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The ORNL Engineering-Economic Model of Residential Energy Use

Eric Hirst
Janet Carney

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THE ORNL ENGINEERING-ECONOMIC MODEL OF RESIDENTIAL ENERGY USE

Eric Hirst
Janet Carney

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ABSTRACT

The ORNL residential energy use model was developed to simulate energy use in the residential sector from 1970 through 2000. The model provides considerable detail on annual energy uses by fuel, end use, and housing type; and also estimates annual equipment installations and ownership, equipment energy requirements, structure thermal performance, fuel expenditures, equipment costs, and costs for improving thermal performance of new and existing housing units. Thus, the model provides considerable detail on residential energy uses and associated costs. These details are useful for evaluating alternative energy conservation policies, programs, and technologies for their energy and economic effects during the next quarter century.

The present version of the model deals with four fuels, eight end uses, and three housing types. Each of these fuel use components is calculated each year as a function of stocks of occupied housing units and new construction, average housing size, equipment ownership by fuel and end use, thermal performance of housing units, average unit energy requirements for each equipment type, and usage factors that reflect household behavior.

Simulations of energy use from 1960 to 1976 show that the model accurately predicts historical data on aggregate energy use, energy use by fuel, energy use by end use, and equipment ownership market shares.

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THE ORNL ENGINEERING-ECONOMIC MODEL OF RESIDENTIAL ENERGY USE

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1. INTRODUCTION

This report describes the structure, inputs, validation, and operation of the ORNL residential energy use model. The purpose of this work is to provide an analytical tool to evaluate a variety of energy conservation policies, programs, and technologies for their effects on energy use, energy costs, and capital costs over time.

The model deals with annual energy use for four fuels* (electricity, gas, oil, other); eight end uses (space heating, air conditioning, water heating, refrigeration, food freezing, cooking, lighting, other); three housing types (single-family, multi-family, mobile homes); and two housing states (new, existing). Household energy use for each component is computed in response to changes in: stocks of occupied housing units and new residential construction, equipment ownership by fuel and end use, size and thermal performance of housing units, average unit energy requirements for each type of equipment, and usage factors that reflect household behavior.

The model simulates annual energy use for each year from 1970 through 2000. Thus, a simulation involves the calculation of 5,760 (30 years x 192) fuel use components. The model also calculates, at the same level of detail, information on new equipment installations, equipment ownership, new and average equipment efficiencies, new and average structure thermal

*Electricity use figures are in terms of primary energy (11,500 Btu/kwhr or 3.37 J/J from 1970-2000); that is they include losses in generation, transmission, and distribution. Figures for gas and oil, however, do not include losses associated with refining and transportation.

performance, usage factors; and annual expenditures on fuels, improved equipment, and thermal improvements to new and existing structures.

This report deals with our national energy model. We also developed regional residential energy use input data so that we can operate the model for each of the ten Federal regions and for each of the nine U.S. Bureau of the Census divisions.[1]

Figure 1 is a schematic diagram of the energy model. The demographics submodel (Section 2) calculates stocks of occupied housing units by type for each year of the simulation. Based on calculations of household formation and retirements from the existing stock of occupied housing units, new construction requirements are calculated for each year to

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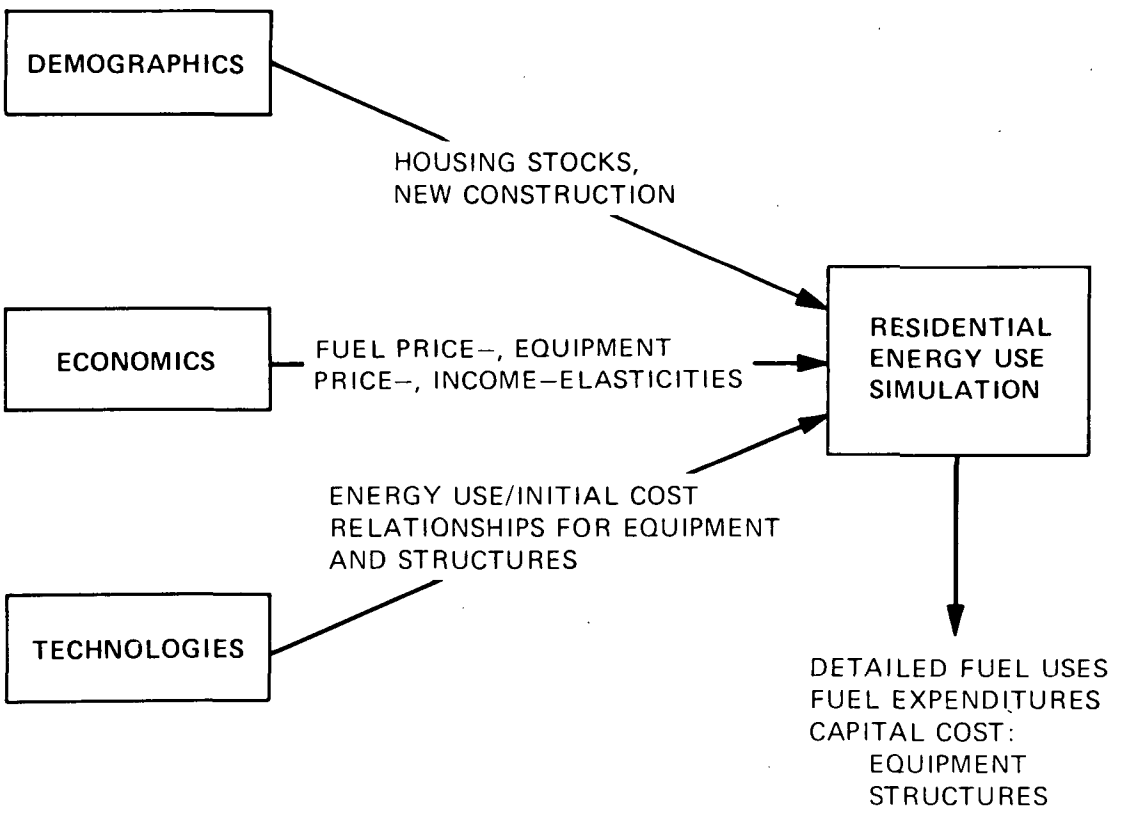

Fig. 1. Schematic of ORNL residential energy use model.

ensure that the stock of occupied housing units matches demand (the number of households that year).

The technologies submodels (Section 3) evaluate changes in equipment energy requirements and purchase price as functions of alternative designs. Detailed engineering submodels were constructed for electric, gas, and oil space heating systems; gas and electric water heaters; refrigerators; and gas and electric ranges. We synthesized data from a number of sources to infer relationships between equipment energy use and initial cost for the other end uses. In a similar fashion, we evaluated changes in thermal performance for new and existing structures as functions of increased capital cost for each housing type.

The economic submodels (Section 4) calculate elasticities that determine the responsiveness of households to changes in economic variables: incomes, fuel prices, equipment prices. Elasticities are calculated for each of the three major household fuels for each of the eight end uses. Each fuel price and income elasticity is decomposed into three components: equipment ownership, equipment and structure efficiencies, and equipment usage. The first gives changes in equipment fuel choice (market share) in response to changes in fuel prices, equipment prices, and incomes. The second gives changes in equipment and structure efficiencies, and the third gives changes in household usage of equipment (holding ownership and efficiencies constant).

Our market penetration methodology is described in section 5. This part of the model calculates changes in new equipment efficiencies and new structure thermal performance over time. These changes are functions of consumer behavior (Section 4), available technologies (Section 3), and time.

Section 6 describes the operation of the overall simulation model. Basically, the simulation model combines outputs from the various submodels (Fig. 1) with appropriate initial conditions for 1970 and boundary conditions (policy variables) for the 1970-2000 period. Outputs from the simulation model include 192 fuel use components for each year.* Each fuel use component is determined in the simulation program as the product of six factors: housing stock, housing size, equipment fuel choice (market share), equipment energy requirement, structure thermal performance, and usage.

Section 7 compares model predictions with historical data from 1960 through 1976. Model predictions are compared with data for each fuel and for equipment ownership market-shares in 1970 and 1975. Finally, distributions of fuel by end use for 1970 and 1975 from the model are compared with independent estimates.

Section 8 presents two projections of residential energy use to the year 2000. Independent estimates of fuel prices and incomes are used as inputs to the model. Two sets of assumptions concerning technical improvements in equipment and structures are postulated. The energy and economic costs of these projections are compared.

Section 9 discusses uncertainties inherent in the development and application of simulation models. Rough estimates of uncertainties in parameter estimates are used to develop "upper" and "lower" bounds on the projections developed in Section 8.

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*Eighty-four of these 192 cells are empty; for example, oil-fired refrigerators.

The final section summarizes the key features of the present model, discusses additional efforts underway to further improve the model, and lists some of the applications of the model for our sponsor, the Department of Energy.

Thus, Sections 2-4 describe the submodels that provide inputs to the simulation model. The following sections discuss the residential energy use simulation model in terms of its structure, operation, ability to match historical data, and typical results.

Table 1 summarizes the key features of our model. Because of these features the model is useful for evaluating various conservation policies, programs, and technologies. As examples, model outputs can be used to evaluate: appliance efficiency standards, thermal standards for new residential construction, alternative fuel price strategies, and financial incentives for retrofit of existing structures. For each of these policies and programs, model outputs include estimates of energy use changes by fuel and end use over time; in addition, outputs include changes in energy costs, capital costs for equipment, and costs for upgrading structure

Table 1. Key features of the ORNL residential energy use model

Explicit	Sensitive to demographic, economic, and technological determinants of energy uses
Simulation	Based on household behavior about equipment and structures purchases and uses
Dynamic	Incorporates time features of equipment and structures lifetimes and behavioral lags
Detailed	Calculates 192 fuel/end use/building type components for each year for energy, energy costs, and capital costs

thermal performance. These cost figures allow one to develop simple benefit/cost measures for each program.

The model can also be used to evaluate the effects of various energy conservation technologies, including R&D projects. For example, the model can estimate the market penetration and energy and economic effects of offering an improved space heating system to consumers (e.g., a gas-fired heat pump) by specifying the efficiency and capital cost characteristics of the new system.

Finally, the model produces projections of residential energy use that are both detailed and internally-consistent.

2. HOUSING

Figure 2 shows the structure of our housing submodel. The submodel first calculates headship rates* for each year from 1970 through 2000 for each of seven age groups: 15-24, 25-29, 30-34, 35-44, 45-54, 55-64, 65+. Headship rates are then multiplied by population estimates for each age group and year to determine the number of households. These households are then distributed among three mutually-exclusive housing types (single-family, multi-family, mobile homes). Next, the submodel calculates the number of housing units retired and net household formation each year; and from this the number of housing units constructed. Finally, the average size of new and existing housing units is calculated for each year. As shown in Fig. 2, these calculations are done for the nation as a whole and for each region (either the 10 Federal regions or the 9 Census divisions).

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*Headship rate is defined as household heads in age group i/population in age group i.

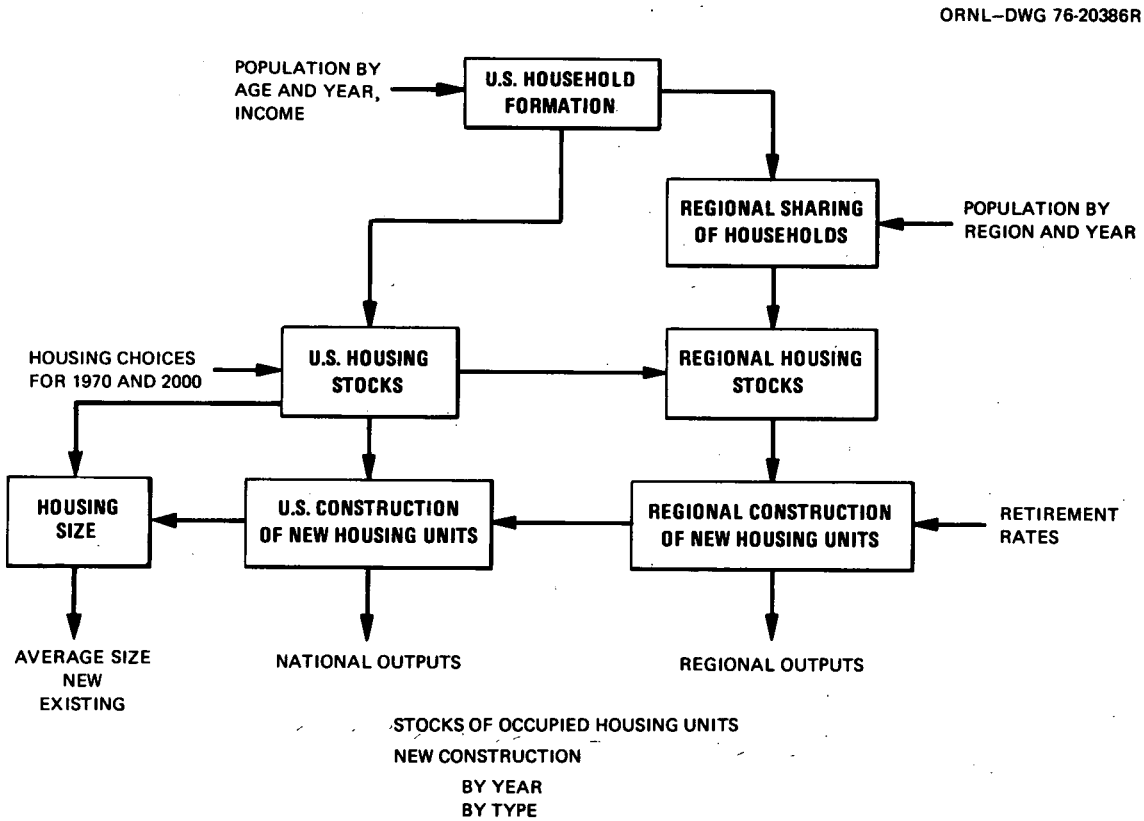

Fig. 2. Schematic of ORNL housing submodel.

Headship rates are assumed to be functions of age, family income, marital status, and last year's headship rate.* The form of the assumed relationship is:

$$\ln\left(\frac{HR_i}{U_i - HR_i}\right)_t = A_i + B_i Y_{it} + C_i SD_{it} + D_i M_{it} + E_i \ln\left(\frac{HR_i}{U_i - HR_1}\right)_{t-1}$$

where

A, B, C, D, E, are coefficients determined from the regression analysis,

---

*R.H. Goshorn developed the headship rate equations (and the housing size equation discussed later in this Section) during the Fall of 1977. Additional detail on this work are in Goshorn's unpublished report, a few copies of which are available from the authors.

HR_i is the headship rate for households in age group i,

U_i is the assumed upper limit on headship rate,

SD_i is the fraction of individuals in age group i who are separated or divorced,

M_i is the fraction of individuals in age group i who are married and living with their spouse,

Y_i is median family income (in constant dollars) for families in age group i,

t is the year of interest, t-1 is the preceding year.

These equations were estimated using data from 1952 through 1976. Data on population,[2] households, [3] family income,[4] and marital status[5] are all from the Bureau of the Census.

We used the logit formulation to ensure that HR remains between its predetermined lower and upper bounds (0.0 and U_i, respectively). The values for U_i from ref. 6 are based on estimates of the number of husband-wife households and the occurrence of other household types for each age group.

Several other independent variables were tested before adopting the set shown above. These include housing price, the ratio of housing price to income, unemployment rate, and fraction of individuals who are single in each age group. Regressions obtained with these variables gave consistently poor results.*

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*We also tested different functional forms for the headship rate equations: log-linear, log-log, and linear. We rejected the linear form because of our preference for the logit formulation. The log-linear model was adopted because it yielded slightly higher t-statistics than did the log-log formulation.

Table 2 shows the coefficient estimates for the seven age groups, obtained using ordinary least squares. Figures in parentheses are computed t-statistics. M is not used as an independent variable for the first five age groups and SD is not used for the last three. The coefficients of these terms in equations that included them had very low t-statistics. Their rejection can also be argued on demographic grounds.[6]

The coefficients for more than half the variables are significant at the 5% level. The R^2 values are also reasonably good. The Durbin K_2 statistic is shown for each equation. These values indicate that autocorrelation is not a problem in any of the equations. Use of the Durbin test must be qualified, however, because it is a large sample test.

Simulations were conducted with the headship rate equations to determine the elasticities of household formation with respect to the independent variables; see Table 3. Household income is a more important

Table 2. Estimated headship rate equations[a]
dependent variable: $ln\left(\frac{HR}{U - HR}\right)$

Age group	U[b]	Constant	Median family income	Fraction married	Fraction separated or divorced	Lagged dependent variable	R^2	D[c]
15-24	0.3	-1.030 (-3.4)	0.0000946 (3.4)	---	20.753 (2.73)	0.490 (3.15)	0.95	0.75
25-29	0.6	-0.497 (-2.93)	0.0001300 (3.2)	---	2.730 (1.39)	0.416 (2.42)	0.96	0.12
30-34	0.6	-0.00198 (0.02)	0.0000428 (1.43)	---	2.505 (1.25)	0.688 (4.37)	0.94	0.71
35-44	0.6	0.275 (1.78)	0.0000523 (1.62)	---	5.210 (1.94)	0.368 (1.25)	0.93	--[d]
45-54	0.6	0.714 (2.85)	0.0000390 (2.29)	---	--	0.488 (2.78)	0.74	1.50
55-64	0.6	-5.445 (-2.36)	0.0000950 (1.68)	9.352 (2.58)	--	0.314 (1.99)	0.88	0.48
over 65	0.7	2.274 (-3.63)	0.0000425 (5.40)	4.513 (3.27)	--	0.168 (1.14)	0.98	0.72

[a]All equations are estimated using ordinary least squares with data from 1952-1976 (24 observations). Figures in parentheses are estimated t-ratios.

[b]U is the assumed upper limit for headship in each equation.

[c]D is the Durbin K_2-statistic.

[d]The Durbin K_2-statistic cannot be calculated for this equation.

Table 3. Elasticities of household formation obtained with the ORNL housing model

	Elasticity with respect to:		
	Income per household	Separated or divorced	Married and living w/spouse
Short-run	0.08	0.03	0.07
Long-run	0.15	0.06	0.08

determinant of household formation than either of the demographic variables. The dynamics of response are different for each variable because the lagged coefficients are different for each age group (Table 2).

The national projection of households (identically equal to stock of occupied housing units) is next disaggregated for each of the nine Census divisions or ten Federal regions. In performing this disaggregation, we assume that each region's share of the nation's households exactly corresponds to that region's share of the nation's population. In 1970, the number of people per household was almost identical across regions. Population projections for each region are obtained from the Bureau of the Census and the Water Resources Council.[7]

Households in each region for each year are then shared among the three housing types on the basis of an assumed housing choice matrix (housing type for each age group) for the year 2000. Choices for each year are based on a linear interpolation between the known 1970 and assumed 2000 mix of housing types. The distributions of housing types for each region are different, based on the 1970 distributions.[8]

The number of new housing units constructed each year in each region is based on new households in each region and retirement of existing housing units (determined by retirement rates input to the model).*

Finally, the submodel calculates the average size of new housing units and of housing units in existence for each year. Ideally, this should include equations for each housing type; such comprehensive data are not available. Thus, calculations are performed only for single-family units.

The equation for new single-family homes sold was developed using data from 1969 through 1976 for the four Census Regions. The assumed relationship is:

$$ln\left(HS_{rt}\right) = A + B\ ln\left(Y_{rt}\right) + C\ ln\left(P_{rt}\right) + D\ ln\left(PPH_{rt}\right) + E\ ln\left(HS_{r,t-1}\right) + F \bullet NC + G \bullet S + H \bullet W$$

where

A, B, C, D, E, F, G, H are coefficients determined from the regression analysis,

HS_r is the average size of new single-family homes sold in region r,

Y_r is median family income (in constant dollars),

P_r is average price per square foot of new homes,

PPH_r is the average number of people per household,

NC, S, W are dummy variables for the northcentral, south, and west regions,

t is the year of interest, t-1 is the preceding year.

---

*For the 1975-2000 period, the assumed retirement rate for single-family and multi-family units is 0.7%/year; for mobile homes it is 4.0%/year (ref.9). These retirement rates are constant in our housing submodel, independent of economic factors such as incomes and heating fuel bills.

Housing size and price,[10] regional population and households,[3] and family income[11] are all from the Bureau of the Census.

Table 4 shows the coefficient estimates and t-statistics obtained with the least-squares-with-dummy-variable method, used to pool the time series/cross section data (28 observations). The coefficients are all significant at the 5% level. The Durbin K_2 statistic suggests that serially-correlated error terms is not a problem.*

Table 4. Estimated new housing size equation[a]
dependent variable: *ln*(average ft^2 of floor area)

Constant	Median family income	Average price per ft^2	Persons per household	Lagged dependent variable	NC	S	W	R^2
3.13	0.57	-0.37	-1.10	0.16	-0.035	0.048	-0.085	0.76
(1.32)	(2.72)	(-2.16)	(3.98)	(1.11)	(-2.05)	(1.10)	(-2.65)	

[a]The equation was estimated using the least-squares-with-dummy-variables method with data from 1969-1976 for the four Census Regions (28 observations). Figures in parentheses are estimated t-ratios.

