWEF 5%	46	61	67
Decrease SWEF 10%	54	72	81
Decrease SWEF 15%	64	86	98
Decrease SWEF 20%	75	102	118

Table 8. -- Sensitivity of Market Discount Rates
Change in Discount Rate for a Million Btu Increase in Energy Use

Appliance	1972	1978	1980
Gas Central Space Heater	1.6	2.2	2.7
Oil Central Space Heater	2.2	3.8	7.3
Room Air Conditioner	4.6	5.9	6.1
Central Air Conditioner	1.6	2.0	2.1
Electric Water Heater	149.5	246.1	256.5
Gas Water Heater	12.3	22.6	30.7
Refrigerator	13.3	16.0	15.4
Freezer	64.6	69.9	67.2

and efficiency of the most efficient products should lead to better estimates of these parameters. We do not believe that the uncertainty will affect the observed change in discount rate over time.

In calculating the discount rates, we assume that purchasers do not anticipate any escalation in real fuel prices. This assumption may not be warranted, but it is a conservative one. Putting an assumed inflation rate for energy into the calculation would result in higher values for the observed discount rates. The new discount rates will be approximately the sum of the rates calculated without energy escalation plus the energy escalation rate.

Market discount rates were also calculated for refrigerators, freezers, gas furnaces, and room and central air conditioners using historical data on efficiencies from several sources. These results are summarized in Tables 9 through 13. Column 1 in these tables give the source of the SWEF data; column 2 gives the years for which data were used to construct the cost-efficiency curves. The discount rates presented in the subsequent columns show the same trends as the CS-179 data, although they differ in magnitude. For a given cost curve and year, differences in discount rates are due only to differences in reported SWEF. When the cost-efficiency curves are fitted to design options over a limited number of years, rather than for the period 1972-80, the slope of the curve changes because more recent design options have required extensive production line changes, so they do not fall on the same smooth curve as the earlier ones. Consequently, the payback periods and market discount rates can be different depending on which design options are included in the cost-efficiency curves.

The high discount rates observed in this study make it difficult to interpret them as the result of the operation of a rational market. If a consumer's discount rate is higher than the current interest rate and if prices reflect costs, a rational consumer would borrow money to purchase a more efficient appliance. The data, however, indicate that this does not occur. Except for air conditioners, higher efficiency in appliances is purchased only if it pays for itself in less than three years. We believe that these results indicate imperfections in the market that inhibit economically optimal decisions -- consumers may not have adequate information about appliance efficiencies or access to capital markets, the person purchasing the appliance may not be the one who uses it, the price of more efficient appliances may be determined by factors other than the cost of efficiency improvements, or high-efficiency appliances may not be produced in large quantities. Thus, any of the participants in the marketplace could contribute to the high discount rate. In the next section, we discuss these contributions in more detail and point out additional studies of market behavior that are needed to better understand appliance efficiency choice.

Table 9. -- Summary of Market Discount Rates for Gas Central Space Heaters

Data Source	Cost Curve	*Aggregate Market Discount Rate* 1972	1975	1976	1977	1978	1979	1980	1981
CS179	1972, 78, 80	39	--	--	--	51	--	56	--
Lennox	1972, 78, 80	--	38	41	45	46	50	53	53
Carrier	1972, 78, 80	--	41	--	--	47	50	53	55

Table 10. -- Summary of Market Discount Rates for Central Air Conditioners

Data Source	Cost Curve	*Aggregate Market Discount Rate* 1972	1975	1976	1977	1978	1979	1980	1981	1982
CS179	1972, 78, 80	19	--	--	--	25	--	18	--	--
Lennox	1972, 78, 80	--	34	27	26	25	22	24	19	16
ARI	1972, 78, 80	19	--	25	24	21	17	19	20	19
Lennox	1980	--	--	--	--	--	--	6	3	1
ARI	1980	--	--	--	--	--	--	3	4	3

Table 11. -- Summary of Market Discount Rates for Room Air Conditioners

Data Source	Cost Curve	*Aggregate Market Discount Rate* 1972	1978	1980	1981
CS179	1972, 78, 80	20	22	19	--
AHAM	1972, 78, 80	22	22	19	20

