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THE LBL RESIDENTIAL ENERGY MODEL

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ABSTRACT

Energy consumption in residences accounts for 20% of total energy and 35% of electricity used in the United States today. Over time, the amount of energy consumed to provide a particular service will change. The mix of fuels consumed also changes; recently, households have increased their electricity consumption and decreased consumption of fossil fuels. For these reasons, an understanding of the components of residential energy consumption is important to utility companies and government policy-makers.

This paper describes the development of the LBL Residential Energy Model to provide improved policy analysis at the end-use level. The major improvements include: representation of recent equipment efficiency trends; new techniques for forecasting future appliance efficiencies and annual appliance replacements; and extension of the model to include heat-pump space-conditioning systems. The resulting forecasts give improved agreement with recently reported energy consumption and provide lower estimates of future energy consumption.

THE LBL RESIDENTIAL ENERGY MODEL: AN IMPROVED POLICY ANALYSIS TOOL *

James E. McMahon

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INTRODUCTION

Residential energy demand comprises 20% of total energy demand in the United States[1], and 35% of the total national electricity consumption. In addition to that used for generating electricity, more than 25% of the natural gas consumed in the U.S. is used directly by residential customers.

The need for new electricity-generating plants depends strongly on residential energy consumption. Residential air conditioners and electric space heating equipment are significant components of electricity load during summer and winter peak demand periods, respectively, exerting a significant impact on the capacity requirements of electric utilities.

The importance of residential energy consumption is highlighted by the policies adopted by some states and electric utility companies to exert some control over increases in demand. Since the types of energy-using equipment in the home are similar throughout the U.S., policies affecting that equipment have been considered at the federal level. The policies considered include appliance labels[2] (Federal Trade Commission), building energy performance standards (U.S. Department of Energy[3], and some states[4]), equipment efficiency standards[+] (U.S. Department of Energy[5], and many states[4]), and utility rebate programs[6]. Estimates of the potential effects of policies depend upon projections of residential energy demand.

The development of computer models to simulate future residential energy consumption is essential for understanding the important determinants of energy demand, anticipating the changes in direction and magnitude of that demand, and planning for adequate and affordable supplies to meet that demand. Simple models of aggregate energy consumption have encountered increasing difficulty in explaining the components of change in demand over the last decade, and

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+ Twenty-three states applied for exemption from the "no standard" determination by the U.S. Department of Energy for eight products.

additional underlying factors have been sought. Early attempts at developing more complex models suffered from the paucity of data collection. A recent review describes the models developed to date.[7] The Oak Ridge National Laboratory (ORNL) Engineering-Economic Model of Residential Energy Use was an early attempt to include end-use detail. The authors designed the model to evaluate possible energy conservation policies.

This paper describes improvements in the ORNL residential energy demand model made since 1979 and their effects on demand projections. The new model is called the LBL* Residential Energy Model. The most important changes involve additions of elements not previously considered in the relationships among causative factors. These changes lead to a more comprehensive and more accurate representation of the factors affecting residential energy demand, making the model more useful for policy analysis. In short, the model now takes advantage of data at a higher level of detail than the aggregate indices previously used. In addition, the paper also addresses a number of potential future improvements. The LBL model has been applied to analysis of proposed U.S. Department of Energy appliance efficiency standards.[8-11]

This section concludes with a history of the ORNL Engineering-Economic Model of Residential Energy Use, referred to subsequently as the old model. The Methods section describes the changes made at LBL. We classify the changes as data changes only, or changes to the specification of the model. We describe each change to the model specification, with a comparison to the old formulation, and the effects of the change on critical outputs. The Results section describes the overall effects of the changes taken together. The Conclusions section describes the significance of the improved model and describes possible future work.

Origin of the residential model

More than ten years ago, two factors were seen as the major determinants of future residential energy demand: economics and technology. The state of the economy was expected to drive energy consumption. This intuition could be rationalized, since the financial well-being of residential energy users would influence the amount of energy consumed, both through the number (and type) of appliances purchased, and through the usage behavior of the appliance owners. At the same time, engineers recognized that a large variety of alternative designs of appliances could perform the same function (such as refrigerating food). These alternative designs have different purchase costs and consume different amounts of energy while providing the same service (i.e., keeping 20 cubic feet of food storage space cooled to 40 degrees F).

* LBL stands for Lawrence Berkeley Laboratory.

The first attempts at energy demand modeling depended on one or the other of these two factors. For example, projections were based upon a linear relationship between economic growth and aggregate energy consumption, derived from historical data. The validity of this approach has since been widely debated.[12] This approach fails because it lacks consideration of changes in equipment efficiency or the substitutability of alternative fuels.