The coefficients in Table 4 are short-run elasticities. Long-run elasticities are obtained by dividing the short-run values by 0.84 (1.0 minus the lagged coefficient). The long-run elasticity of average new single-family home size with respect to family income is 0.7; the long-run elasticity with respect to housing price is -0.4. The long-run elasticity with respect to persons per households (PPH) is -1.3.

This negative coefficient for PPH seems unlikely at first glance. However, as household size declines - holding income constant - house-

*Recall that the K_2 statistic is valid only for large sample sizes.

holds will have more discretionary income. Apparently this effect dominates the need for larger homes by larger households.*

We developed several projections of household growth, housing stocks, new construction, and housing size using our submodel plus different assumptions concerning income growth, marital status, housing prices, and housing choices in the year 2000. All our projections assume that population will grow according to the Census Series II projection.[12] Our reference projection of per capita income is derived from a Data Resources, Inc. (DRI) projection of GNP[13] and the Series II population projection. The average annual growth rate of real per capita income in this case is 2.4% between 1976 and 2000. For purposes of comparison, we also developed housing projections assuming that per capita income grows at 3.0 and 1.0%/year between 1976 and 2000. The DRI projection yields a value of per capita income in 2000 of $10,600 (1975-$). The 1% and 3% projections yield values of $7,700 and $12,300. Per capita income in 1976 was $6,050.

We made two different assumptions about the housing choice matrix for 2000. The first assumes that housing choices by age of household head remain at their 1970 values.[8] The second assumes that changes in

---

*Although the sign of this coefficient is acceptable, the magnitude of the elasticity is disturbingly high. A biased coefficient might be due to the fact that not all households live in single-family units; a decline in PPH might involve a shift from one housing type to another. Average family size might be a better variable because most single-family homes are occupied by families rather than by other types of households. In addition, the PPH variable may be picking up the effects of other variables not included in the analysis such as age of household head, household wealth, and urban versus rural location. Unfortunately, lack of an adequate data base prevents us from conducting further analysis of housing size. Because of these problems, we arbitrarily reduced the PPH coefficient from 1.1 to 0.9 for simulation.

housing choices that occurred between 1960 and 1970[8] continue linearly to the year 2000.

Between 1970 and 1976, the percentage of the adult population that was separated or divorced increased from less than 5% to almost 7%.[5] We assume that this percentage will continue increasing to the year 2000, but at a much slower rate (3% rather than 6%/year). We also assume that the fraction of individuals married and living with their spouse for the two oldest age groups will remain constant between 1976 and 2000, compared with an average growth of 1%/year between 1970 and 1976.[5] Finally, we assume that the real price of housing per square foot will increase at 1%/year, slightly less than the 1.4%/year rate from 1970 through 1976.[10]

Figure 3 shows our baseline projection of occupied housing units (households) with the DRI income assumption. The number of households

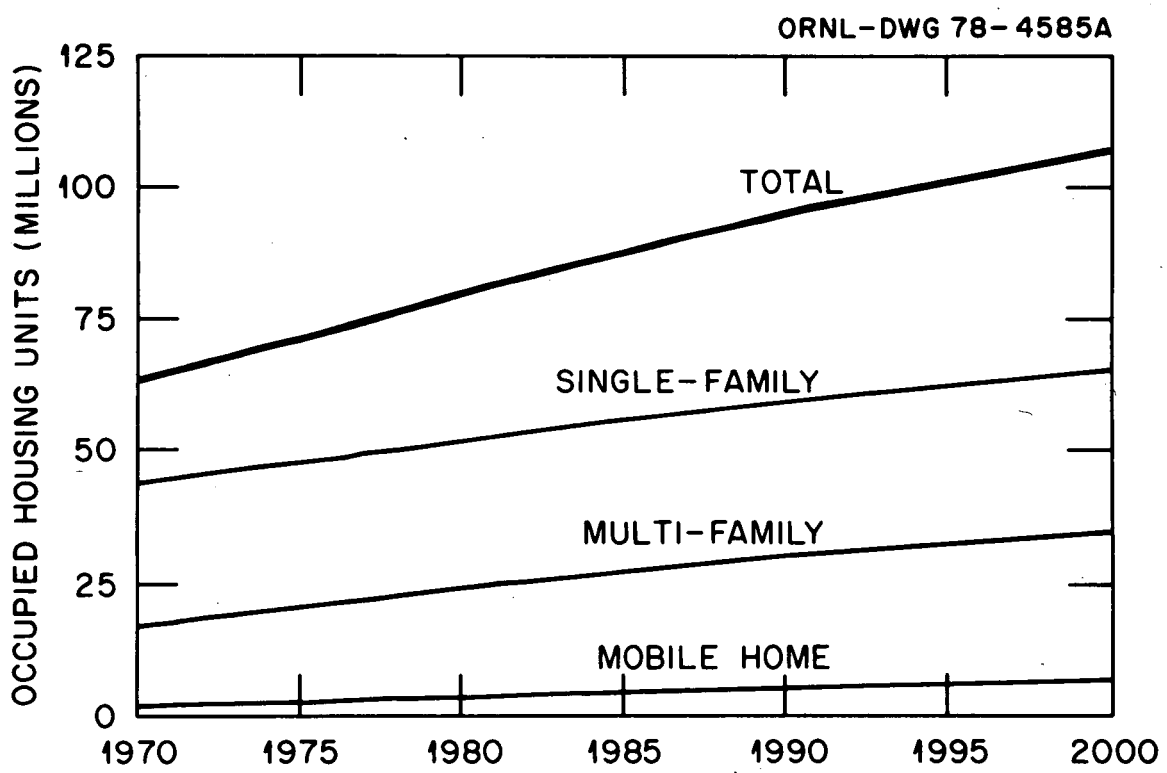

Fig. 3. Baseline projection of stocks of occupied housing units.

is projected to increase from 73 million in 1976 to 95 million in 1990 and 106 million in 2000, with an average growth rate of 1.6%/year. Single-family units continue to be the dominant housing type during the projection period.

Projections with the 3% and 1% income growths yield household estimates for 2000 only slightly different from the baseline: 108 and 104 million, respectively. The 3% projection is identical with the high Census projection for 1990; the 1% projection is slightly higher than the low Census projection for 1990.[14] These projections (and others not discussed) suggest that income, marital status, and the population's age structure all influence household formation.

Figure 4 shows projected distributions of housing choices over time using the two housing choice matrices for 2000 discussed above. We also show Census estimates of housing distributions for 1970, 1973, 1974 and 1975.[8,15] The shift away from single-family units that occurred between 1960 and 1970 is continuing. However, recent data show no change in multi-family occupancy rather than the increase expected from the 1960-70 trends. Finally, recent data show a more rapid shift to mobile homes than the 1960-70 trend indicates. The two housing choice matrices assumed for 2000 (Fig. 4) seem to cover the range of likely housing distributions between 1970 and 2000.

Figure 5 shows growth in average size of new single-family units assuming that the average price per ft^2 of new units increases at average annual rates of 0%, 1%, and 2% between 1976 and 2000. New housing size in the year 2000 ranges from 2,050 ft^2 to 2,540 ft^2 (24% range), compared with 1,710 ft^2 in 1976.[10] The effect on <u>existing</u> housing units in 2000 is much less: a range in size of only 6%.

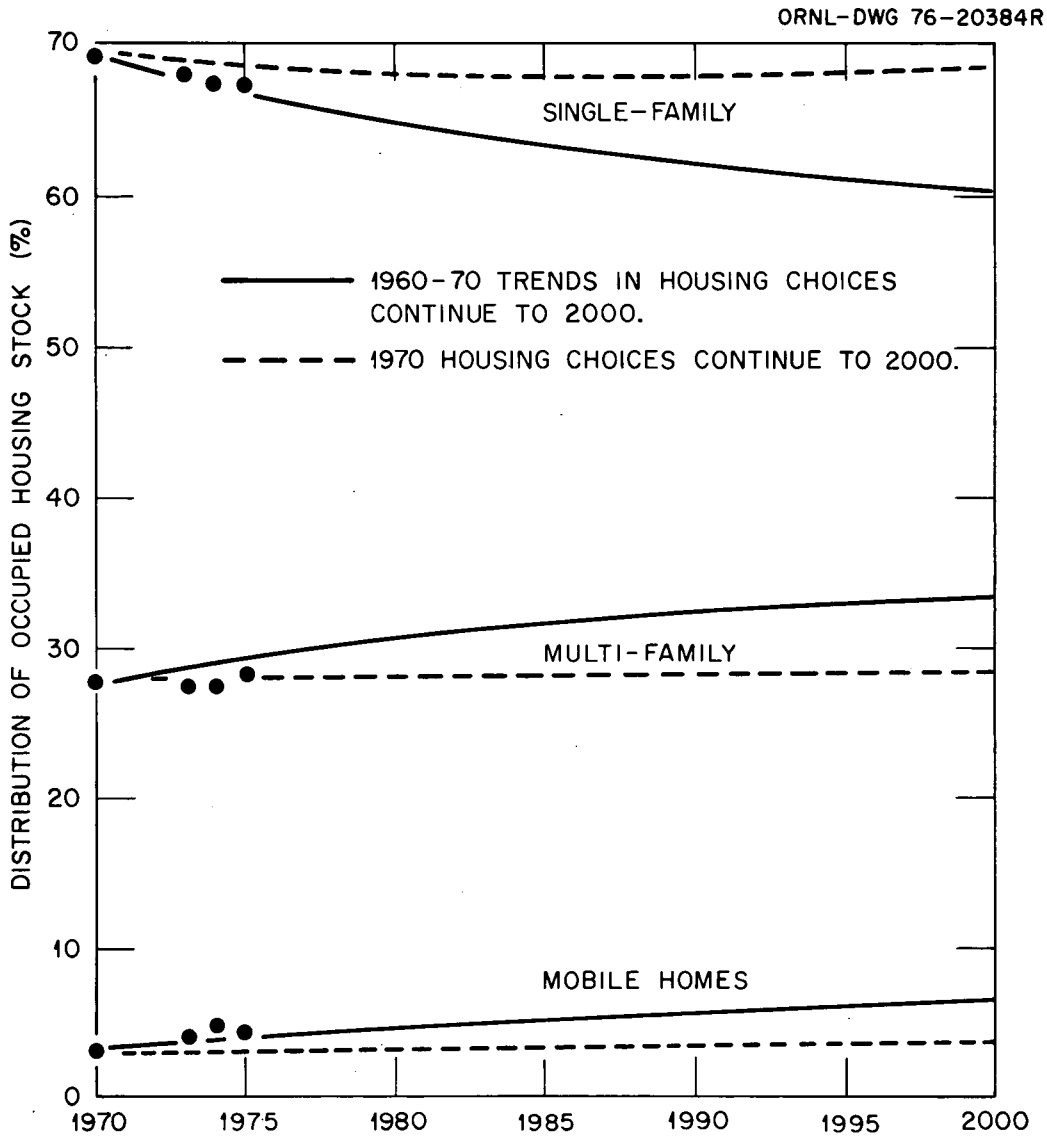

Fig. 4. Projected distribution of households by type of housing unit.

The present housing submodel is a significant improvement over earlier versions. Household formation is now explicitly sensitive to changes in income and demographic variables. Housing size is a function of economic and demographic variables.

However, work remains to be done before we have a completely satisfactory submodel. Projections of housing choices are now primarily a function of the user's assumptions concerning housing choices in the

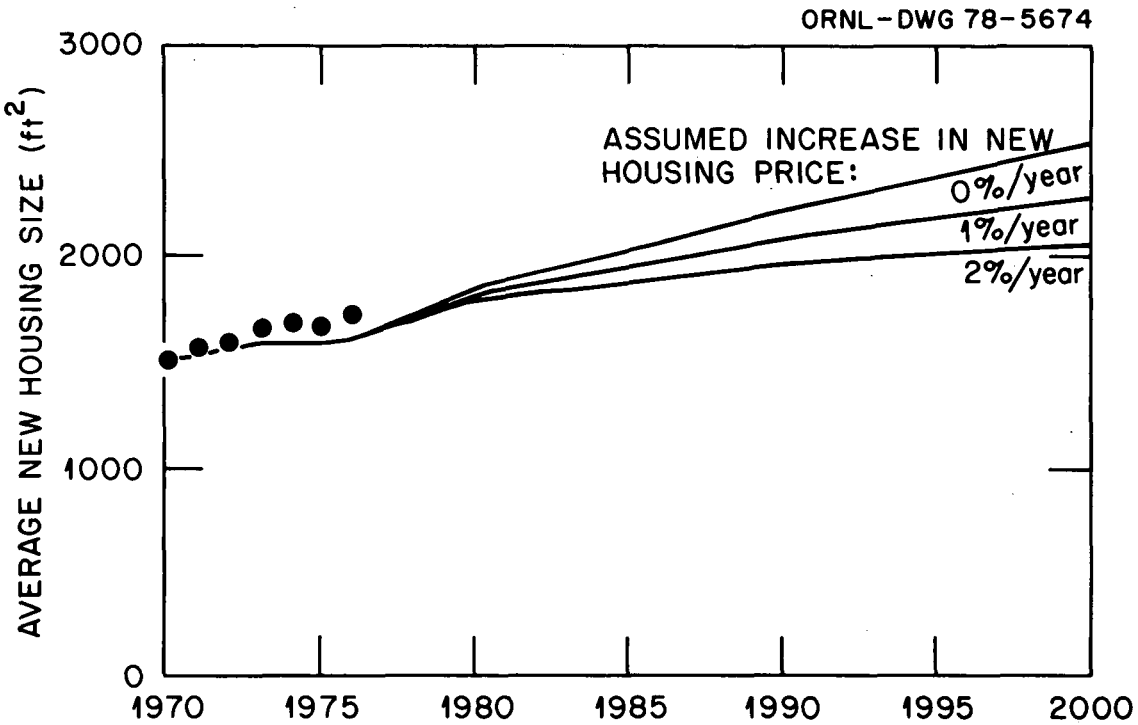

Fig. 5. Projections of average new housing size.

year 2000; we hope to replace these assumptions with a set of equations that specify housing choices for each age group as funtions of income, housing prices, demographic factors, and other variables.[6] Additional work is also needed to develop better estimates of the lifetimes and retirement rates for each of the housing types.

3. TECHNOLOGIES

The technology submodels evaluate relationships between equipment or structure energy intensiveness (inverse of energy efficiency) and changes in capital cost for the present technological "state-of-the-art." Figure 6 shows how the energy and cost analyses are combined to define these relationships.

Detailed engineering and cost analyses were conducted for electric, gas, and oil space heating systems;[16] gas and electric water heaters;[17]

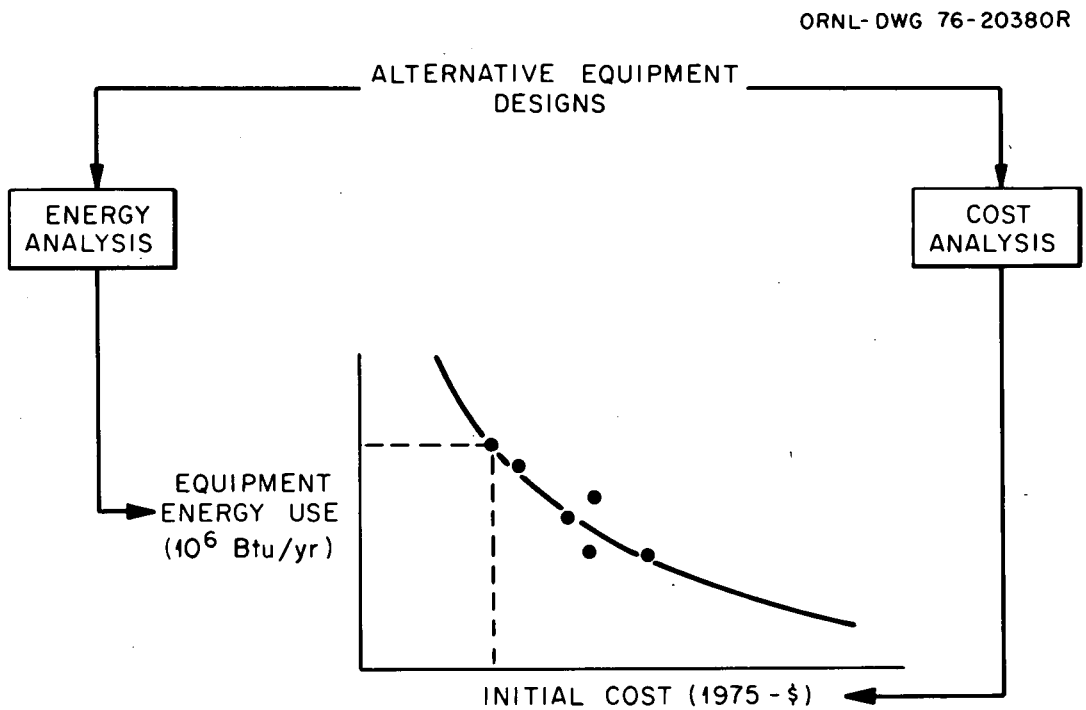

Fig. 6. Schematic of ORNL residential technology submodels.

and refrigerators.[18] A preliminary analysis of gas and electric ranges was also completed; we do not anticipate further effort on ranges because they account for only 5% of residential energy use. We assumed that the relationship between annual energy use and capital cost for freezers is the same as for refrigerators. We reviewed the available literature to determine this type of relationship for residential air conditioning equipment.[19] In a similar fashion, we evaluated changes in winter heat loss and summer heat gain for each of the three housing types.[20-22]

Our analysis of water heaters is discussed as an example of the equipment technology submodels.[17] A computer code was developed to evaluate flows of energy (either electricity or gas) into and through typical water heaters. This code was then used to evaluate the annual energy requirements for different water heater designs.

The program treats the following energy components: energy input to the water heater, energy into the water, distribution pipe loss, water heater jacket loss; and for gas water heaters, pilot light, main burner combustion, and flue losses. Outputs from the program include a complete energy balance, overall energy efficiency; and for gas units, the number of hours/year that the main burner is on. The program is written so that the user can change environmental conditions (e.g., ambient temperature, incoming water temperature), use conditions (gallons/day of hot water, outlet temperature), and unit characteristics (size, jacket insulation thickness).

The following design changes were evaluated with the water heater code: changes in jacket insulation thickness and/or conductivity, addition of insulation to the distribution pipe, reduction in pilot light rate, reduction in excess air for combustion, and elimination of the pilot light/addition of flue damper and electric ignition. The initial costs for these changes were obtained from communications with manufacturers and others conducting similar studies.

Figures 7 and 8 summarize the results of this analysis for gas and electric water heaters. For use in our simulation model, we convert the envelope of points in Figs. 7 and 8 into an analytical expression.* These relationships between annual energy use and capital cost all show negative first derivatives and positive second derivatives. Imposing these constraints ensures that the systems conform to the law of diminishing marginal returns.

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*This is similar to a production function.

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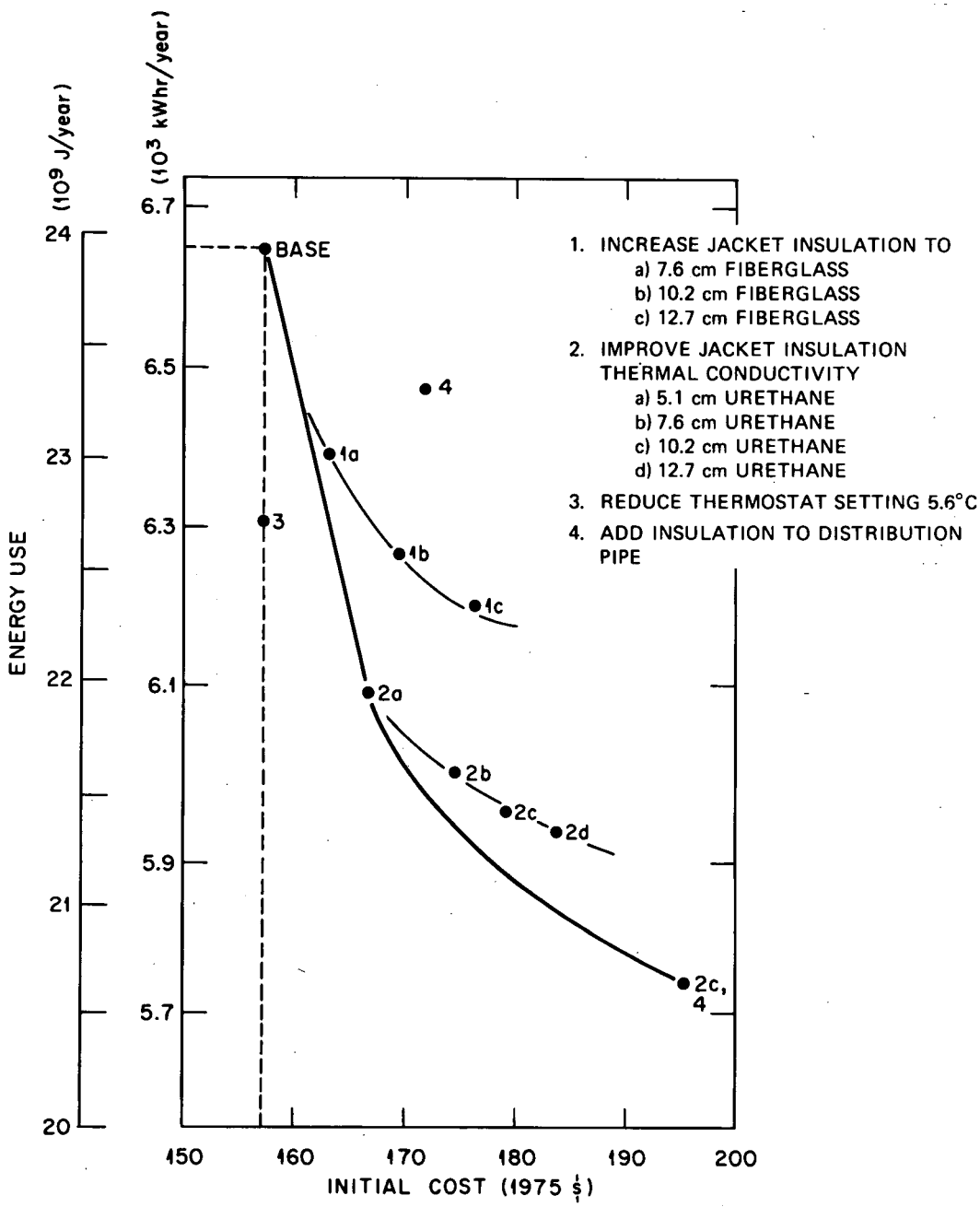

Fig. 7. Annual energy use vs retail price for a typical electric water heater.