Table 12. -- Summary of Market Discount Rates for Refrigerators

Data Source	Cost Curve	*Aggregate Market Discount Rate* 1972	1978	1980	1981
CS179	1972, 78, 80	105	96	78	--
AHAM	1972, 78, 80	127	101	82	73
CS179	1978, 80	--	286	221	--
AHAM	1978, 80	--	308	237	201
CS179	1980	--	200	153	--
AHAM	1980	--	216	164	138
CS179	1980, 81	--	--	135	--
AHAM	1980, 81	--	--	144	121

Table 13. -- Summary of Market Discount Rates for Freezers

Data Source	Cost Curve	*Aggregate Market Discount Rate* 1972	1978	1980	1981
CS179	1972, 78, 80	379	307	270	--
AHAM	1972, 78, 80	285	205	165	157
CS179	1980	--	--	118	--
AHAM	1980	--	--	117	116

INTERPRETATION OF OBSERVED DISCOUNT RATES

Several generalizations can be made from the basic results summarized in Tables 5 and 6: (1) the values of the aggregate market discount rate are high (between 40 and 825 percent per year) with the exception of room and central air conditioners (which are about 20 percent); (2) the payback periods and aggregate market discount rates appear to be relatively constant over time, with rates for some products (space and water heating) increasing somewhat over the past decade and rates for others (freezers and refrigerators) decreasing over the same time period, when similar assumptions are made for each of the years; and (3) the sensitivity analyses show considerable changes in results as inputs are varied. This large variation combined with other limitations of the analysis suggests that considerable care must be used in discussing the numerical results; however, we believe the first two observations are meaningful in a qualitative sense. We now discuss these three observations in some detail.

(1) *High Values of Aggregate Market Discount Rate*

Overall, the high values of the aggregate market discount rates in Table 5 indicate that the average appliance or heating and cooling system purchased does not include some energy efficiency measures that yield very high returns on investment. For example, an investment of $21 to include increased door insulation, a higher compressor efficiency, a double door gasket, and an anti-sweat heater switch in a refrigerator would save $22/year at 1980 fuel prices, an annualized rate of return of 175 percent on the investment. Yet the average refrigerator purchased in 1980 did not have these features. For those appliances with aggregate discount rates higher than 100 percent (freezers, electric water heaters) some efficiency measures which pay for themselves in less than one year were not included in the average product purchased in 1980.

Discount rates have also been derived implicitly from a discrete choice model of household decisions to install space heating and cooling systems in new residences. The decision depends on the capital and operating costs of the system as well as other factors. The discount rate is not calculated explicitly, but is defined as the ratio of the estimated capital to operating cost coefficients in the model. Goett and Earl (1982), in an analysis of national data for single-family dwellings, find an implicit discount rate of 21 percent for space heating equipment with central air conditioning and 4.4 percent without central air conditioning. For central air conditioning systems alone, their implicit discount rate is 3.4 percent. Berkovec, *et al* (1983), estimating a similar model on data from the Pacific Northwest, derive an implicit discount rate of 25 percent for the space heating system choice.

It is important to recognize that the implicit discount rates derived from the analysis of fuel choice decisions relate to a different decision from the choice of energy efficiency. In particular, the discrete choice models that have been estimated up to now do not include efficiency as an explicit variable. Like our model, they calculate a discount rate from the tradeoff between purchase and operating costs, but an efficiency is assumed in calculating these costs. Dummy variables are included in the models to account for fuel and equipment preferences, so that a single discount rate is calculated for each end use. In short, the low implicit discount rates associated with fuel choice -- while relating to some of the same decision factors in the choice of energy efficiency of appliances -- does not, in our judgment, lead one to doubt the high market discount rates we have calculated for efficiency choice.

For all products other than air conditioners (where our results and those of others show lower values of the discount rate), our aggregate discount rates are greater than expected from previous studies of residential energy conservation measures. For example, Levine and Scott (1983) report values in the range of 15 to 40 percent real for aggregate market discount rates associated with investments in thermal integrity (ceiling and wall insulation and multiple glazings) in new houses. In spite of the research (on air conditioners and thermal integrity) which found lower values of discount rates, our review of the literature has identified no low estimates for large energy using residential products other than air conditioners. The only other residential consumer product for which estimates of discount rates can be found in the literature is the refrigerator, for which consumer discount rate estimates range from about 50 to 300 percent (Gately, 1980; Meier and Whittier, 1982).