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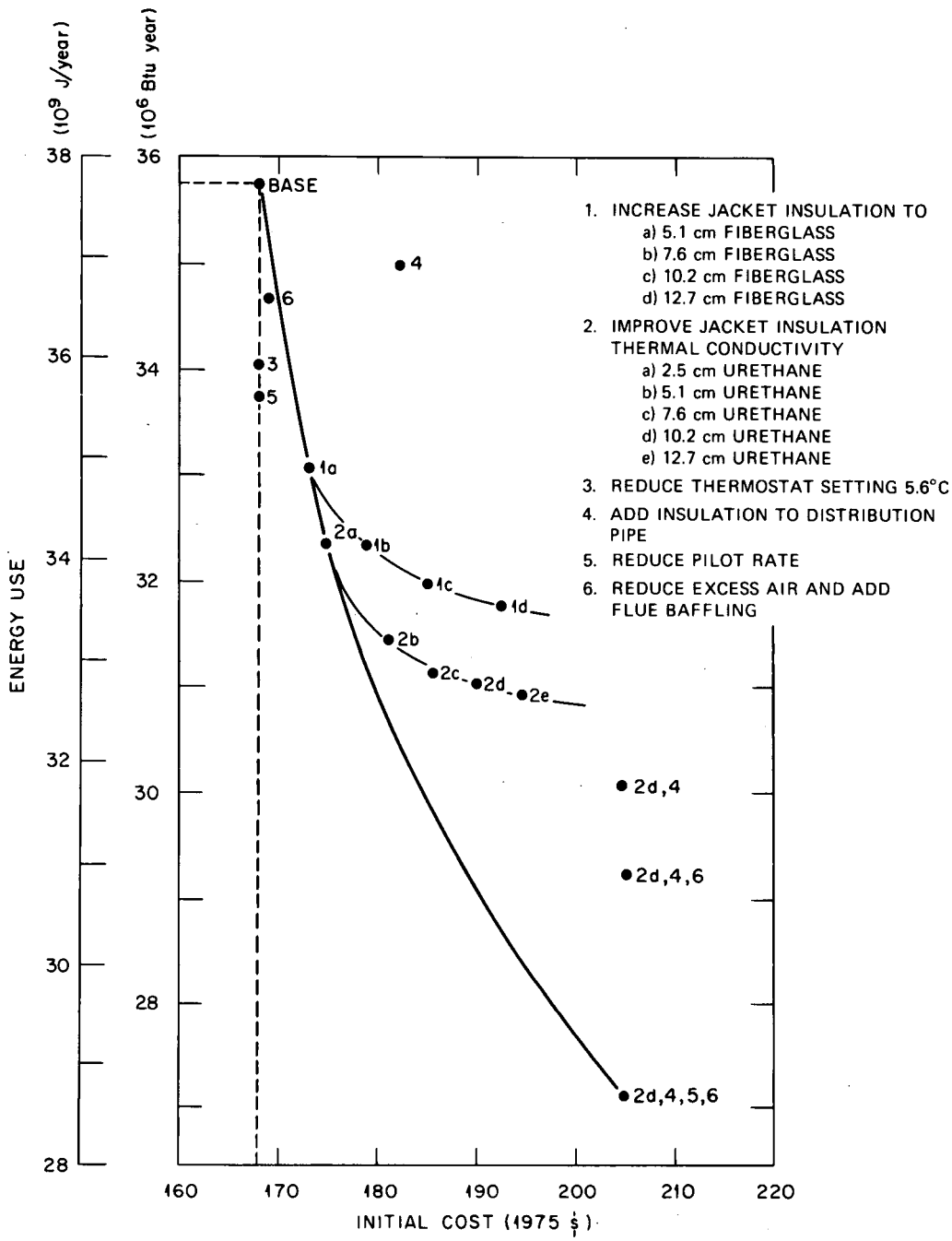

Fig. 8. Annual energy use vs retail price for a typical gas water heater.

A three-parameter equation that satisfies the two derivative constraints is:

$$E/E_o = E_\infty/E_o + \left(\frac{B + 1}{B + C}\right)^A$$

where

E = annual energy use (e.g., Btu/year),

C = initial cost (e.g., 1975-$),

E_∞, A, B are parameters. E_∞ is the asymptotic limit on efficiency improvements and $A(1 - E_\infty)/(B + 1)$ is the slope of the curve when $E = E_o$ (and $C = C_o$).

The subscript $(\ )_o$ refers to the reference (1970) unit. That is, E_o and C_o are the annual energy requirement and initial cost, respectively, of a typical unit sold in 1970.

Values of E_∞/E_o, A, and B for each type of equipment are shown in Table 5. The resultant equations define the optimal (minimum cost) design alternatives for each system.

A similar set of analyses was conducted for housing units. Figure 9 shows the relationships between thermal performance* and incremental capital cost for new and existing single-family units.[20] Figure 10 shows the same relationship for new mobile homes.[22]

The equation used in the simulation model to represent the thermal performance/cost tradeoff for structures is:

$$TIN/TIN_o = TIN_\infty/TIN_o + \left(\frac{B}{B + C}\right)^A$$

---

*Thermal performance (TI or TIN) is defined as the annual heat loss (winter) or heat gain (summer) through the shell of a housing unit. TI and TIN are used in the simulation model relative to their 1970 values, i.e., $TI_{1970} = TIN_{1970} = 1.0$.

Table 5. Equipment and structure technology characteristics

	Equipment								
	Electric			Gas			Oil		
	E_∞/E_o	A	B	E_∞/E_o	A	B	E_∞/E_o	A	B
Space heating	0.52	8.0	1.95	0.70	1.8	-0.85	0.75	3.0	-0.79
Air conditioning	0.55	2.0	-0.82						
Water heating	0.80	10.0	1.00	0.70	10.0	0.50	0.70	10.0	0.50
Refrigerators and freezers	0.45	10.0	-0.45						
Cooking	0.80	1.5	-0.82	0.50	2.0	-0.90			

	Structures[a]								
	Electric			Gas			Oil		
	T^*	A	B	T^*	A	B	T^*	A	B
Single-family	0.45	10	3570	0.40	10	4760	0.40	10	4760
Multi-family	0.45	10	1150	0.40	10	1500	0.40	10	1500
Mobile home	0.45	10	1670	0.40	10	2260	0.40	10	2260

[a] $T^* = TIN_\infty/TIN_o$

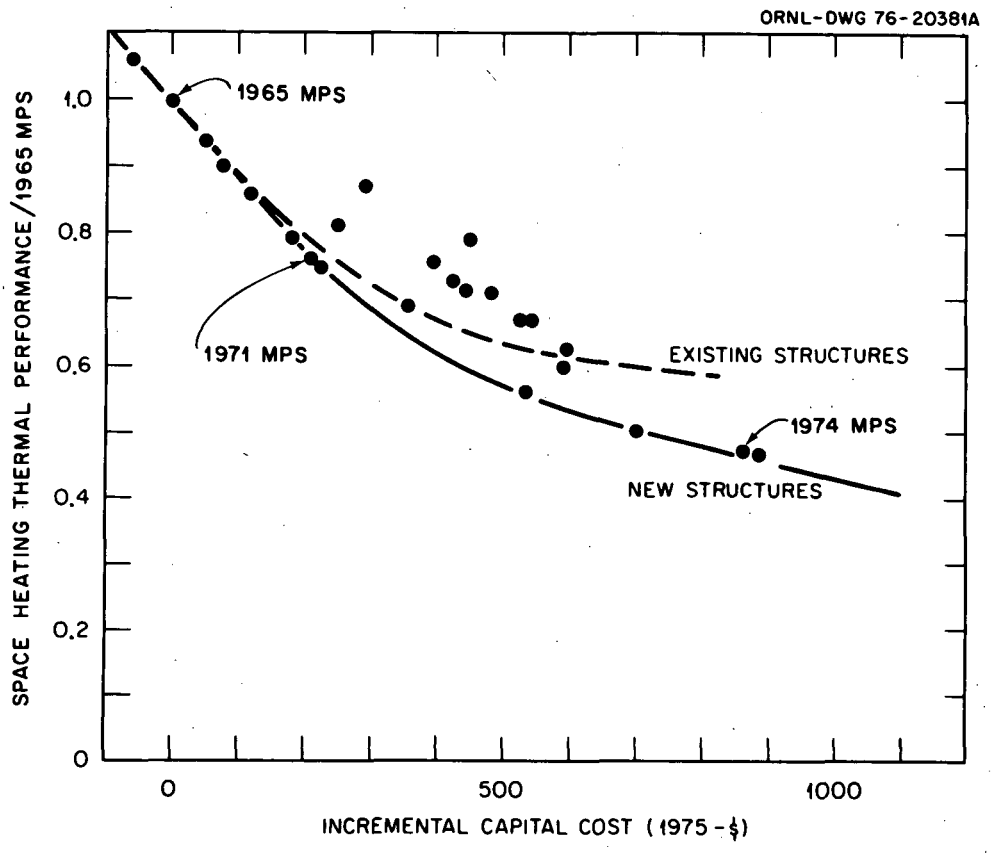

Fig. 9. Space heating thermal performance for new and existing single-family units vs increased capital costs. Federal Minimum Property Standards (MPS) for new construction are shown.

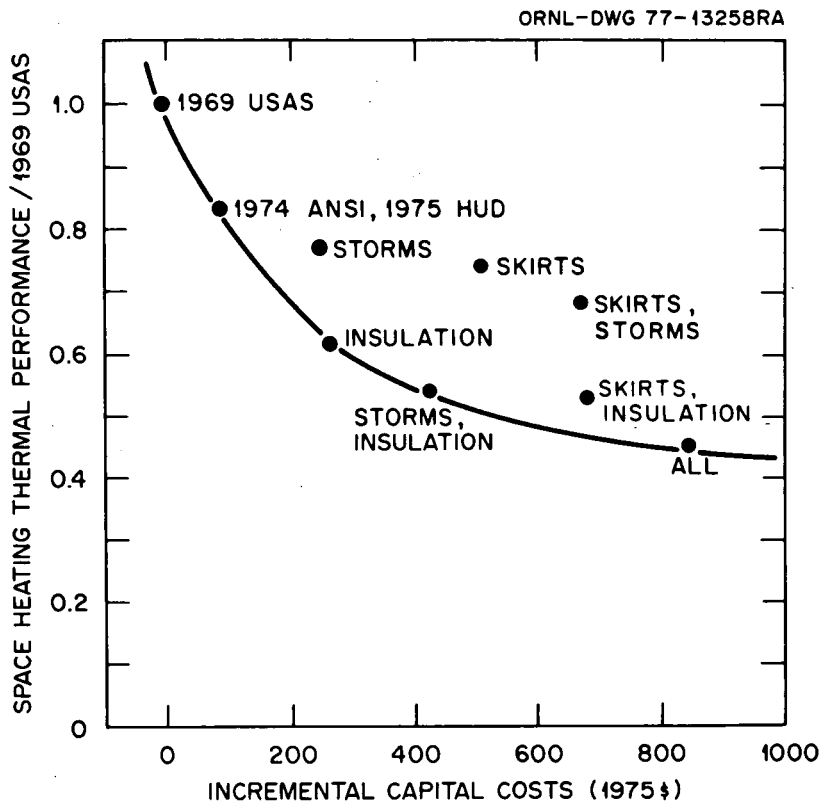

Fig. 10. Space heating thermal performance for new mobile homes vs increased capital costs. Federal standards are shown.

where

TIN is thermal performance (normalized to 1970, $TIN_{1970} = 1.0$),

C is the change in initial cost of the structure due to the TIN change (1975-$),

TIN_{∞}, A, B are parameters.

Values of TIN_{∞}/TIN_{o}, A, and B for new structures are shown in Table 5.

We are continuing our engineering analysis to develop better estimates of changes in energy requirement as functions of changes in initial cost. Part of this effort involves an examination of new residential technologies such as gas-fired heat pumps, advanced electric heat pumps, solar water heating and space heating systems, and integrated appliances. Figure 11 shows how these technologies can be represented in the same

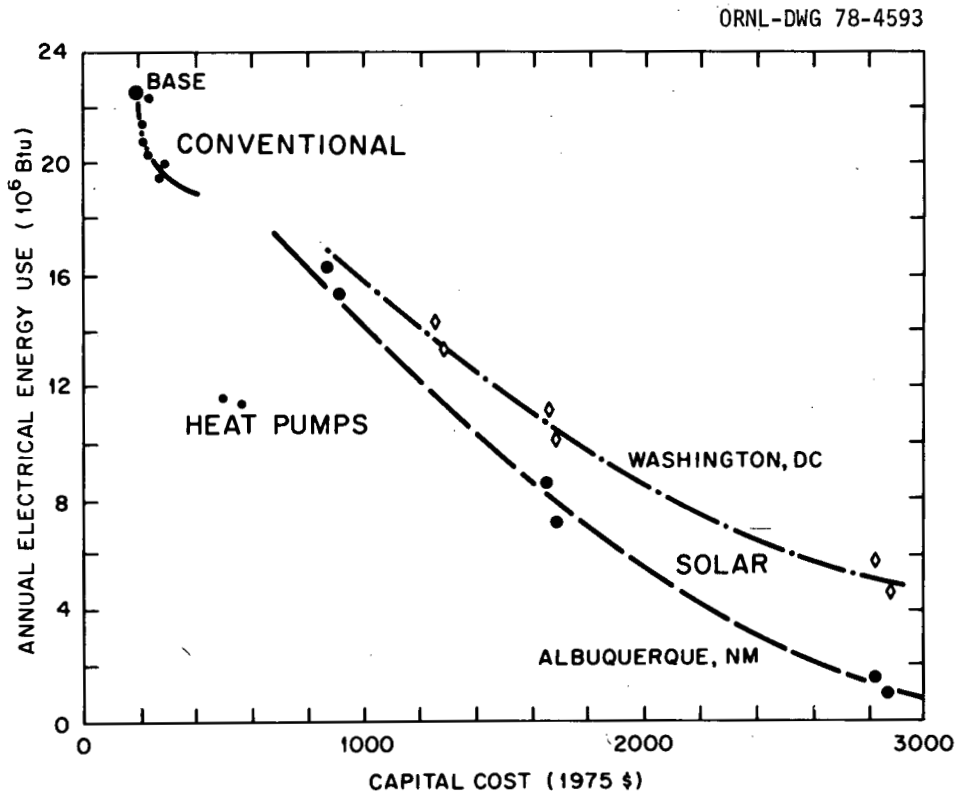

Fig. 11. Annual energy use vs retail price for conventional, advanced, and solar electric water heaters.

manner. Figure 11 shows the electric water heater options of Figure 7; plus heat-pump water heaters and solar water heaters. Changing values of E_∞, A, and B allows one to represent conventional, advanced conservation, and/or solar water heaters.

4. ECONOMICS

Households respond to changes in fuel prices in three different ways. In the short-run, they change the way in which they operate existing stocks of equipment and structures (e.g., lower winter temperature settings). In the long-run, they also change their capital stocks by switching from one fuel to another, by improving the efficiency of their capital stocks (e.g., purchasing a water heater with more insula-

tion on the jacket), or both. Thus, the elasticity of demand for a particular fuel with respect to the price of that fuel can be decomposed into three elements - usage elasticity (E_u), equipment fuel choice (market share) elasticity (E_{ms}) and technical efficiency elasticity (E_e)*:

$$E = E_u + E_{ms} + E_e.$$

Figure 12 is a diagram showing how these elasticities are developed and their relationship to aggregate household elasticities. Overall control of the detailed elasticities is based on a set of econometric models of household demands for electricity, gas, and oil[23] (shown in the upper right of Fig. 12). These models were constructed using a large data base containing variables for each state and each year from 1951 through 1974. Both cross-sectional and dynamic models of household fuel use were constructed.

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*E_e is actually the elasticity of energy intensiveness (inverse of energy efficiency) with respect to fuel price.

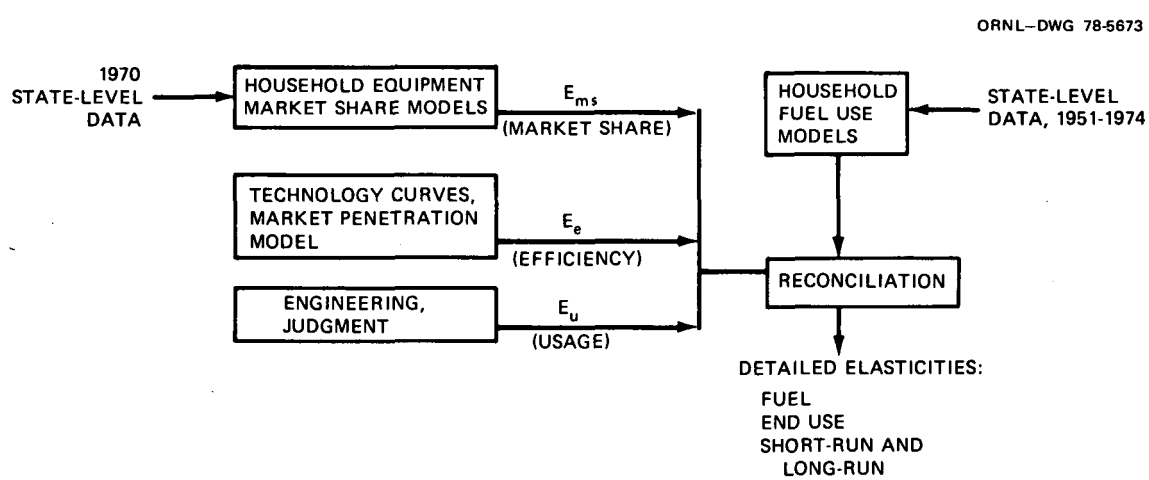

Fig. 12. Schematic of ORNL energy economic submodels.

Market share elasticities were determined from a cross-sectional analysis of residential fuel choices (equipment ownership market shares) for five major end uses: space heating, air conditioning, water heating, food freezing, and cooking,[24] shown in the upper left of Fig. 12. These models were constructed using state-level data for 1970.

Equipment and structure technical energy intensiveness elasticities were derived from the annual energy use vs capital cost relationships discussed in Section 3 and the market penetration model discussed in Section 5. These elasticities show how technical efficiencies change over time with respect to changes in own-fuel prices.

Usage elasticities are based on engineering possibilities (e.g., space heating energy savings per ^{o}F temperature reduction) and our judgments.

These detailed elasticities are reconciled with the overall fuel price and income elasticities in an interactive computer program called Elasticity Estimator. This program calculates overall short- and long-run elasticities from the detailed elasticities and compares these results with input values. The user can then modify the detailed elasticities until an adequate reconciliation is achieved.

Each of the elements is described below. The household fuel demand equations (cross-sectional)[23] are all specified in a log-log (constant elasticity) formulation, with fuel demand per household as the dependent variable. Independent variables include: prices of electricity, gas and oil; per capita income; and two climatic variables (heating degree days and mean July temperature). Estimated elasticities of household demands for electricity, gas, and oil obtained with cross-sectional

models were derived for 1951, 1955, 1960, 1965, 1970, 1971, 1972, 1973, and 1974.

These results show considerable stability over time for the own-price coefficients for electricity and natural gas; long-run elasticities average -1.0 and -2.1, respectively. The own-price elasticity of demand for oil shows more variation, with values ranging from -0.2 in 1955 to -2.5 in 1965; the average of the fuel oil own-price elasticities is -1.3.

Cross-price elasticities for both electricity and gas generally increased in magnitude and statistical significance over time, especially during the last six years of the data series. This suggests that households have become more aware of relative fuel costs and have acted accordingly in their fuel choice decisions.

The absolute magnitude of the own-price elasticity for oil is considerably less (44%) than the cross-price elasticity of oil with respect to the price of gas, averaging 1.8. The implication that the quantity of oil demanded is more responsive to changes in the price of gas than changes in the price of oil is counter-intuitive. This result appears to stem from gas availability problems in the North East. Although the price of natural gas tends to be high in large oil-consuming states (Maine, New Hampshire, Vermont), oil consumption is also influenced by the unavailability of gas. Thus the cross-price elasticity of oil with respect to gas price reflects both a price effect and an availability effect.

The per capita income elasticity of demand for natural gas is considerably higher and more stable over time than corresponding values for electricity and oil. The income elasticity of demand for gas averaged 1.8; for electricity and oil these elasticities averaged -0.1 and +0.1

respectively, indicating a clear preference for natural gas in high income states.

A conditional logit formulation was used to estimate residential fuel choices[24] (equipment market shares): $ln[(S_i/(1 - S_i)]$ was used as the dependent variable, where S_i is the fraction of households that use fuel i for the particular end use. Independent variables were fuel prices, equipment prices, per capita income, heating degree days (for space heating), cooling degree days (for air conditioning), fraction of households in urban areas (for food freezers), and fraction of households in single-family units (for food freezers).

Reference 24 presents the coefficient estimates obtained with a semi-log logit model for 1970 plus results for 1970 and 1960 using a log-log logit formulation. Own-fuel price elasticities are all greater than unity, except for gas ranges. Only one of the fuel price elasticities has the wrong sign (demand for oil space heating with respect to electricity price). Most coefficients are significant at the 10% level or better. These elasticities show that consumers respond to fuel price changes in selecting among alternative equipment choices. The equipment ownership elasticities used in our simulation model are shown in Table 6.

Almost all equipment price elasticities are greater than unity and larger than the corresponding fuel price elasticities. The equipment price coefficients all have the correct signs and are generally statistically significant at the 10% level or better. These results show that equipment and appliance prices are important determinants of residential fuel choices.

The technology relationships discussed in the preceding section are used to define the technological possiblilities for each end use. (For

Table 6. Long-run equipment ownership market share elasticities

	Price of:			Income
	Electricity	Gas	Oil	
Space heating				
Electric	-2.0	0.5	0.5	0.3
Gas	0.4	-1.3	0.4	0.5
Oil	0.2	1.1	-1.2	-0.4
Other/none				-1.8
Air conditioning	-0.3			0.9
Water heating				
Electric	-2.0	0.8	0.5	0.0
Gas	0.8	-1.4	0.4	0.7
Oil	0.8	1.1	-2.0	0.0
Other/none				-3.9
Refrigeration	-0.2			0.1
Food freezing	-0.5			0.3
Cooking				
Electric	-1.0	0.6		0.0
Gas	0.7	-0.9		0.8
Other/none				-3.9
Lighting	-0.4			0.3
Other				
Electric	-0.4	0.0		0.5
Gas	0.0	-0.4		0.2

heating and air conditioning, changes in both structure and equipment are considered.) These engineering relationships are combined with the market penetration algorithm discussed in the following section. Outputs from the energy use simulation model then give the responsiveness of equipment energy intensiveness (and structure thermal performance for heating and cooling) to changes in own-fuel prices; see Table 7.

The responsiveness of households to fuel price and income changes in terms of operational changes (holding equipment and structure capital stocks fixed) determines the usage elasticities. These elasticities are

Table 7. Long-run technical energy intensiveness elasticities

	Electricity	Gas	Oil
Space heating	-0.82	-0.76	-0.71
Air conditioning	-0.50		
Water heating	-0.22	-0.30	-0.30
Refrigeration	-0.63		
Food freezing	-0.65		
Cooking	-0.12	-0.44	
Lighting	0.00		
Other	-0.20	-0.20	

input to the Elasticity Estimator program, based on engineering possibilities and our judgment. For example, a 1°F setback in winter temperature (for a full 24-hour day) cuts space heating fuel use by about 5%. A comparable increase in summer temperature reduces air conditioning fuel use by almost 10%. Opportunities to reduce energy use in refrigerators, on the other hand, are much more limited; households can reduce the number of door openings and clean condenser coils occasionally. Because of these differences, usage elasticities for heating and cooling are assumed to be much greater than for refrigerators and freezers; see Table 8.

Table 8. Long-run usage elasticities

	Own-price	Income
Space heating	-0.40	0.10
Air conditioning	-0.40	0.30
Water heating	-0.25	0.05
Refrigeration	-0.05	0.02
Food freezing	-0.05	0.02
Cooking	-0.10	0.04
Lighting	-0.10	0.10
Other	-0.10	0.10

The Elasticity Estimator reads in values of E_u, E_{ms}, and E_e for each of the eight end-uses. The program also reads in values of overall household fuel demand elasticities with respect to fuel prices and incomes, both short-and long-run. Short-run usage, efficiency, and market share elasticities are calculated within the program. The ratio of short-run to long-run usage elasticities is an input to the program, set equal to 0.5 here. This implies that 50% of the total usage response occurs during the first year after a change in own-fuel price or income. We assume that changes in technical efficiencies and equipment ownership are constrained only by equipment lifetimes.*

The program then sums the detailed elasticities to produce estimates of the aggregate elasticities (for both the short-run and long-run):

$$E^{ij} = \sum_{k=1}^{8} f^{ik} (E_u + E_{ms} + E_e)^{ik},$$

where E^{ij} is the elasticity of household demand for fuel i with respect to independent variable j (one of three fuel prices or income), and f^{ik} is the fraction of household use of fuel i for end use k.† If the calculated values of E^{ij} do not agree well with the inputs for these overall elasticities, the user can change some or all of the detailed elasticities. The program then recalculates the overall elasticities and iterates until the user is satisfied with the final set of elasticities.

---

*As shown later (Table 12), these assumed relationships between short- and long-run responses yield reasonable values for overall short- and long-run elasticities.

†$\sum_{k=1}^{8} f^{ik} = 1.0.$

Although the usage elasticities are arbitrarily specified, we can compare their weighted sum with estimates derived from econometric analysis. Anderson[25] shows that 1/4 - 1/3 of the total long-run response to a change in fuel price is due to usage changes. Our final results from the Elasticity Estimator show ratios of 0.20 for electricity, 0.28 for gas, and 0.31 for oil. These ratios increase in going from electricity to gas to oil because of the increasing importance of space heating in going from one fuel to the next. These results provide another indication (beyond that offered by our engineering estimates) that the usage elasticities are not ridiculous.

Values of new equipment market-share elasticities with respect to equipment price are derived from the corresponding fuel price market-share elasticities and a set of "real" interest rates input to the simulation program. These interest rates (Table 9) are determined largely from results in ref. 24 and changes in real fuel prices during the late 1960s. The equipment price elasticities for purchase of new equipment of type i (E_{cpms}) are calculated as:

$$E^{ijk}_{cpms} = E^{ijk}_{ms} \frac{PQ^{jk}}{P^j \cdot EU^{jk}} \left[\frac{r}{1 - (1 + r)^{-t}} \right],$$

where E^{ijk}_{ms} is the market-share elasticity for equipment ownership with respect to fuel price j, PQ^{jk} is the consumer purchase price for that type of equipment, P^j is the price of fuel j, EU^{jk} is the annual energy requirement for a typical piece of equipment that uses fuel j for end use k, r is the real interest rate, and t is the average lifetime for that type of equipment (Table 10).[1]

Table 9. Real interest rates used in the ORNL residential energy model to determine equipment price elasticities

	Real interest rate (%) for:		
	Electric	Gas	Oil
Space heating			
Electric	8	11	11
Gas	11	8	11
Oil	11	11	8
Air conditioning			
Room	15		
Central	12		
Water heating			
Electric	12	15	15
Gas	15	12	15
Oil	15	15	12
Refrigeration	15		
Food Freezing	15		
Cooking			
Electric	15	18	
Gas	18	15	
Lighting	15		
Other			
Electric	15		
Gas		15	

Table 10. Assumed average equipment lifetimes

	Lifetime (years)
Space heating	15
Air conditioning	10
Water heating	7
Refrigeration	14
Food Freezing	18
Cooking	13
Lighting	1
Other	10

Figure 13 illustrates the dynamics of energy use in response to a change in gas price for gas water heating. The curves show changes in usage, equipment ownership, equipment efficiency; and the combined response due to a step increase in the price of gas in year 0.

The price increase causes an initial response in terms of reduced hot water usage. This response reaches a peak five years after the price increase and then begins to subside.

The price increase induces two responses concerning new water heaters. Some households that would have purchased gas units switch to

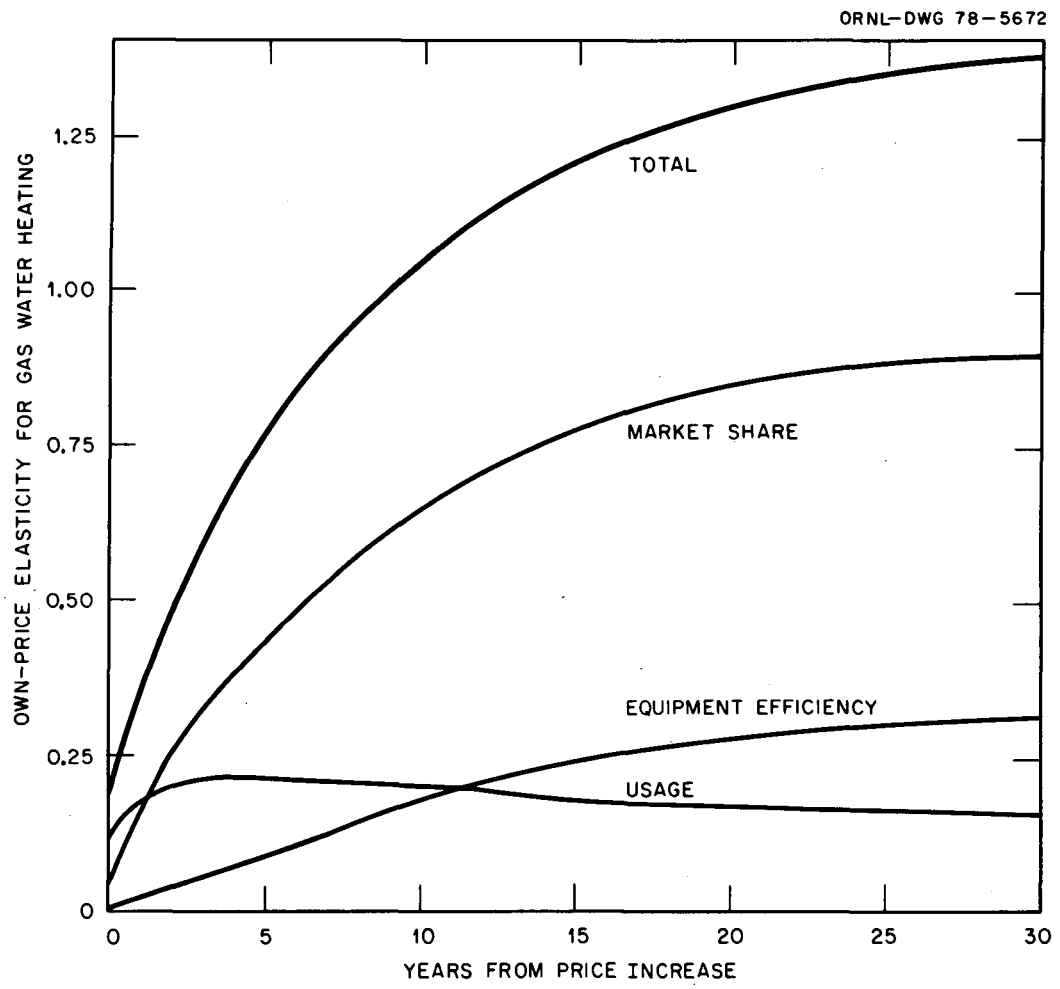

Fig. 13. Effects of a step change in the price of gas on ownership, efficiency, and usage of gas water heaters.

electric or oil water heaters. Those households selecting new gas water heaters choose more efficient units than they would have if the price of gas had not increased. These two equipment ownership responses occur much more slowly than does the usage response: ownership changes are limited by the lifetime of water heaters (average of seven years). Only as existing water heaters wear out can changes be made in terms of fuel choices and energy efficiencies.

As the average efficiency of gas water heaters improves, households adjust their usage accordingly. Thus, after 30 years the usage change is 80% of its maximum value (after five years).

The top curve in Fig. 13 shows the total change in gas use for water heating in response to the price change. The total is the sum of the three individual responses. Figure 13 shows both the complexity of responses to a change in an exogenous variable and differences in dynamics for these responses. Usage responds rapidly while ownership changes occur much more slowly. During the first two years after the price increase, usage accounts for more than half the change in gas use for water heating. After 30 years, usage accounts for only 10% of the total response; changes in fuel choice account for 65% and changes in equipment efficiency account for 25%.

In summary, the submodels discussed in this section produce a detailed set of 272 elasticities for use in the simulation model:

new equipment market-share elasticities (4 choices x 7 fuel price, equipment price, and income variables x 8 end uses);

equipment usage elasticities (3 fuels x 2 own-price and income variables x 8 end uses).

Unfortunately, the statistical basis for many of our cross-price and income elasticities is weak. Lack of detailed data forced us to make several assumptions to derive the 272 elasticities used in the simulation model. Also, the applicability of fuel price and income elasticities derived with data from a period in which fuel prices were declining to a future in which prices are likely to rise significantly is unknown. Clearly, more work must be done to develop good data series on household fuel uses and prices and on econometric estimation to produce improved elasticity estimates.

5. MARKET PENETRATION

This section explains how the simulation model endogenously determines changes in new equipment and structure efficiencies in response to changes in fuel prices and the state of technologies (i.e., relationships between equipment or structure efficiency and capital cost). There are three elements involved in the market penetration analysis:

Consumer behavior
Producer behavior
Demand/supply interaction.

Consumer behavior in the energy use model is represented by fuel price, equipment price, and income elasticities, as derived in Section 4. Manufacturer behavior is determined in the model by supply curves that relate equipment (or structure) energy requirements to equipment (or structure) purchase price; see Section 3.

The market penetration algorithm integrates the demand (consumer) and supply (manufacturer) sides to provide a dynamic equilibrium that determines efficiencies over time. There are two steps to this analysis. The first

involves determination of average efficiencies for new equipment and structures for each year of the simulation. These efficiencies are functions of fuel prices, implicit interest rates (related to fuel price and equipment price elasticities), and the technology relationships.

The second step is determination of equipment choices for new installations for each year of the simulation. The model determines new equipment market shares each year as functions of operating costs (efficiencies and fuel prices) and capital costs, as well as household income.

Table 11 summarizes the major elements of the demand and supply sides for new structures. The demand side is characterized by an interest rate and an investment lifetime, assumed to be 6% and 25 years, respectively. (These values are input to the model and can be readily changed. For example, one might hypothesize that consumers use only five years as their horizon for investment decision, although structures last much longer).

The supply side is represented by curves that relate thermal performance to changes in capital cost for the residence; see Figs. 9 and 10. If the curve of Fig. 10 is rotated 90°, one obtains Fig. 14. Adding operating costs (for space heating and air conditioning) to the capital

Table 11. Assumed determinants of consumer and producer behavior with respect to thermal performance of new structures

1. Consumer behavior

   6% "real" interest rate
   25-year lifetime

   Assumptions can be readily changed in model

2. Supply-side behavior

   relationship between structure performance and initial cost (e.g., Fig. 10)

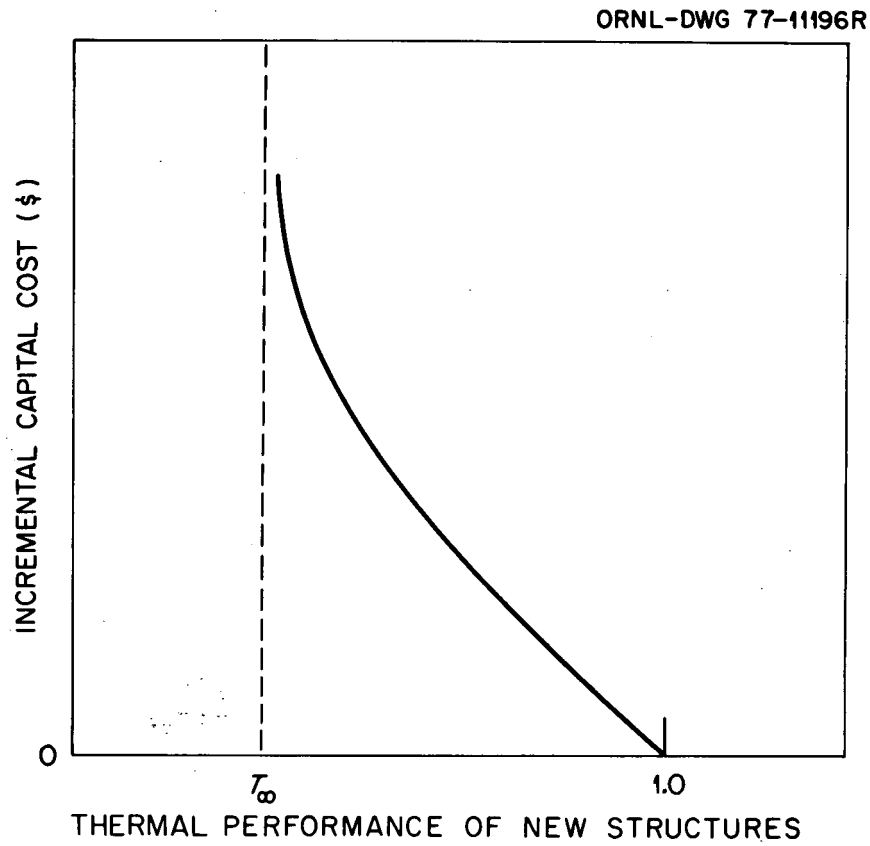

Fig. 14. Relationship between thermal performance and incremental capital cost for new structures (T = 1.0 refers to the 1970 condition).

cost relationship of Fig. 14 yields the lifecycle cost (LCC) curve of Fig. 15.

Figure 15 shows the typical behavior of declining and then increasing LCC as capital cost changes. The point of minimum LCC is denoted by $T_{optimal}$, the structure thermal performance/capital cost point at which LCC is minimized. However, historical data show that the system does not operate at the optimal point; it operates at a point of lower capital cost (less efficient structure), denoted by T_{actual}.

We hypothesize that the difference between $T_{optimal}$ and T_{actual} persists over time as fuel prices change. Figure 16 illustrates changes

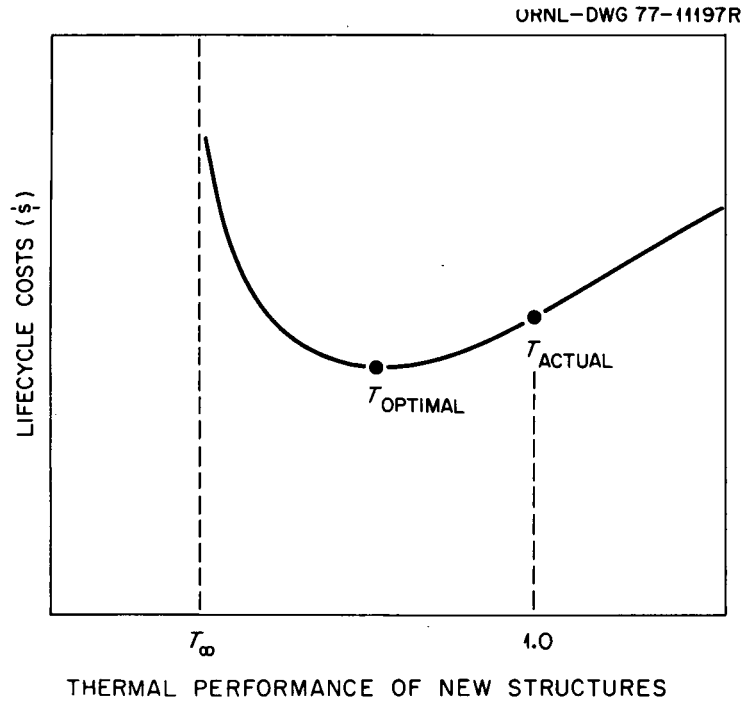

Fig. 15. Lifecycle costs for heating and cooling structures as a function of thermal performance.

in $T_{optimal}$ and T_{actual} as fuel prices change. As the price of fuel increases from P_o to P_1 and P_2, $T_{optimal}$ moves to the left and so does T_{actual}. $T_{optimal}$ is always the minimum on the LCC curve. T_{actual} is calculated from $T_{optimal}$ by assuming that D (the vertical distance between $T_{optimal}$ and T_{actual}) varies inversely with fuel price:

$$D = D_o(P_o/P)^n,$$

where $n \geq 0$.* Thus as fuel prices increase, the "distortion" between the optimal and actual states will decline.