Aggregate market discount rates in the range of 20 to more than 800 percent are surprising and noteworthy. They mean that the market is foregoing the possibility of receiving a return of 20 to over 800 percent on a small additional investments. An average purchase of a new refrigerator could, as we have noted save $22 per year (increasing each year if the real price of electricity escalates) for a one-time extra investment of $21. Similarly, the purchase of other appliances and heating equipment could achieve large returns on small investments. Few investors would turn down such high returns. This situation is even more striking since a purchaser, who can afford or can borrow enough to pay for a new product, could undoubtably borrow additional money at 15 to 20 percent nominal (from the retail store or a credit card) on which he or she receives a return of more than 100 percent real.

Several explanations of underinvestment in energy efficiency in the residential sector can be found in the literature. (For a discussion of this subject, see Levine and Craig (1982).) These explanations include:

(1) Purchasers lack information about costs and benefits of energy efficiency improvements or may not understand how to use this information if it is available;

(2) Purchasers may not have sufficient capital to acquire funds to purchase more energy-efficient products;

(3) Purchasers may have a threshold below which savings may not be significant or worth the additional effort to obtain.

(4) The prevalence of indirect or forced purchase decisions (e.g., landlord purchase of equipment for rental property; need for immediate replacement of malfunctioning equipment);

(5) The most efficient efficiency equipment may not be available in retail stores or may be available only with other features (so-called "gold-plating") that may not be desired by most purchasers;

(6) Manufacturer's decisions to improve product efficiency are often secondary to other design changes and take several years to implement;

(7) Marketing strategies by manufacturer or retailer intentionally lead to sales of less efficient equipment.

Lack of information

The energy labeling required on all new major appliances by the Federal Trade Commission since 1980 would be expected to make a difference in efficiency of these products if the first explanation were likely. Incomplete data for 1981 do not show any significant reduction in the aggregate market discount rate for these products, but it is probably too early to discern a trend in this direction. Thus, while the FTC energy labeling program may change the efficiency choice decisions in the future, the evidence is not yet available to show effects of the program. If the second part of the first explanation is correct -- i.e., if purchasers fundamentally do not understand the costs and the benefits of increased energy efficiency -- then the FTC labeling program alone is not sufficient to change the purchase patterns of appliance purchasers.

Lack of access to capital markets

Lack of capital may prevent or discourage many persons from purchasing more efficient appliances and heating and cooling equipment. This is most likely to be a problem in the purchase of more efficient furnaces and air conditioners, where the incremental cost of higher efficiency units runs into the hundreds of dollars. This problem is best conceptualized by recognizing that the higher cost of more efficient equipment combined with the uncertain knowledge of the benefits of higher efficiency result in a situation in which many purchasers are inclined to buy the lowest cost appliance that meets his or her requirements. For individuals who are otherwise short of money but need to make a purchase, the higher cost of more efficient units may preclude their purchase, even in those cases in which the purchaser realizes the short payback of more efficient units.

Purchaser Thresholds

According to some theories of consumer behavior, purchasers do not perceive or act upon small differences in price. The analogous behavior for purchasers of energy-using appliances is to ignore small differences in operating costs. Efficiency improvements to water heaters, refrigerators, and freezers would result in savings in operating costs to the average consumer of $20 - $40 per year. Expected future savings of this size may not be large enough to be considered consumer decisions. A threshold behavior of this sort would explain the relatively high discount rates for these appliances. However, efficiency improvements for air conditioners show similar cost savings, but their discount rates are about 20 percent. Thus threshold behavior is not the only explanation of high discount rates.

A related purchaser threshold may be due to the "transaction costs" of obtaining a more efficient appliance. If the high-efficiency models are not widely stocked by dealers, the additional time and effort required to locate and purchase them may be a barrier to their purchase. In effect, these "transaction costs" add to the purchase cost of the more efficient models. We expect that this effect would be more pronounced for appliances with relatively low purchase costs such as refrigerators, freezers, and water heaters. Although these appliances show high discount rates, so do gas and oil furnaces which have the highest purchase costs. Room and central air conditioners both have low discount rates, but there are large differences in their purchase costs. The importance of "transaction costs" depend on whether the purchase is made by an individual or by a volume purchaser such as a builder. Data on efficiency choice by class of consumer would be useful in determining the effect of purchaser thresholds on market behavior.