*Absent data on the appropriate value for n, we use n = 1. We can also run the model with n = ∞ to see how consumers respond in a world with no market imperfections (i.e., rational consumers, complete information, competition among suppliers, etc.).

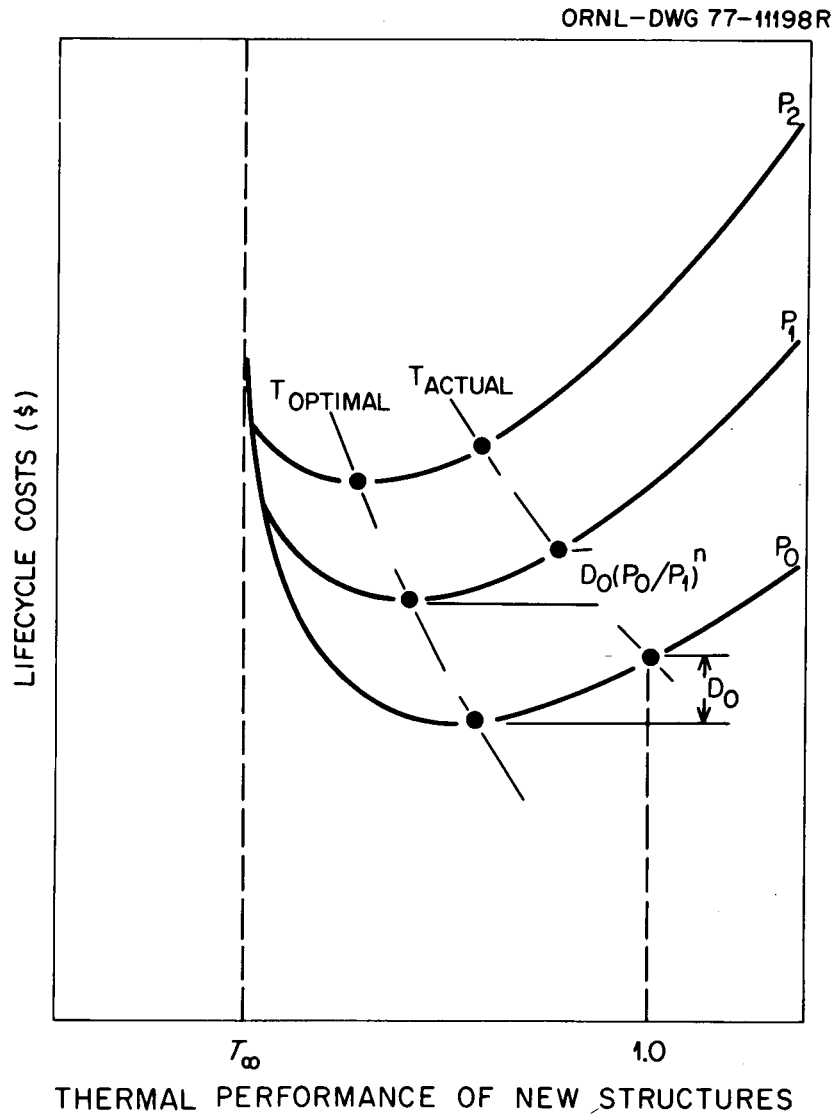

Fig. 16. Changes in thermal performance of new structures as a function of fuel price.

D represents the difference between the actual and optimal states. We hypothesize the (non-zero) existence of D because of market imperfections on both the demand and supply sides: lack of consumer information, costs of processing information, lack of incentives for producers to operate at the optimal point, lack of motivation from financial institutions, etc.

We also assume that as fuel prices rise, these market imperfections will be reduced.*

The model operates in a similar fashion in determining efficiencies of new equipment. However, an additional step is involved: determination of new equipment market shares. Market shares are determined in the energy model as functions of capital and operating costs for each choice and per capita personal income (see Section 6):

$$\text{Market share}_i = F_i \text{ (capital \& operating costs for all choices)} + G_i \text{ (income)},$$

$$i = \text{electricity, gas, oil, other/none.}$$

These relationships yield lines of constant market share as operating and capital costs for the system change (assuming that the characteristics of competing systems and incomes do not change). The slope of these constant market share lines determines the implicit interest rate at which consumers trade off operating for capital costs (Table 9 and Fig. 17).

The supply side is represented by curves that relate equipment energy requirements to equipment purchase prices; Figs. 7 and 8 (Section 3) show such relationships for water heaters.

Once again, the demand and supply relationships can be combined on a single graph (Fig. 17) to determine the intersection. In Fig. 17, point A represents the actual intersection for a particular year (e.g., 1970).

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*An alternative approach to evaluating market-induced changes in structure thermal performance is to select the consumer interest rate at a sufficiently high value so that T_{actual} and $T_{optimal}$ coincide. This would imply that consumers do minimize lifecycle costs but at a very high interest rate that reflects their uncertainty and lack of information about their choices. Outputs from simulations run with this assumption differ only slightly from those obtained with the market penetration algorithm described above.

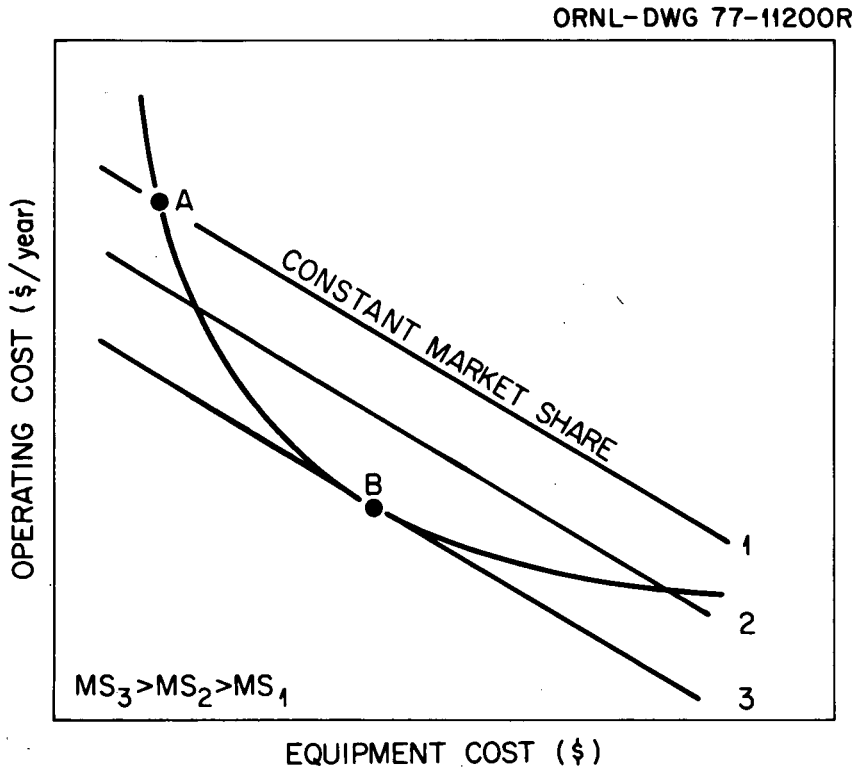

Fig. 17. Intersections between consumer preferences and technology relationships for new equipment (Point A represents the 1970 "equilibrium," Point B represents the "optimal").

Point B represents the optimal point, i.e., the point at which marginal improvements in equipment efficiency yield the consumer's implied rate of return.*

Figure 18 shows how, as fuel prices change, the efficiency and market share for new equipment also change. Again, the difference between the actual and optimal states is denoted by D. D is assumed to vary inversely with fuel price. As fuel prices change, the optimal point (point of tangency between supply and demand curves) changes. Moving perpendicular

*Here again we could have selected much higher interest rates so that points A and B of Fig. 17 would coincide.

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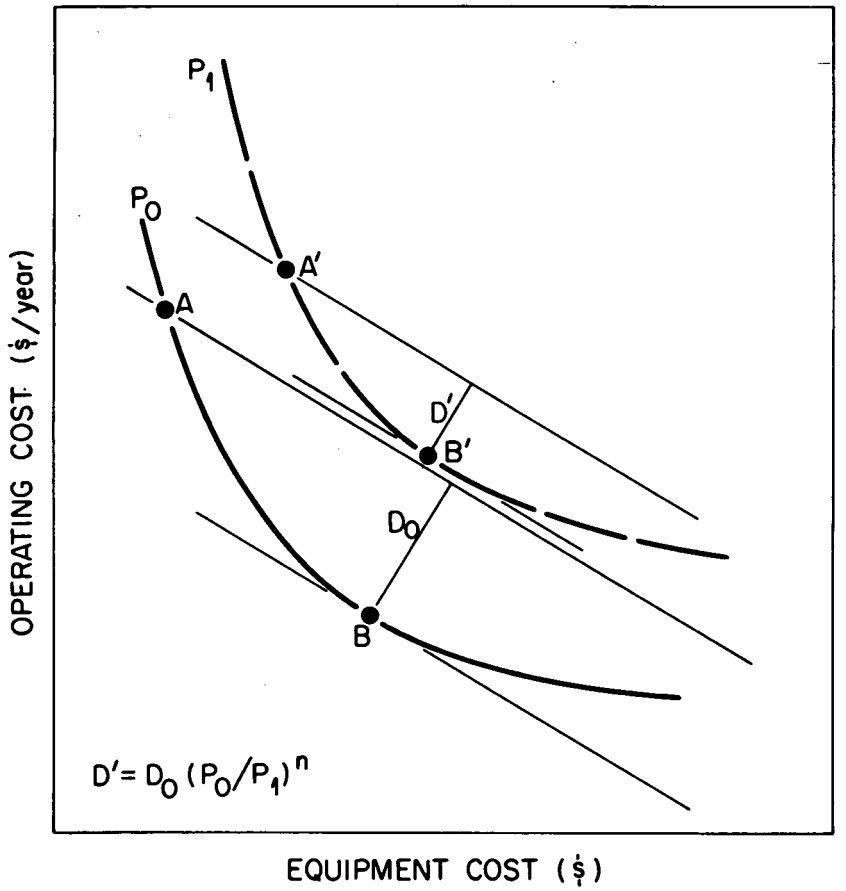

Fig. 18. Changes in new equipment efficiencies and market shares as functions of fuel price.

from the optimal point the distance D yields the market share line and efficiency for the new equipment.

The market penetration algorithm seems to operate well. That is, runs made with various inputs to the simulation model yield results that are intuitively plausible. However, effort is required to empirically validate the algorithm (in particular, determine a value for n) and to establish a theoretical basis for the formulation developed here.

6. SIMULATION MODEL

The residential energy use simulation model combines outputs from the housing, economic, and technology submodels (Fig. 1); plus appropriate

initial conditions for 1970 and policy variables for the 1970-2000 period. Outputs from the model include detailed estimates of annual national energy use by fuel, end use, and housing type; and corresponding information on equipment installations and ownership, equipment energy requirements, structure thermal performance, fuel expenditures, equipment costs, and costs for improving thermal performance of new and existing structures. Figure 19 is a diagram of the simulation model that shows how the various inputs are combined to produce these detailed outputs.*

*The computer program for the simulation model was written in FORTRAN IV for an IBM computer. Copies of the source deck and user's guide are available from the authors.

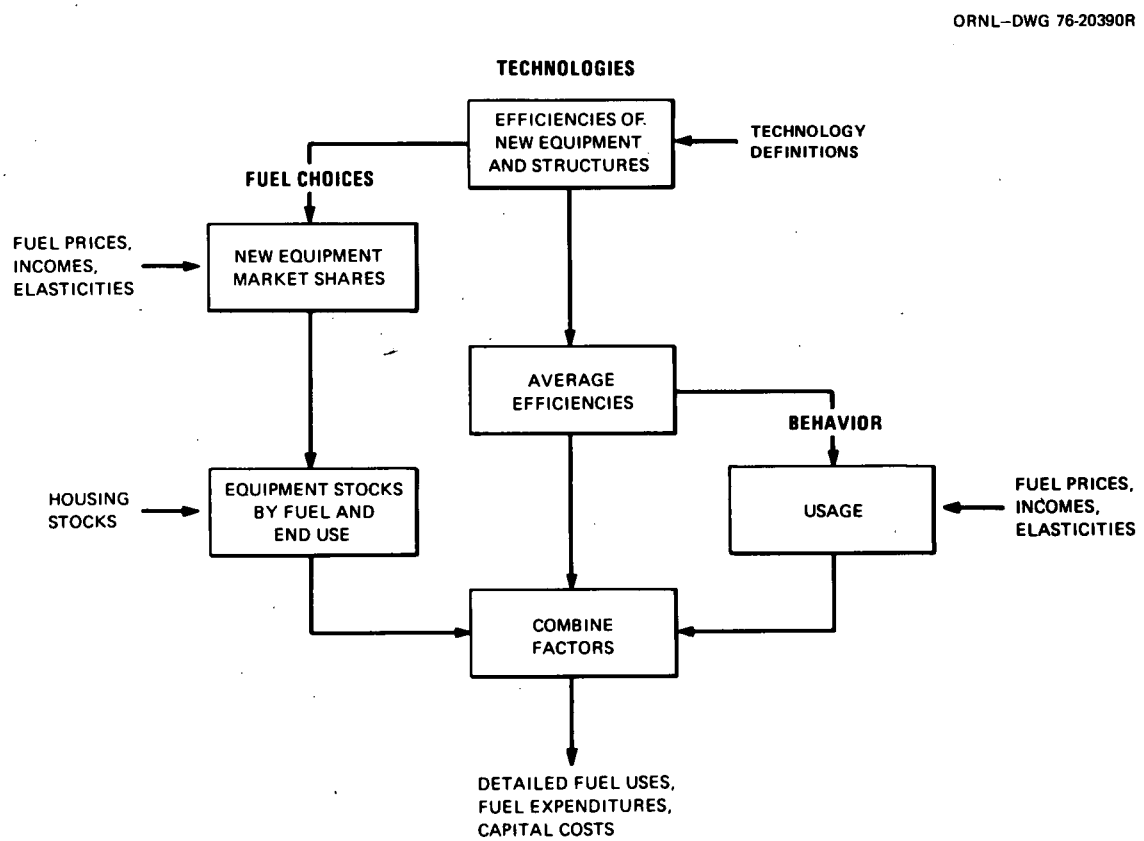

Fig. 19. Schematic of ORNL residential energy use simulation model.

The basic equation in the simulation model that defines residential use of fuel i for end use k in housing type m during year t is:

$$Q_t^{ikm} = HT_t^m \; HS_t^m \; C_t^{ikm} \; TI_t^{ikm} \; EU_t^{ikm} \; U_t^{ik},$$

where HT is the stock of occupied housing units, HS is the average size of housing units (for space heating and air conditioning only), C is the fraction (market share) of households with a particular type of equipment, TI is the thermal performance of housing units (for space heating and air conditioning only), EU is the average annual energy use for the type of equipment, and U is a usage factor.

As an example, consider consumption of electricity for space heating in single-family homes. HT is the stock of occupied single-family homes and C is the fraction of single-family homes that use electricity for heating. HS is the average size of single-family homes. TI is the average thermal performance (scaled to 1970, $TI_{1970} = 1.0$) of single-family homes that use electricity for heating, EU is the average annual energy requirement in Btu/unit of an electric space heating system, and U is a usage factor ($U_{1970} = 1.0$) that reflects how intensely households use their electric heating systems.

Stocks of occupied housing units (HT) by type of unit and average housing size (HS) are calculated in the housing submodel, discussed in Section 2.

The fraction of households of type m that use fuel i for end use k (C^{ikm}) is determined from:

$$C_t^{ikm} = \frac{(1 - R^k) \; C_{t-1}^{ikm} \; HT_{t-1}^m + CN_t^{ikm} \; NU_t^{km}}{HT_t^m},$$

where

R = fraction of last year's equipment stock that is scrapped.

R is related to average equipment lifetime (Table 10) by

$$R = 1 - \frac{1}{2^{1/t_{average}}},$$

CN = fraction of new equipment (NU) installed during year t that uses fuel i for end use k in housing type m,

NU = number of new units installed during year t that provide end use k in housing type m. The number of new units installed equals growth in households plus replacement of units that are scrapped in year t.

The fraction of new units (CN) is calculated from the following equation:

$$ln\left(\frac{CN_t^{ikm}}{1 - CN_t^{ikm}}\right) = A^{ikm} + \sum_{j=1}^{3} (B^{ijk} \bullet X_t^j \bullet EUN_t^{jkm} \bullet TI_t^{jkm}) + \sum_{j=1}^{3} (C^{ijk} \bullet PEQ_t^{jkm}) + D^{ik} \bullet Y_t$$

where

A, B, C, D = coefficients derived from the market share elasticities discussed in Section 4,

X = fuel price,*

EUN = new equipment energy use,

TI = average thermal performance,

PEQ = new equipment purchase price,*

Y = per capita income.*

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*Prices and incomes are expressed in constant 1975-$.

This set of equations is solved twice: once for new equipment installations in new housing units and once for installations in existing housing units. The C coefficients can differ for the two types of installations to reflect differences in implicit interest rates used in decision making. For example, installations in new housing units might involve a lower interest rate because new home mortages carry a lower interest rate than do home improvement loans. Also, the thermal performance values (TI) differ for new and existing housing units.

In these new equipment market share equations,* consumer choices are functions of both operating cost (fuel price x equipment energy use) and equipment cost. This formulation provides a strong link within the simulation model between technological changes (in EUN, TI, and/or PEQ) and economic changes (in fuel prices).

The EU terms (average annual equipment energy use) are calculated within the model based on EUN values, equipment lifetimes, and existing stocks of equipment:

$$EU_t^{ikm} = \frac{EUN_t^{ikm}\ CN_t^{ikm}\ NU_t^{km} + EU_{t-1}^{ikm}\ C_{t-1}^{ikm}\ HT_{t-1}^{m}\ (1 - R^k)}{C_t^{ikm}\ HT_t^m} ,$$

EUN values can be calculated within the model as functions of the technology relationships and implicit interest rates, as discussed in Section 5. Alternatively, EUN values can be supplied as inputs to the simulation model to reflect imposition of equipment/appliance efficiency standards. When such standards are imposed, the model calculates EUN as

*We use an upper limit of 1.2 (rather than 1.0) in the logit equation for refrigerators and an upper limit of 2.0 for lighting. Thus we assume that the number of refrigerators per household can increase by no more than 20% and the number of lighting fixtures per household can increase by no more than 100%, relative to 1970 ownership.

explained in Section 5 and compares calculated values with the imposed standards. The lower of the two values is then used within the model.

The TI terms (applicable only for space heating and air conditioning) are derived in a manner similar to that for the EU terms. However, TI can change in two ways within the model: for new housing units* and for existing units (retrofit). The simulation program keeps track of new housing construction, removals of past housing stocks, and the appropriate values of TI for each fuel, end use, housing type combination.

The usage terms (U) are determined by equations of the form:

$$ln\left(\frac{U_t^{ik} - 0.5}{1.5 - U_t^{ik}}\right) = E^{ik} + F^{ik} \bullet ln\ (X_t^j \bullet EU_t^{jkm} \bullet TI_t^{jkm}) + G^{ik} \bullet ln\ Y_t + H^{ik} \bullet ln\ U_{t-1}^{ik}.$$

where

E, F, G, H = coefficients derived from usage elasticities discussed in Section 4.

This logit formulation ensures that the intensity with which household equipment is used varies by no more than ±50% from the 1970 usage. These upper and lower bounds are set so that major improvements in equipment efficiency (e.g., solar water heating systems that use only 1/4 as much energy as conventional systems) do not yield ridiculously high usage values.

The intensity with which households use equipment depends on incomes and the operating cost for that type of equipment. Here again, energy use depends on both technological and economic factors.

The model also requires a set of initial conditions for 1970. These 1970 data include equipment ownership (market shares),[8] annual

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*Thermal performance for new structures (TIN) is treated the same way as is EUN: the model can either accept thermal standards for new construction as inputs or calculate free market changes in TIN.

equipment fuel use,[1,26] equipment prices,[20,24,27] and new equipment installations - for each fuel/end use/housing type combination. Fuel prices[28] and housing stocks[8] are also required.

Finally, a set of boundary conditions for the 1970-2000 period must be input to the model. These inputs include stocks of occupied housing units and new construction (from the housing submodel of Section 2), fuel prices, incomes, new equipment standards, thermal performance standards for new structures, thermal performance for retrofit programs, and characteristics of new technologies. Changing some or all of these inputs allows the user to evaluate the energy, energy expenditure, and capital cost impacts of various residential energy conservation policies, programs, and technologies.*

Outputs produced by the simulation model include 192 fuel use components (Fig. 20) calculated for each year from 1970 through 2000. The model calculates, at the same level of detail, new equipment installations, equipment ownership, average equipment energy use, equipment expenditures, average thermal performance, thermal performance expenditures, and usage factors. Thus the outputs produced by the simulation model are quite detailed; approximately 540 different quantities are calculated for each year of a simulation run.

Table 12 shows the short- and long-run fuel price and income elasticities obtained with the simulation model. The model was run six times

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*Not all conservation policies can be evaluated with this model. Strategies that affect electric and gas utility rate structures (rather than average prices) such as time-of-day pricing, changes in block rate structures, and elimination of master-metering cannot be handled with the model. Changes in consumer attitudes and awareness (in response to information and education programs) cannot be explicitly modeled.

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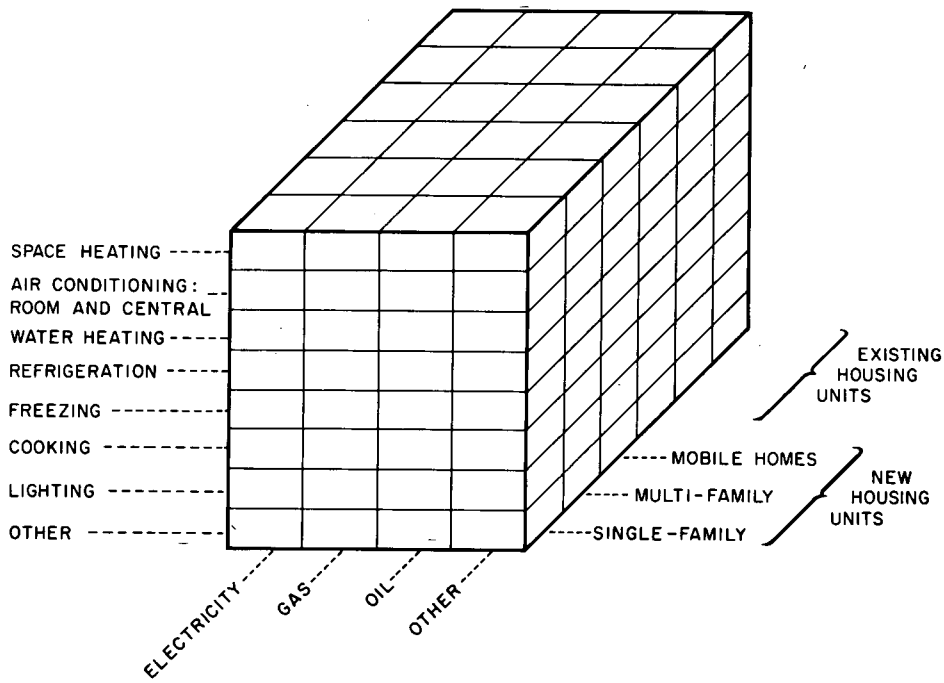

Fig. 20. Level of detail provided by simulation model for fuel uses, equipment ownership, new equipment installations, fuel costs, equipment costs, and structure thermal performance costs.

Table 12. Elasticities obtained with the ORNL residential energy use model

	Price of:				
	Electricity	Gas	Oil	All fuels	Income[a]
Electricity					
short-run	-0.16	0.02	0.0	-0.13	0.14
long-run	-0.83	0.20	0.04	-0.61	0.43
Gas					
short-run	0.02	-0.20	0.01	-0.17	0.14
long-run	0.16	-0.95	0.12	-0.67	0.58
Oil					
short-run	0.01	0.04	-0.22	-0.18	0.11
long-run	0.04	0.68	-1.13	-0.49	-0.13
Total					
short-run	-0.06	-0.05	-0.04	-0.15	0.13
long-run	-0.37	-0.10	-0.10	-0.59	0.36

[a]Income elasticities include the effects of income on household formation, housing size, and fuel use per household.

to obtain these elasticities: once with fuel prices held constant at their 1970 values from 1970 through 2000, and then with prices of individual fuels, income, or all fuels increased by 10% in 1971 and held constant thereafter. The values in Table 12 are the elasticities calculated for 1971 and 2000. These numbers suggest that, in the long-run, a 10% increase in the price of all fuels will cut energy demand by 6%. Similarly, a 10% increase in incomes will, in the long-run, increase energy demand by almost 4%.

7. MODEL VALIDATION

Results obtained with the simulation model are compared with historical data for the 1960-1976 and 1970-1976 periods. Comparisons are performed between data and predictions for: annual consumption of electricity, gas, oil, and total residential energy; equipment ownership market shares; and energy use distributions by end use.

In addition to the input data required for the initial year (1960 or 1970) discussed in Section 6, the user must specify new equipment market shares (CN values). Adequate data are not available with which to determine these CN values. Therefore, we adjust these inputs (4 fuels x 8 end uses = 32 values) so that the model predicts equipment ownership market shares at the next census year (1970[8] for the run started in 1960, 1973[15] for the run started in 1970) with reasonable accuracy.

Also, the user must specify three usage factor ratios (U_{1959}/U_{1960} or U_{1969}/U_{1970}) for electricity, gas, and oil. We adjust these values until the model's predictions for the first few years after the simulation begins are reasonably accurate.

Because of these 35 "free" inputs, the model accurately predicts energy use for at least a few years after the simulation begins.

Figure 21 compares model predictions of residential fuel uses (electricity, gas, oil, total) with data from 1960 through 1976.[28] The model slightly underpredicts total energy use in the late 1960's and overpredicts energy use in the mid 1970's. The discrepancies, however, are minor: the largest error in the model's prediction is 7% for 1974 and 1975.

Predictions of gas use are quite good until the late 1960's. Then, predicted gas use consistently exceeds actual gas use. This is primarily due to gas shortages and curtailments that first appeared in the late 1960s and became more serious in the early 1970s. Predictions of oil

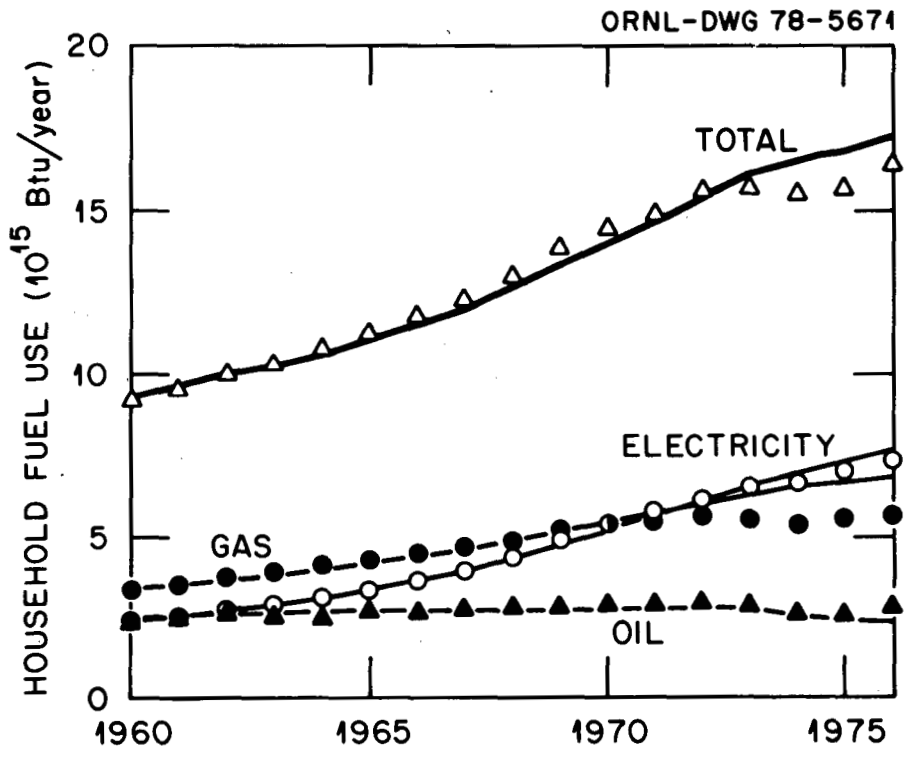

Fig. 21. Comparisons of residential energy use data and model predictions, 1960 to 1976.

use are good. The sharp decline in oil use that occurred between 1973 and 1974 is captured by the model. Electricity use predictions are quite accurate throughout the 17 year period.

Table 13 presents values of the mean square percentage error (MSPE)* for the 1960-76 and 1970-76 periods from the 1960-76 run and for the 1970-76 period from the 1970-76 run. These MSPE values show that the 1960-76 run does a much better job for the full 17 years than for the last seven years. However, the MSPE for total residential fuel use is quite low for both periods. Fortunately, the errors in predicting individual fuel uses tend to cancel each other.

Table 13. Comparison of residential energy use predictions and data

	Mean square percentage error (%)		
	1960-76 simulation		1970-76 simulation
	1960-76	1970-76	1970-76
Electricity	2.4	3.2	3.2
Gas	9.5	14.4	2.7
Oil	5.6	7.8	6.4
Total	3.5	4.8	1.8

Starting the model in 1970 yields smaller values for MSPE than those obtained for the same six year period with the 1960-76 run. The 35 1970 CN and 1969/1970 U inputs start the simulation in the right direction. The major difference between the two simulation runs concerns gas use. Starting the model with 1970 data implicitly captures the

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*

$$\text{MSPE} = 100 \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(\frac{\text{prediction}_i - \text{data}_i}{\text{data}_i} \right)^2} .$$

effects of natual gas shortages. Thus, the overprediction of gas shown in Fig. 21 does not occur with the 1970-76 run.

Table 14 compares model predictions (from the 1960-76 run) with Census estimates of equipment ownership market shares for 1970 and 1975.[8,15,29] (Comparisons between these data and results from the 1970-76 run are not shown because the 1970-76 run yields excellent predictions, primarily because of the user-specified 1970 CN values.) The 1970 predictions are very close to Census data, primarily because we adjusted the 1960 CN values to ensure a close fit. Predictions of electric equipment market-shares for 1975 are slightly lower than actual values; predicted values of gas equipment ownership for 1975 are higher than

Table 14. Comparison of actual and predicted values of equipment ownership market shares (%)[a]

	1960	1970		1975	
	Actual	Actual	Model	Actual	Model
Space heating					
Electricity	1.8	7.7	8.2	12.6	11.0
Gas	43.2	55.2	53.9	56.4	58.5
Oil	32.5	26.0	26.0	22.5	22.1
Other/none	22.5	11.1	11.9	8.5	8.4
Air conditioning					
Room	10.5	25.0	23.9	29.4	31.4
Central	1.9	10.7	12.3	20.0	18.8
None	87.6	64.3	63.8	50.6	49.8
Water heating					
Electricity	20.4	25.4	25.9	30.3	28.5
Gas	47.5	55.0	53.7	53.7	56.8
Oil	11.7	9.8	10.3	8.9	8.5
Other/none	20.4	9.8	10.1	7.1	6.2
Food Freezing	18.4	28.2	28.7	35.0	33.0
Cooking					
Electricity	30.9	40.7	41.1	46.8	44.3
Gas	51.5	49.1	48.5	44.8	48.2
Oil	1.1	0.5	0.5	0.1	0.4
Other/none	16.5	9.7	9.9	8.3	7.1

[a]Actual equipment ownership market shares are from refs. 8, 15, and 29.

actual values. These differences are probably due to gas shortages; these errors also account for discrepancies in fuel use predictions shown in Fig. 21. Predictions of oil equipment market-shares (space heating, water heating) are quite close to the Census estimates. Finally, predictions of freezer and air conditioner ownership are good.

Table 15 shows a comparison between the 1960-76 simulation predictions of residential energy use by end use for 1970 and 1975 with estimates obtained from refs. 8, 15, 26, and 28.* Predicted distributions for both years are close to the actual distributions. The model overpredicts energy use for water-heating and space heating and slightly underpredicts electricity use for refrigerators and for other purposes. The refrigerator underprediction is caused by changes in the characteristics of refrigerators purchased during the 1960s. These new units were larger than their replacements and much more likely to have automatic defrost features. Thus, the new units consumed more electricity than did their replacements.

*The comparisons in Table 15 should not be taken too seriously because of the difficulties associated with estimating "actual" energy use by end use.

Table 15. Comparison of actual and predicted household energy end use distributions[a]

	1970 (percent)		1975 (percent)	
	Actual	Model	Actual	Model
Space heating	55	57	52	54
Air conditioning	5	6	7	8
Water heating	14	16	14	16
Refrigeration	6	5	6	5
Food Freezing	2	2	2	2
Cooking	5	5	5	5
Lighting	6	4	6	4
Other	8	6	8	6
Total	101	101	100	100

[a]Actual energy end use distributions are estimated from data in refs. 8, 15, 26, and 28.

Underprediction of other electricity uses is probably due to lack of disaggregation within the model of these uses: dishwashers, washing machines, clothes dryers, televisions, and other small appliances.

These results suggest that the simulation model accurately predicts historical residential energy use trends and patterns for the 1960-1976 period. Close agreements between data and predictions for aggregate energy use, energy use by fuel, energy use by end use, and equipment ownership market shares lend confidence to our use of the model to simulate future residential energy use trends and patterns.

8. PROJECTIONS TO THE YEAR 2000

We develop two projections of residential energy use: a baseline that includes no government conservation programs and a case that includes the programs proposed in the *National Energy Plan*[30] and new residential technologies developed because of government and private industry research programs.[31] Differences between the two projections provide estimates of the energy and economic effects of implementing these conservation programs.

We assume that population grows according to the Bureau of the Census Series II projection.[12] Per capita income is derived from a DRI projection of GNP[13] and the population projection. Projections of household formation, stocks of occupied housing units, and average housing unit size are from our housing submodel. In developing our estimates of housing stocks, we assume that trends in housing choices (among single-family, multi-family, and mobile homes) between 1960 and 1970 will continue through the end of the century. Fuel prices are from the Department of Energy and the Brookhaven National Laboratory.[13]

Table 16 shows the values of population, households, fuel prices, and incomes from 1970 through 2000 used in the baseline projection. Between 1976 and 2000, population grows at an average annual rate of 0.8%, while the number of households grows at 1.6%. Higher growth in household formation is due to income growth (2.4%/year) and the changing age composition of the population. Gas prices are projected to increase substantially during this period (3.1%/year), while oil (1.7%/year) and electricity (1.0%/year) prices increase more slowly.

Figure 22 shows the projection of energy use to the year 2000 produced by our model using the inputs discussed above. The model estimates that fuel use will grow from 14.4 QBtu in 1970 to 16.3 QBtu in 1976, 17.7 QBtu in 1980, and 24.9 QBtu in 2000. Average annual growth rate in energy use from 1976 to 2000 is 1.8%, compared with 3.6%/year from 1950 to 1976.[28] Energy use per household grows at an average annual rate of 0.2% between 1976 and 2000, compared with 1.6%/year between 1950 and 1976.[28] Growth in energy use to the year 2000 is slower than during the past 26 years because of higher and rising fuel prices, slower growth in per capita income, and slower growth in population and households.[30]

Table 16. Inputs used in the baseline projection of residential energy use to 2000

	Population (10^6)	Households (10^6)	Fuel prices (1975-\$/10^6 Btu)			Per capita income (1975-\$)
			Electricity[a]	Gas	Oil	
1970	205	63	2.53	1.47	1.84	5,420
1975	214	71	2.78	1.69	2.81	5,850
1976	215	73	2.83	1.88	2.83	6,050
1980	222	80	3.01	2.18	3.16	7,150
1985	233	88	3.16	2.60	3.46	7,970
1990	244	95	3.31	3.04	3.70	8,890
2000	260	106	3.57	3.94	4.20	10,570

[a]Recall that electricity is given in terms of primary energy.

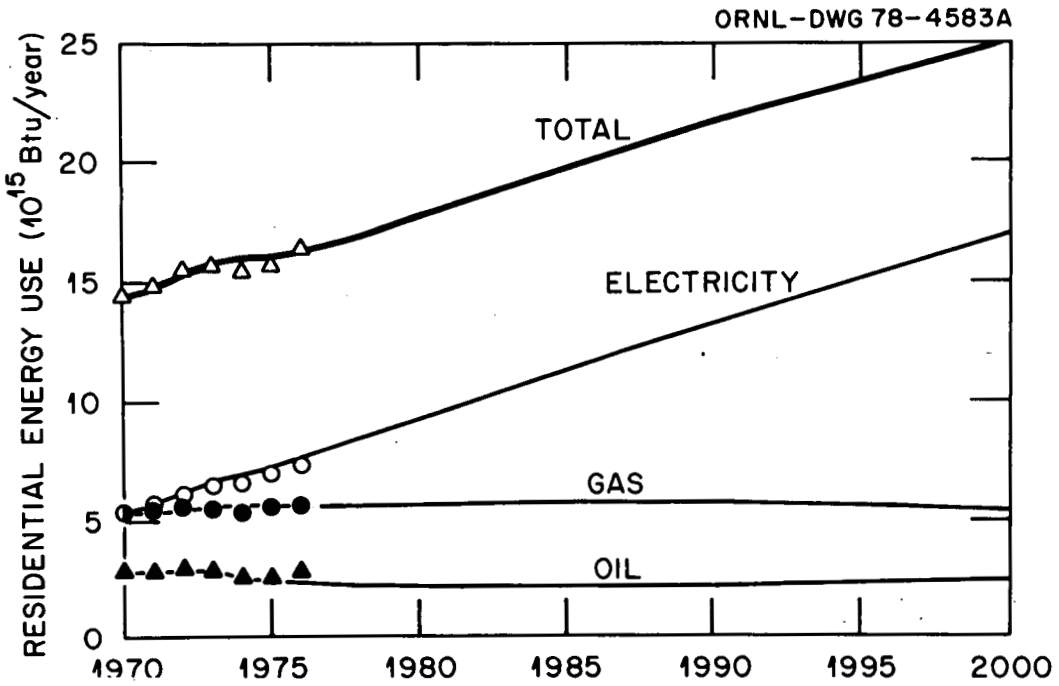

Fig. 22. Baseline projection of residential energy use.

Figure 23 shows the distribution of energy use by fuel. Electricity use grows rapidly at 3.4%/year from 1976 to 2000, while gas and oil uses remain essentially constant. These differences in fuel use growth are due to historical equipment choice preferences (ref. 28), different fuel price trajectories (Table 16), and differences in price elasticities for each fuel (Table 12). Because of these changes, the share of household energy accounted for by electricity increases from 47% in 1976 to 68% in 2000.*

The distribution of energy by end use is shown in Fig. 24. Space heating (the most important end use for the entire period) declines in

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*Treating electricity in terms of end use energy (3,412 Btu/kwhr), its share of household energy use increases from 21% in 1976 to 38% in 2000. The share contributed by gas declines from 51 to 41%, that by oil from 22 to 18%, and that by other fuels from 6 to 3%. In terms of primary energy, electricity is the dominant household fuel throughout the projection period. In terms of end use energy, gas is the dominant fuel.

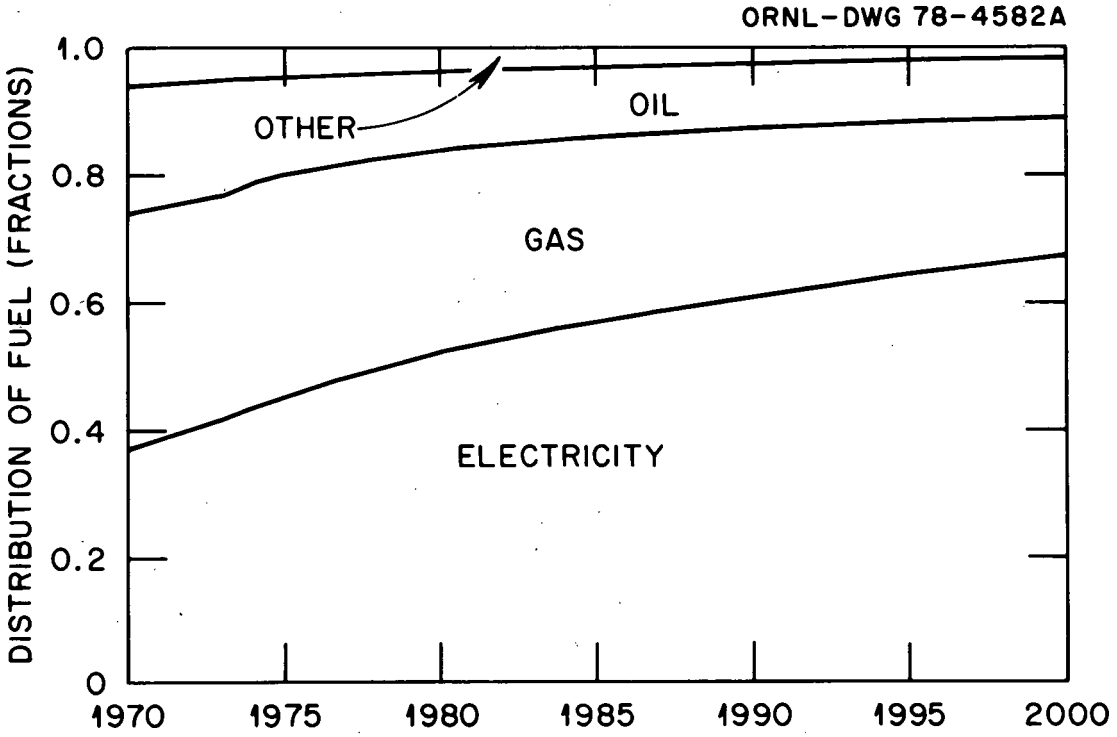

Fig. 23. Baseline projection distribution of residential energy use by fuel.