Indirect purchase decisions

The fourth explanation -- large percentage of indirect or forced purchase decisions -- receives support from Reid (1980) who estimates that as many as 50 percent of purchase decisions are made by consumers who are likely to be weakly motivated to invest in energy efficiency and about 37 percent who are likely to be insensitive to energy savings. This leaves less than 15 percent who might be expected to be fully responsive to cost-effective energy savings resulting from the purchase of more efficient equipment. More detailed studies of homeowner buying patterns for central heating systems, refrigerators, water heaters, and room air conditioners by Reid (1982) show that homeowners do in fact purchase features that increase the energy efficiency of products. For all of these products except room air conditioners, appliances possessed by home owners had between 50 and 100 percent more energy efficiency features than were installed in rental units. Interestingly, the occurrence of energy saving features correlated with home ownership but not with other variables such as family income. This suggests that the purchase decisions for the renter segment of the market does have a significant affect on the efficiency of appliances purchased (with the exception of room air conditioners, as noted). However, correcting for the purchases of less efficient equipment for the rental market segment still leaves a higher discount rate for most products (other than air conditioners) than anticipated before undertaking this work.

"Gold-plating"

The fifth possible explanation for the high aggregate market discount rates was unavailability of highly efficient units or "gold-plating" of the most efficient unit. The data showing distribution of sales by energy efficiency illustrate that for most products a range of efficiencies is widely available in the market. These figures also show that the highly efficient units are not yet manufactured in large volume, so that many consumers are effectively precluded from the highest efficiency range. This is expected, however, since these units are new models just starting to penetrate the market.

The important point is that there is a large choice of efficiencies of most products available in the marketplace. (We have not investigated the regional distribution of product sales to determine if a full range of efficiencies is available throughout the nation. California, which is a large market, has eliminated the least efficient appliances from the market through its appliance standards. However, we consider it unlikely that most consumers would not have available a reasonable portion of the range of efficiencies -- at least the middle half of the distribution -- available nationally.) This means that unavailability *per se* is probably not a large contributor to the high discount rate.

The issue of "gold-plating" of energy efficient units provides an indirect limitation on availability. That is to say, if the most efficient products are only available with numerous extra features that raise the purchase price and are not desired by a large majority of purchasers, then consumers are considerably less likely to purchase energy efficient products. Unlike the case of automobiles, in which the most fuel efficient autos tend to be those with the fewest frills (in part because of the relationship between weight and fuel economy), the most efficient appliances may tend to be top of the line models.

This explanation may provide some insight into the lower aggregate discount rates associated with the purchase decision for room and central air conditioners. Room and central air conditioners have very few frills. Their cost of manufacture is roughly proportional to their weight. Because advanced compressor design is not yet available in the mass market, the weight is also proportional to energy efficiency. (Increased weight means a larger heat exchanger which means higher efficiency.) Thus, to the extent that price of air conditioners in retail outlets is directly related to cost (as is likely for this product), the consumer can choose to pay more for the more efficient units without having to sort out the value of other features.

We have collected empirical evidence related to the ″gold-plating″ hypothesis for three products that are sold with many features: refrigerators, freezers, and ovens. The efficiency versus cost of the three most popular classes of automatic defrost refrigerators indicated the less efficient models cost more. This decrease in efficiency with higher cost is dictated by technical design considerations. Our results for freezers are similar, although they are less clear cut because there is less difference in energy consumption among models. Consumers prefer to purchase more convenient, higher priced models which are less efficient. Standard and self-cleaning electric ovens have comparable SWEFs and efficiency distributions. The larger capacity, higher priced gas and electric ovens have lower efficiencies than smaller models.

The consumer products we have investigated do not provide evidence that supports the hypothesis that additional features must be purchased to acquire high-efficiency appliances. Rather, price appears to be correlated with the cost of technical design options to provide the consumer with additional conveniences. We conclude that the ″gold plating″ hypothesis has not been proven.