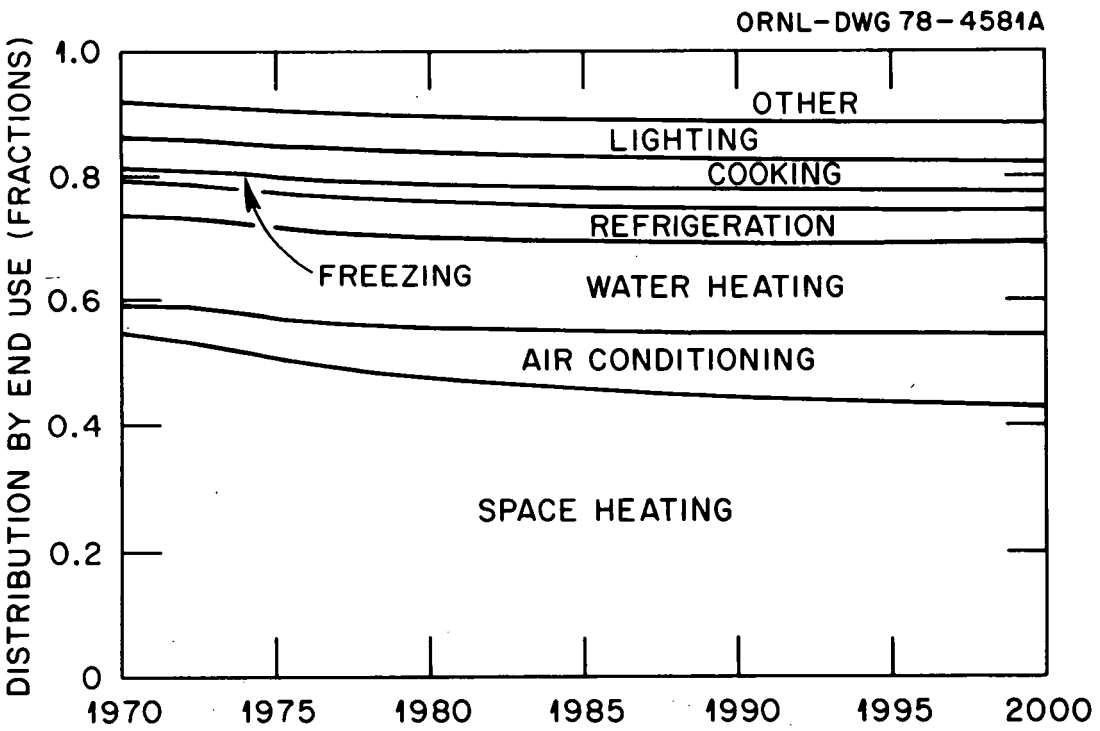

Fig. 24. Baseline projection distribution of residential energy use by end use.

importance from 50% in 1976 to 43% in 2000. Air conditioning, on the other hand, increases its share of the total from 7% to 12% between 1976 and 2000. Shares of energy accounted for by other end uses remain nearly constant.

The second projection includes several conservation programs. Because these programs and our analyses of them are discussed in detail elsewhere (refs. 30 and 31), we only summarize results here. This case includes higher prices for oil (about 5%) and gas (15%) because of the proposed changes in price regulations in the *National Energy Plan*, shown in Fig. 25; regulations concerning efficiency of new household equipment, appliances, and structures; information and incentive programs to encourage weatherization of existing homes; and the introduction of new residential technologies (e.g., advanced electric heat pumps, gas-fired heat pumps, LITEK lamp) produced as a result of private and government RD&D.

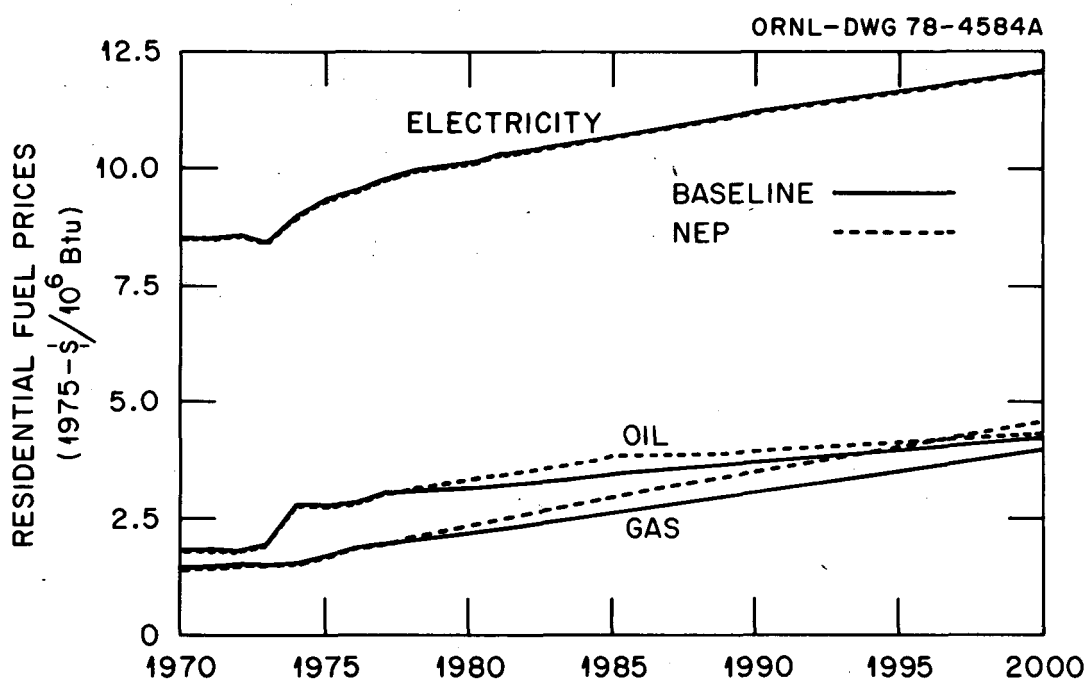

Fig. 25. Projections of real residential fuel prices, with and without *National Energy Plan*.

Figure 26 and Table 17 summarize the effects of these programs on residential energy use and household economics. Energy use is cut by 7% in 1980, 14% in 1990, and 17% in 2000. Overall, these programs reduce energy growth from 1.8 to 1.0%/year.

Between 1977 and 2000 a total of 64 QBtu are saved because of these programs. Almost half the savings are electricity; gas and oil account for almost 40% and almost 20%, respectively. The present worth of

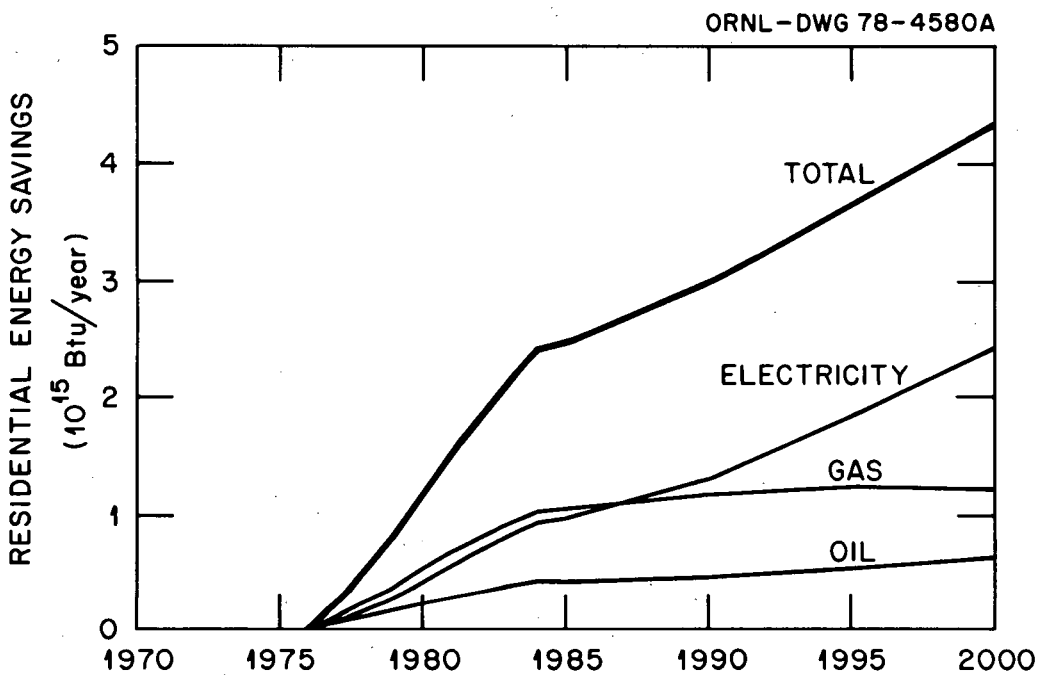

Fig. 26. Energy savings due to residential conservation programs.

Table 17. Cumulative (1977-2000) energy and economic effects of conservation programs

Energy	(QBtu)	Economic[a]	(billion 1975-$)
Electricity	30	Fuels	54
Gas	24	Equipment	-10
Oil	10	Structures	-21
Total	64	Net	23

[a]Present worth calculations are performed with a real interest rate of 8%.

reduced household fuel bills is $54 billion. This is partly offset by the present worth of increased expenditures on improved equipment and structures ($31 billion). Thus the net benefit to society (exclusive of the cost of government programs) is $23 billion. From the standpoint of the typical household, the benefit/cost ratio for these programs is 1.7.*

9. UNCERTAINTY

Despite the precision with which computer models yield outputs, the results themselves are subject to at least four kinds of uncertainties:[32]

1. Parameter estimation - the data and statistical techniques used yield model coefficients that are uncertain. For example, the fuel price and income elasticities used in our model are estimates of the (unknown) actual values. Similarly, the parameters that define engineering relationships between equipment energy use and capital cost are known only approximately.

2. Exogenous variables - incorrect assumptions about trajectories for the independent variables will yield incorrect projections of the dependent (endogenous) variables. For example, uncertainties in our assumed fuel price and per capita income trajectories lead to uncertainties in our estimates of future residential energy use.

3. Misspecification - Use of the incorrect form for equations (e.g., log-log vs linear) or omission of important variables can lead to incorrect projections. In our model, for example, the age structure of the population does not influence either the choice of household goods or the intensity with which they are used. One might expect households with children to use more energy for water heating (showers, laundry, food preparation) than would older families with no children at home.

4. Structural change - Models are constructed with historical data that encompass certain ranges in the dependent and independent variables. Systems might behave differently outside these historical ranges. For example, we assume in our model that consumer choices among competing systems (e.g., water heaters) vary smoothly as functions of capital and

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*The Appendix contains the computer output summary pages (from the simulation model) for the two cases discussed in this section.

†The analysis and discussion in this section are motivated by the ideas and suggestions presented by René Malès (Electric Power Research Institute) in discussions at ORNL and in his draft paper, ref. 32.

operating costs. However, consumer behavior may change abruptly at some unknown high level of fuel prices. The existence of thresholds and discontinuities in future behavior are possible, but are not incorporated into our model. Also, new energy-intensive residential functions might become very important in the future. (In 1950, less than 1% of the nation's households were air-conditioned; today more than 50% are air-conditioned.)

The third and fourth problems are extremely difficult to treat quantitatively; they are not discussed further. The second problem (independent variables) is best handled by running several different scenarios in which independent variables are changed. Our earlier studies present results of these scenario exercises (refs. 30 and 31); also the sensitivity of model results to independent variables is given by elasticities, as shown in Tables 3, 4, 6, 7, 8, and 12.

This section treats the first problem - uncertainty in parameter estimates. Ideally, we should specify an expected value (mean) and a distribution function for each of the approximately 300 coefficients in our energy model. Then, we should run the simulation model several hundred times, allowing the parameters to vary randomly for each run. The results of such a Monte Carlo simulation exercise would reveal the sensitivity of model results (e.g., a distribution of model outputs for energy use in 2000) to variations in these parameters.

We do not perform such an exercise. As our discussions in Sections 2-6 indicate, the parameters in our model are based only in part on statistical analysis. Thus we have no rigorous method for defining a distribution function (or even a standard deviation) for each coefficient. Even if we could, the cost in both computer programming and computing time to conduct such a Monte Carlo simulation would be prohibitive.

Therefore, we use a simpler approach to evaluate the sensitivity of model results to variations in parameter estimates. We define two sets of

values for those parameters that most strongly influence model results - one set of values to yield a high projection of energy use and one set to yield a low projection.

Table 18 lists the parameters that we varied in these runs, the assumed variation, and the section in this report where these parameters are discussed. Our upper and lower limits for these parameters are guesses at reasonable values. For example, our review of econometric analyses of household fuel choices[24] suggests that own-price market share elasticities are known with much greater reliability than are cross-price elasticities. Hence, we vary the cross-price elasticities in this exercise by ±25%. Similarly, values of usage elasticities with respect to both own-price and income are based primarily on judgments and engineering feasibility. So we vary these values by ±25%.

In actuality, it is unlikely that our parameter estimates are all too low (or too high) by 25%. In a Monte Carlo simulation, these parameters

Table 18. Variations in parameter estimates

Parameter		Change		Section
		High	Low	
Cross-price market share elasticities	E_{ms}	+25%	-25%	4
Own-price usage elasticities	E_u	-25%	+25%	4
Usage elasticities with respect to income	E_u	+25%	-25%	4
Equipment technology characterization exponents	A	-25%	+25%	3
New structure technology characterization exponents	A	-25%	+25%	3
Exponent in market penetration submodel	n	0.5	2.0	5

would be varied randomly so that some would increase while others would decrease in each run. In our case, we vary the parameters together to their "extreme" values to yield either a high projection or a low projection of energy use. (On the other hand, 25% is not necessarily the outer limit on the uncertainty associated with these parameters.)

Thus we vary 76 of the 310 parameters in the model. Our judgment and previous simulation runs suggest that the influence of the other parameters on energy use projections is much less.

We ran our baseline case (discussed in the preceding section) with the two adjusted sets of parameters. Figure 27 shows the original baseline and the two perturbed runs. Clearly, changing these 76 parameters affects projections of residential electricity, gas, oil, and total fuel use. However, the variation in results is less than one might expect. For example, although the parameters are varied by ±25%, the variation in

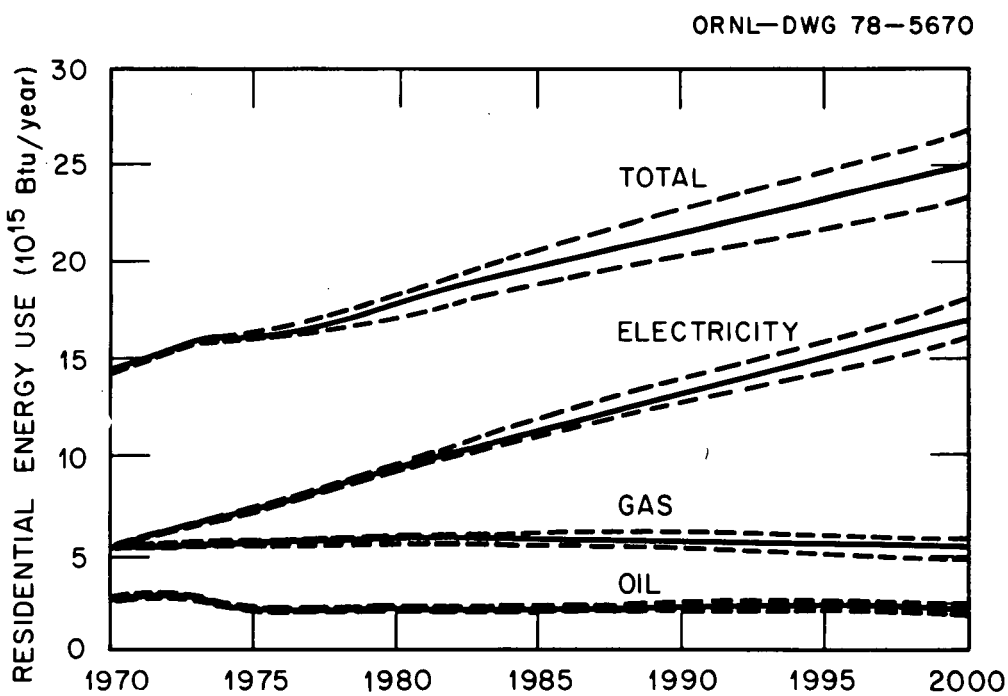

Fig. 27. Effects of parameter variation on projections of residential energy use: baseline.

total energy use is only ±3% in 1980, ±6% in 1990, and ±8% in 2000. Thus, feedbacks within the energy model dampen the effects of coefficient variation. Figure 27 also shows that the variation in results is approximately symmetrical about the nominal baseline. The percentage variation in projections is greatest for oil (±18% in 2000) and least for electricity (±6% in 2000). This variation is probably due to differences in space heating energy use among fuels.

We also reran the conservation case discussed in the last section with the two sets of parameters (Fig. 28). The variation in energy projections is less than for the baseline case: ±6% in 1980 and 1990 and ±7% in 2000. However, the variation around the nominal conservation case is not symmetrical. The government regulatory programs limit growth in energy use and reduce the high-side variation.

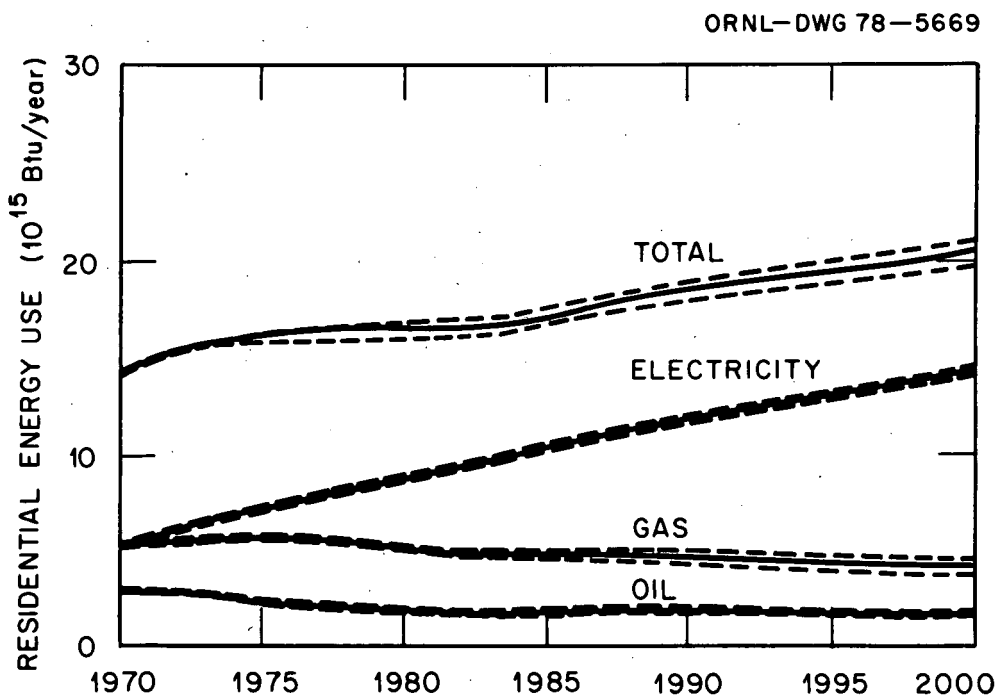

Fig. 28. Effects of parameter variation on projections of residential energy use: conservation case.

Finally, we evaluate the effects of parameter variations on differences between the baseline and conservation cases; see Fig. 29. The variation in estimated energy savings among the three cases (high, nominal, low) is less than the variation in baseline energy use, but more than the variation in the conservation case energy use. We had expected that variations in parameter estimates would affect all runs in roughly the same fashion. This particular exercise suggests that such is not the case. The effects of parameter variation are much larger for the base case (Fig. 27) than for the conservation case (Fig. 28). Therefore, the variation in estimated energy savings falls in between the two ranges (Fig. 29).