Manufacturer's decisions

Another possible explanation is that although the industry is competitive for existing models, there is little competition among manufacturers to introduce innovative design changes. Design changes usually arise from attempts to reduce production costs or improve product reliability rather than from market demand for high-efficiency products. The cost of design changes to incorporate energy-conserving features is a small fraction of the overall cost of the product. Incorporating these changes is often incidental to the major design changes made for other reasons. Usually, one manufacturer will introduce a more efficient model (e.g. Lennox's pulse-combustion furnace), and the other manufacturers will follow if it is successful enough to threaten their market share.

Once the design changes have been decided upon, manufacturers require up to two years to implement them. The lead times are needed for engineering design, tooling design, and tooling manufacture or purchase. Simple changes, such as replacing an existing component with a more efficient one, could take as little as six months if it were available from a supplier. DOE (DOE, 1980) estimates that major changes to incorporate energy-conserving design options require lead times of 18 to 24 months for a single model and even longer for an entire product line. As discussed above, changes to improve efficiency are a minor part of the effort to upgrade a production line. Hence a typical cycle for introducing new appliance models can be three or more years. Unless the manufacturer can anticipate changes in energy prices, the design will not be the optimal one when it is finally produced. In times of rapidly increasing fuel prices, such long delays appear to distort the market and lead to high discount rates.

This raises the question of timing and anticipation of future market conditions in calculating market discount rates. The design of the models that are sold in today's market took place several years ago when fuel prices may have been substantially lower. Unless manufacturers are able to anticipate the higher fuel prices, the design options available in the market may not be appropriate. The high discount rates we observe may be the result of lags in adjusting to higher prices. To test this hypothesis, we calculated the 1980 discount rates using 1978 energy prices. The discount rate for oil furnaces were 50 percent lower (65 vs. 127 percent per year), for gas appliances 25 percent lower, and for electrical appliances 5 to 10 percent lower. These results show an inverse relationship between the change in discount rate and the increase in energy price between 1978 and 1980, exactly what one would expect if manufacturers do not anticipate future energy price increases. Even correcting for the time lag the market discount rates are high. We believe that lags are not the complete explanation of the rates we observe.

Marketing strategies

The final possible explanation concerned marketing and pricing decisions. Because full information on the price of different models is not available, this explanation cannot be tested at this time. However, the ″gold-plating″ phenomenon discussed above is, in essence, a potential pricing and marketing strategy; additional information may reveal other facets of the chain between the manufacturer, wholesaler, and retailer that influence the purchase decisions on appliances.

(2) *Constancy of the Aggregate Market Discount Rate over Time*

A significant finding from Tables 5 and 6 is that the payback periods and discount rates have changed only modestly. (The relatively small change in the aggregate discount rates over time for each of the products is not highly sensitive to the absolute values of the discount rates. Thus, as new and better data become available, some of the numbers may change but the time trends are likely to change little.) We are aware of no previous work that has investigated the behavior of the market for energy efficiency in residential appliances over time. This work indicates that the behavior of the market for energy efficiency has been relatively unchanged from 1972 to 1980, in spite of the large changes in awareness of energy issues and the rapid increase in residential energy prices over this period. This is similar to the results for investment in thermal integrity in houses obtained by Levine and Scott, and the reader is referred to that paper for a more complete discussion of this finding. The basic point is that the market for appliances appears to have many underlying features that are not easily subject to change.

(3) *High Sensitivity of Results to Inputs*

Table 7 and Figure 5 show considerable sensitivity of the results to input data and assumptions. A small change in the estimated shipment-weighted energy factors or other parameters can cause the estimated aggregate discount rate to change by a relatively large amount. This high sensitivity of results to input is intrinsic to the calculation, in part because for many products small investments in energy efficiency improvements can yield rather large paybacks. Better data and further analysis can refine the numbers and increase their accuracy somewhat; however, small uncertainties in data will continue to exist and cause relatively large uncertainty in the absolute value of the estimated aggregate market discount rate.