Table 19 shows the cumulative energy and economic benefits for the conservation programs discussed in the preceding section for the three sets of parameters. Although the estimated energy and economic benefits

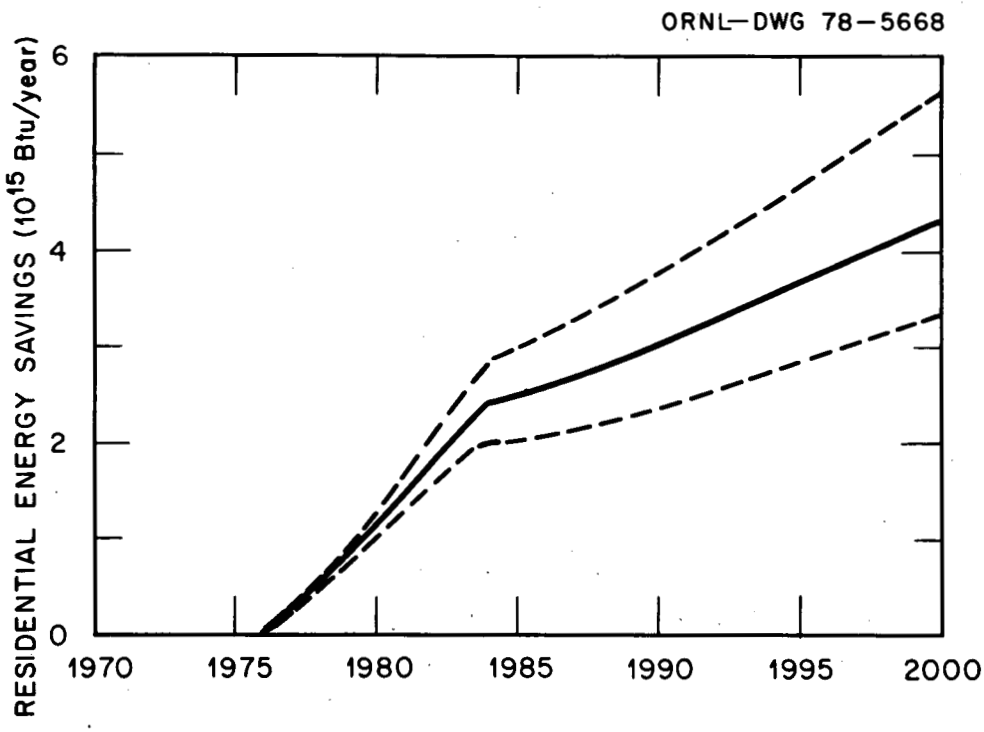

Fig. 29. Effects of parameter variation on projections of residential energy savings.

Table 19. Cumulative (1977-2000) energy and economic effects of conservation programs: sensitivity to model parameters

	Energy (QBtu)				Economic[a] (billion 1975-$)		
	High	Nominal	Low		High	Nominal	Low
Electricity	40	30	22	Fuels	71	54	41
Gas	27	24	21	Equipment	-12	-10	- 9
Oil	14	10	8	Structures	-24	-21	-25
Total	81	64	51	Net	35	23	7

[a]Present worth calculations are performed with a real interest rate of 8%.

depend on the coefficients, these results show positive savings for all three sets of coefficients.

These results suggest that projections of energy use (and economic effects) produced with our simulation model are not too sensitive to reasonable variations in the estimates of key coefficients. This fortunate occurrence is due primarily to feedbacks within the model. For example, if equipment efficiencies are more costly to implement (i.e., we reduce the A coefficients), then usage will adjust more than it otherwise would to compensate for the increased operating cost of equipment.

10. SUMMARY

The model developed here simulates national energy use on an annual basis for four fuels, eight end uses, and three housing types. Each of these fuel use components is determined within the model as a function of housing stocks and new construction, housing size, equipment installations and ownership by fuel and end use, energy efficiencies for new and existing equipment, thermal performance for new and existing housing units, and usage factors that reflect household behavior. These factors, in turn, are functions of fuel prices, equipment prices, incomes, and technologies.

Thus, the residential simulation model is sensitive to the major demographic, economic, and technological determinants of residential energy use.

Comparisons of model results with data from 1960 to 1976 show that the model accurately predicts residential energy use in aggregate, by fuel, and by end use. Predictions of equipment ownership market shares are also good.

We have been using, and continue to use, our model for our program sponsors in DOE to evaluate a variety of conservation programs. We examined the energy and economic impacts of different levels of appliance efficiency standards, standards for construction of new homes, and different incentives to encourage weatherization of existing housing units.[30] We also evaluated the likely market penetration and consequent energy and economic effects of developing new residential technologies such as gas-fired heat pumps and high efficiency refrigerators.[31]

In addition, we used our model for the Congressional Office of Technology Assessment to evaluate the potential of new conservation programs; the President's Council on Environmental Quality to understand recent trends in residential energy use; and the President's Council of Economic Advisers to evaluate the potential savings of different retrofit programs. Our model was used in the National Academy of Sciences study on nuclear and alternative energy systems (CONAES) to develop alternative projections of residential energy use under different fuel price and income assumptions. Finally, we used our regional models for the General Accounting Office to estimate future trends in electricity demand in the TVA region.

The present version of our residential energy use model is much more flexible, detailed, and powerful than were earlier versions. In partic-

ular, the present version has more detail with respect to new equipment installations in new and existing housing units, more detail in the specification of technology relationships, more flexibility in the market penetration algorithm, and better equations for estimating household formation and housing size. Nevertheless, our model is far from perfect. Limitations that should be addressed include:

1. Improved econometric estimates of price elasticities. The weakest part of our present model relates to the equipment market share and usage elasticities. These elasticities are obtained with an inadequate (and to some extent, inaccurate) data base, poorly specified models, and are based on a time period that may not relate well to future changes (see discussion of uncertainties in Section 9). We are presently re-estimating our overall fuel demand models (similar to those in ref. 23) in an effort to address these problems.

2. Market penetration. Our model contains a simple algorithm, described in Section 5, that estimates changes in new equipment and structure efficiencies over time as functions of consumer interest rates, fuel prices, and available technologies. However, our model is ad hoc; it lacks a theoretical basis and empirical validation. We are presently reviewing the literature on market penetration models and hope to develop an improved model within a year.

3. Housing choices. Our present housing model is a great improvement over earlier versions. However, housing choices are determined entirely by user assumptions. We hope to replace these assumptions with a set of equations that share households among housing types as functions of age of household head, housing prices, incomes, and other relevant economic and demographic variables.

4. Improved characterization of residential technologies. We are continuing our engineering analysis of residential structures and have begun to analyze the energy use/capital cost relationships for solar water and space heating systems.

5. Equipment decay rates. We presently assume that residential equipment and structures decay at an exponential rate. This greatly simplifies calculations within the model. However, the limited data available on equipment lifetimes suggest a decay function that is more nearly logistic, in which very few units are discarded during the first few years, then during a middle period many units are discarded, and finally a few units last for very long times. As new data on equipment and structure lifetimes become available, this information should be incorporated into the model using a more realistic (and computationally burdensome) decay function.

6. Other end uses. Our energy model does not explicitly allow for the introduction of new end uses (e.g., sidewalk deicing, swimming pool heating, inside air filtration). The model includes an "other" end use that is allowed to grow as income rises, depending on growth in fuel prices. However, this may not adequately account for the possible introduction and adoption of some new energy-intensive uses.

7. Data. Because the model is so detailed, it requires a very disaggregate data base. The lack of sufficiently detailed accurate data forced us to make various engineering approximations and personal judgments. Improved data are becoming available and this will allow us to refine these approximations and assumptions.

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APPENDIX: Computer Output for the Baseline and Conservation Case

RESIDENTIAL ENERGY USE SIMULATIONS, 1970-2000, VERSION 5 (DECEMBER 1977), OAK RIDGE NATIONAL LABORATORY
BASELINE --- NO GOVERNMENT PROGRAMS — ELECTRICITY IN TERMS OF PRIMARY ENERGY

SUMMARY OF PROGRAM OUTPUTS

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1983	1985	1990	1995	2000
HOUSING STOCK (MILLIONS)																	
SNGL	43.99	44.68	45.63	46.35	47.13	47.74	48.46	49.35	50.20	51.07	51.89	52.64	54.25	55.74	59.32	62.37	65.11
MULT	17.37	17.95	18.72	19.39	20.06	20.70	21.43	22.14	22.84	23.59	24.33	25.01	26.27	27.54	30.42	32.49	34.49
MOBL	2.05	2.18	2.35	2.50	2.65	2.80	2.97	3.13	3.29	3.47	3.65	3.82	4.16	4.50	5.37	6.13	6.87
TOTAL	63.41	64.82	66.69	68.23	69.83	71.24	72.86	74.63	76.34	78.13	79.86	81.47	84.68	87.78	95.11	100.99	106.47
NEW HOUSING UNITS STOKN (MILLIONS)																	
SNGL	0.0	1.06	1.31	1.08	1.13	0.96	1.07	1.25	1.21	1.24	1.19	1.13	1.17	1.13	1.09	1.03	0.99
MULT	0.0	0.72	0.90	0.80	0.80	0.78	0.86	0.86	0.85	0.90	0.89	0.84	0.80	0.81	0.71	0.67	0.61
MOBL	0.0	0.22	0.25	0.25	0.25	0.26	0.28	0.29	0.29	0.31	0.32	0.33	0.34	0.36	0.38	0.40	0.42
TOTAL	0.0	1.99	2.46	2.13	2.19	2.00	2.22	2.39	2.35	2.45	2.41	2.30	2.30	2.30	2.17	2.10	2.02
FUEL USE BY FUEL TYPE (QBTU)																	
ELEC	5.36	5.73	6.21	6.66	7.01	7.29	7.63	8.02	8.42	8.84	9.26	9.66	10.47	11.27	13.23	15.04	16.85
GAS	5.35	5.39	5.47	5.58	5.66	5.64	5.58	5.57	5.58	5.61	5.64	5.68	5.72	5.73	5.70	5.56	5.34
OIL	2.86	2.86	2.90	2.88	2.60	2.43	2.35	2.27	2.21	2.18	2.16	2.15	2.14	2.14	2.17	2.25	2.37
OTHR	0.86	0.84	0.82	0.80	0.77	0.75	0.74	0.72	0.70	0.68	0.67	0.65	0.61	0.58	0.51	0.44	0.38
TOTAL	14.44	14.83	15.40	15.91	16.05	16.12	16.29	16.57	16.91	17.32	17.73	18.15	18.95	19.71	21.61	23.28	24.93
FUEL USE BY END-USE FUNCTION (QBTU)																	
SPACE HEAT	7.89	8.01	8.24	8.41	8.29	8.17	8.12	8.14	8.20	8.31	8.41	8.55	8.80	9.02	9.61	10.13	10.67
AIR COND	0.67	0.75	0.84	0.94	1.00	1.05	1.11	1.18	1.25	1.34	1.42	1.51	1.67	1.83	2.23	2.59	2.93
WATER HEAT	2.07	2.13	2.20	2.27	2.32	2.35	2.38	2.44	2.49	2.55	2.60	2.66	2.76	2.87	3.15	3.41	3.69
REFRIG	0.83	0.84	0.87	0.89	0.91	0.93	0.95	0.97	0.99	1.01	1.03	1.05	1.09	1.12	1.19	1.24	1.28
FREEZERS	0.29	0.31	0.33	0.35	0.37	0.39	0.41	0.43	0.45	0.46	0.48	0.50	0.53	0.56	0.63	0.68	0.73
COOKING	0.69	0.71	0.73	0.75	0.77	0.79	0.81	0.83	0.85	0.87	0.89	0.91	0.94	0.98	1.06	1.12	1.17
LIGHTING	0.82	0.84	0.87	0.90	0.92	0.92	0.93	0.95	0.97	1.00	1.03	1.06	1.11	1.16	1.29	1.41	1.53
OTHER	1.18	1.24	1.32	1.39	1.46	1.52	1.58	1.64	1.71	1.78	1.85	1.92	2.04	2.17	2.46	2.71	2.94
FUEL USE BY HOUSING TYPE (QBTU)																	
SNGL	11.36	11.60	11.97	12.30	12.32	12.29	12.34	12.48	12.67	12.90	13.13	13.39	13.86	14.34	15.48	16.53	17.55
MULT	2.68	2.79	2.95	3.10	3.18	3.25	3.35	3.45	3.56	3.69	3.82	3.94	4.16	4.38	4.91	5.32	5.75
MOBL	0.40	0.43	0.48	0.52	0.55	0.58	0.61	0.65	0.69	0.73	0.78	0.82	0.91	1.00	1.22	1.43	1.64
ANNUAL FUEL COSTS BY FUEL TYPE (BILLIONS OF 1975 DOLLARS)																	
ELEC	13.56	14.51	15.87	16.68	18.81	20.28	21.62	23.34	24.91	26.39	27.88	29.58	32.59	35.63	43.85	51.74	60.09
GAS	7.87	8.00	8.37	8.45	8.74	9.62	10.50	10.88	11.32	11.80	12.27	12.86	13.96	14.91	17.36	19.36	21.03
OIL	5.27	5.32	5.27	5.66	7.32	6.81	6.65	6.92	6.85	6.83	6.84	6.94	7.14	7.39	8.03	8.90	9.95
OTHR	1.70	1.67	1.66	1.62	1.77	1.80	1.83	1.86	1.85	1.85	1.83	1.83	1.80	1.76	1.66	1.54	1.41
TOTAL	28.40	29.50	31.16	32.41	36.64	38.51	40.61	43.01	44.94	46.87	48.83	51.21	55.48	59.69	70.90	81.54	92.48
ANNUAL EXPENDITURES FOR NEW EQUIPMENT (BILLIONS OF 1975 DOLLARS)																	
TOTAL	0.0	13.49	15.10	14.51	14.87	14.41	15.30	16.24	16.51	17.17	17.43	17.50	18.21	18.83	20.06	21.14	22.14
ANNUAL EXPENDITURES FOR TI IMPROVEMENTS (BILLIONS OF 1975 DOLLARS)																	
TOTAL	0.0	0.00	0.01	0.01	0.64	0.61	0.59	0.62	0.59	0.63	0.66	0.25	0.31	0.35	0.46	0.54	0.62

TOTAL FUEL USE AND EXPENDITURES, 1977-2000, REAL INTEREST RATE = 8.00 PERCENT

ELEC	TOTAL FUEL USE (QBTU)	301.42	TOTAL EXPENDITURES	408.09
GAS	TOTAL FUEL USE (QBTU)	134.87	TOTAL EXPENDITURES	167.89
OIL	TOTAL FUEL USE (QBTU)	52.98	TOTAL EXPENDITURES	85.80
OTHR	TOTAL FUEL USE (QBTU)	12.87	TOTAL EXPENDITURES	19.82
TOTALS		502.13		681.60

EQUIPT EXPEN 189.64 TI EXPEN 4.21 TOTAL 875.44

RESIDENTIAL ENERGY USE SIMULATIONS, 1970-2000, VERSION 5 (DECEMBER 1977), OAK RIDGE NATIONAL LABORATORY
NEP COMBINED PROGRAMS, ALL RDGD — ELECTRICITY IN TERMS OF PRIMARY ENERGY

SUMMARY OF PROGRAM OUTPUTS

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1983	1985	1990	1995	2000
HOUSING STOCK (MILLIONS)																	
SNGL	43.99	44.68	45.63	46.35	47.13	47.74	48.46	49.35	50.20	51.07	51.89	52.64	54.25	55.74	59.32	62.37	65.11
MULT	17.37	17.95	18.72	19.39	20.06	20.70	21.43	22.14	22.84	23.59	24.33	25.01	26.27	27.54	30.42	32.49	34.49
MOBL	2.05	2.18	2.35	2.50	2.65	2.80	2.97	3.13	3.29	3.47	3.65	3.82	4.16	4.50	5.37	6.13	6.87
TOTAL	63.41	64.82	66.69	68.23	69.83	71.24	72.86	74.63	76.34	78.13	79.86	81.47	84.68	87.78	95.11	100.99	106.47
NEW HOUSING UNITS STOKN (MILLIONS)																	
SNGL	0.0	1.06	1.31	1.08	1.13	0.96	1.07	1.25	1.21	1.24	1.19	1.13	1.17	1.13	1.09	1.03	0.99
MULT	0.0	0.72	0.90	0.80	0.80	0.78	0.86	0.86	0.85	0.90	0.89	0.84	0.80	0.81	0.71	0.67	0.61
MOBL	0.0	0.22	0.25	0.25	0.25	0.26	0.28	0.29	0.29	0.31	0.32	0.33	0.34	0.36	0.38	0.40	0.42
TOTAL	0.0	1.99	2.46	2.13	2.19	2.00	2.22	2.39	2.35	2.45	2.41	2.30	2.30	2.30	2.17	2.10	2.02
FUEL USE BY FUEL TYPE (QBTU)																	
ELEC	5.36	5.73	6.21	6.66	7.00	7.28	7.63	7.95	8.25	8.57	8.84	9.10	9.64	10.29	11.91	13.20	14.43
GAS	5.35	5.39	5.47	5.58	5.62	5.63	5.58	5.45	5.33	5.23	5.10	4.99	4.79	4.68	4.52	4.30	4.10
OIL	2.86	2.86	2.90	2.88	2.58	2.43	2.35	2.21	2.10	2.02	1.94	1.88	1.76	1.71	1.71	1.71	1.72
OTHR	0.86	0.84	0.82	0.80	0.77	0.75	0.74	0.72	0.70	0.68	0.66	0.65	0.61	0.58	0.50	0.43	0.36
TOTAL	14.44	14.82	15.40	15.91	15.97	16.09	16.29	16.33	16.38	16.49	16.55	16.61	16.80	17.25	18.64	19.64	20.62
FUEL USE BY END-USE FUNCTION (QBTU)																	
SPACE HEAT	7.89	8.01	8.24	8.41	8.22	8.15	8.12	7.92	7.76	7.65	7.53	7.42	7.28	7.35	7.76	7.97	8.16
AIR COND	0.67	0.75	0.84	0.94	1.00	1.05	1.11	1.15	1.19	1.24	1.28	1.32	1.40	1.51	1.82	2.09	2.35
WATER HEAT	2.07	2.13	2.20	2.27	2.32	2.35	2.38	2.43	2.47	2.51	2.55	2.58	2.66	2.75	2.97	3.09	3.22
REFRIG	0.83	0.84	0.87	0.89	0.91	0.93	0.95	0.97	0.99	1.00	1.00	1.01	1.02	1.03	1.07	1.09	1.10
FREEZERS	0.29	0.31	0.33	0.35	0.37	0.39	0.41	0.43	0.44	0.46	0.48	0.49	0.51	0.54	0.59	0.63	0.66
COOKING	0.69	0.71	0.73	0.75	0.77	0.79	0.81	0.83	0.85	0.87	0.89	0.91	0.94	0.98	1.06	1.13	1.20
LIGHTING	0.82	0.84	0.87	0.90	0.92	0.92	0.93	0.95	0.97	1.00	1.01	1.00	0.99	0.98	0.99	1.02	1.07
OTHER	1.18	1.24	1.32	1.39	1.46	1.52	1.58	1.64	1.71	1.77	1.83	1.88	1.99	2.10	2.38	2.62	2.86
FUEL USE BY HOUSING TYPE (QBTU)																	
SNGL	11.36	11.60	11.97	12.30	12.25	12.26	12.34	12.25	12.21	12.20	12.15	12.11	12.10	12.32	13.13	13.70	14.25
MULT	2.68	2.79	2.95	3.10	3.18	3.25	3.34	3.43	3.50	3.58	3.65	3.72	3.85	4.01	4.42	4.70	4.99
MOBL	0.40	0.43	0.48	0.52	0.55	0.58	0.61	0.64	0.68	0.71	0.75	0.78	0.85	0.91	1.09	1.23	1.38
ANNUAL FUEL COSTS BY FUEL TYPE (BILLIONS OF 1975 DOLLARS)																	
ELEC	13.56	14.51	15.86	16.68	18.76	20.26	21.61	23.13	24.41	25.57	26.62	27.85	30.01	32.54	39.49	45.42	51.46
GAS	7.87	8.00	8.37	8.45	8.68	9.39	10.49	10.66	11.13	11.60	12.00	12.39	13.09	14.02	15.87	17.40	18.70
OIL	5.27	5.32	5.27	5.66	7.26	6.79	6.65	6.74	6.60	6.53	6.47	6.42	6.38	6.53	6.72	7.06	7.45
OTHR	1.70	1.67	1.66	1.62	1.77	1.80	1.83	1.86	1.88	1.89	1.88	1.89	1.87	1.84	1.71	1.55	1.40
TOTAL	28.40	29.50	31.16	32.41	36.47	38.45	40.59	42.39	44.02	45.59	46.97	48.55	51.34	54.93	63.78	71.43	79.01
ANNUAL EXPENDITURES FOR NEW EQUIPMENT (BILLIONS OF 1975 DOLLARS)																	
TOTAL	0.0	13.49	15.10	14.51	14.87	14.42	15.30	16.30	16.81	17.79	18.41	18.39	19.20	19.88	21.37	22.80	24.01
ANNUAL EXPENDITURES FOR TI IMPROVEMENTS (BILLIONS OF 1975 DOLLARS)																	
TOTAL	0.0	0.00	0.01	0.01	1.82	0.60	0.63	3.61	3.78	3.87	4.15	4.14	4.17	0.77	0.87	0.94	1.00

TOTAL FUEL USE AND EXPENDITURES, 1977-2000, REAL INTEREST RATE = 8.00 PERCENT

ELEC	TOTAL FUEL USE (QBTU)	271.62	TOTAL EXPENDITURES	374.23
GAS	TOTAL FUEL USE (QBTU)	110.96	TOTAL EXPENDITURES	157.23
OIL	TOTAL FUEL USE (QBTU)	42.74	TOTAL EXPENDITURES	75.61
OTHR	TOTAL FUEL USE (QBTU)	12.68	TOTAL EXPENDITURES	20.28
TOTALS		438.00		627.35

EQUIPT EXPEN 199.71 TI EXPEN 25.63 TOTAL 852.70

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