Although it is possible to improve the data and obtain more accurate results, we do not believe that these will alter our basic conclusion. While there may be uncertainty of ± 50 percent (or possibly more for some products) in the estimates of the aggregate discount rates, the values obtained lead to an unambiguous conclusion that a large number of cost-effective energy efficiency measures are not currently achieving market penetration. One may be uncertain about whether the aggregate discount rate for refrigerators is 50 percent or 100 percent; but in either case, there are significant investments in energy efficiency with high returns that are not, on average, being made.

If the prices of appliances do not accurately reflect the cost of increased efficiency, then the resulting distortion in the marketplace may be evidenced by high discount rates. Price and efficiency may be confounded because of other features that must be purchased to obtain efficient units. If this is the case, then this affects the interpretation of the results rather than the results themselves. The relatively low aggregate discount rates for air conditioners, where other features are not available, combined with the much higher aggregate discount rates for the other products, tend to suggest that the consumers would choose more efficient products if they could. This explanation, if accurate, is a very subtle type of market failure and one different from the authors' original expectations. More work needs to be done to estimate the degree to which ″gold-plating″ has influenced market decisions and the degree to which other phenomena -- the large renter market segment, inadequate information, manufacturers' decisions -- have also resulted in aggregate decisions that result in reduced sales of energy efficient equipment.

CONCLUSIONS

The basic conclusions of the research to date are

(1) The energy efficiency of residential equipment purchased during the period 1972-80 appears to be significantly less than required to achieve cost effective levels of efficiency.

(2) This underinvestment in efficiency is reflected in an aggregate market discount rate that is greater than 40 percent for most products and exceeds 800 percent for one product.

(3) Room and central air conditioners are an exception to these conclusions, showing real aggregate market discount rates of about 20 percent.

(4) To the extent that the aggregate market discount rates estimated in this work are accurate measures of market performance, there has been little change in aggregate energy efficiency decisions for residential equipment during the 1970's (1972-1980).

(5) Our interpretation of the "failure" of the market to achieve cost effective levels of energy efficiency in the sales of residential equipment includes:

- the likelihood that consumers are not able to purchase energy efficiency features because manufacturers have not improved their products in a timely manner;
- the fact that a large segment of the market is interested in rapid purchases (to replace failures) or minimizing first cost (e.g., the rental market) and do not seek out cost-effective levels of efficiency;
- The possibility that the savings are not large enough to be significant to many purchasers or worth the additional effort to obtain;
- the possibility that many purchasers may not have access to the additional capital needed to acquire more efficient products;
- the possibility that reliable information is either not fully available or not effectively used to evaluate the costs and benefits of energy efficiency measures;
- the possibility that manufacturer, distributor, and retailer pricing and marketing policies and procedures may also have important effects on the market for energy efficient residential equipment.

(6) It does *not* appear that consumers are required to purchase expensive "luxury" features to acquire energy-efficient products.

The various reasons for underinvestment in energy efficiency listed above have different policy implications. An effective labeling program or a widespread advertising campaign by manufacturers and utilities to demonstrate the benefits of energy efficient products would increase consumer information and possibly lower their thresholds. Utility rebate programs could be effective if consumers lack access to capital markets or if pricing policies such as "gold plating" increase the cost of efficient appliances. Efficiency standards (or the threat of standards) would impel manufacturers to produce more high-efficiency products. Hence they would be effective when consumer thresholds, forced purchase decisions, or lack of information are important factors. However, standards which raise first costs may not be useful if purchasers do not have access to the extra capital required for added efficiency. Purchasers of replacement appliances may decide to do without, repair their existing equipment, or buy used appliances that would otherwise be scrapped.

Notwithstanding these conclusions, there are considerable areas of uncertainty. To forecast efficiency choices in the absence of standards and to place greater reliance on the quantitative results (in Table 4), research in the following areas is needed:

(1) Assessment of the relationship between appliance price (rather than cost plus markup) and energy efficiency.

(2) Quantitative analysis of the investment decisions of the various classes of purchasers, including additional research on appliances purchased for the rental market.

(3) Differentiation of the roles of manufacturers, distributors, retailers, and consumers as factors that cause high market discount rates.

(4) Consideration of parameters other than aggregate market discount rates as indicators of market behavior in the sales of energy efficiency in appliances.

(5) Additional research on air conditioners (especially in different regions with large variations in usage patterns) to gain better knowledge of the mechanisms at work in the purchase of these products that lead to lower discount rates.

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