Alternatively, simple engineering comparisons provided estimates of future energy savings based upon hypothetical equipment design changes. The engineering approach provides overly simplistic estimates if it compares a hypothetical design with current models, neglecting economic factors. Among the effects ignored are the efficiency improvements to be expected from market forces; changing market shares among alternatives selected by equipment purchasers; and changes in usage behavior after the purchase is made. Furthermore, a forecast of the rate of penetration of new technologies requires consideration of economic conditions.

The first successful attempt to integrate these two factors was made at Oak Ridge National Laboratory (ORNL) in the mid-1970's.[13] The integration was performed in order to create a framework that considered end-use detail (using engineering estimates of equipment costs and efficiencies) and economics (forecasting market shares of competing fuels, equipment efficiencies, and usage behavior of the appliance owner). This approach attempts to consider the problem at a sufficient level of disaggregation to utilize engineering information without neglecting the important economic determinants of market behavior. The model has been documented[13] and critiqued elsewhere[14-18], so only an overview is provided here.

The ORNL Model is a set of equations that ultimately produce an estimate of the energy consumption by fuel type expected from each type of residential appliance, in future years of interest. The model incorporates engineering and cost estimates of the likely range of appliance designs available, with economic effects, including the influence of energy prices and equipment prices on purchase and usage decisions. The energy use depends on exogenous projections of future energy prices, changes in the number of households in the U.S., and changes in per capita income. The major model calculations (Figure 1) include: future efficiency choices, investments in thermal integrity improvements of buildings, changes in the number of households owning one (or more) units of each appliance, changes in the market share for each fuel (such as gas vs. electric water heaters), and changes in usage behavior (such as hours of use of air conditioners).

ORNL made several changes to adapt the model for analyzing Consumer Product Efficiency Standards before transmitting it to LBL. In particular, the entire model data base was updated from 1970 to 1977 as the base year. They extended the forecast period from the year 2000 to 2005. The cross-price market share elasticities were recognized to be in error, because the projected saturations for electric space and water heating were higher than the saturations subsequently observed in national surveys. Therefore, they adjusted these elasticities so that the model forecasts of saturations were more in line with the data for the late 1970's.* In order to accommodate the specific set of consumer products given first priority by DOE, ORNL also changed the set of end-uses, making room for clothesdryers and room heaters by dropping lighting and miscellaneous.

Other Residential Energy Demand Models

A recent review of past and present models has been published.[7] There are two engineering/economic-based models, both progeny of the Hirst model, under continuing development: the LBL model described here, and the ORNL Residential Reference House Energy Demand Model (RRHED).[20] These two models represent independent development efforts in largely different directions from a common starting point.

The Electric Power Research Institute funded development of the Residential End-use Energy Planning System (REEPS), which is unique in using household-specific data in the fuel/technology choice for space conditioning.[21] RRHED and REEPS are applied primarily to regional or utility company projections. No comparisons with LBLREM national simulations are possible, and no comparisons of local simulations have been published.

The Energy Information Administration has moved away from detailed engineering/economic models toward a simpler econometric model, the Household Model of Energy (HOME).[22] Based on recent Residential Energy Consumption Survey data, HOME produces short-term forecasts for 4 end-uses (space heating, air conditioning, water heating, and other), and cannot be used for analysis of policies such as appliance efficiency standards.

Conditional demand models have been reviewed elsewhere.[23] Many state and electric utilities use their own models of residential energy consumption. A comparison of the California Energy Commission Residential Model with the original ORNL Engineering-Economic Model of Residential Energy Use has been published.[17]

METHOD

* This change was not documented by ORNL, but is apparent by comparing the elasticities in the model input data base in DOE publications[5] with those described by ORNL.[13]

We converted the ORNL model into the LBL Residential Energy Model gradually over a period of four years. We made two kinds of changes. This section first describes data changes, then model changes. Each model change is described in comparison with the old model, with estimates of the effect of the change on critical outputs. The effect of all the changes taken together is described in the Results section below.

DATA CHANGES

Some of the exogenous inputs (such as projected energy costs) are affected by unpredictable events, including changes in governmental policies. These require updating on a regular basis to keep up with current events. Other input can be improved as more complete data or data reflecting a change in trend becomes available to replace more judgmental or incomplete sources. We implemented changes both in response to public comments on the Notices of Proposed Rulemaking for Consumer Product Efficiency Standards and in order to utilize data available from more recent or more complete surveys or from better analyses of existing data.

1. Housing starts/stocks.

The 1980 Census[24] gives higher estimates of the housing stocks than previous surveys. At the same time, the construction forecast has been revised downward. Table 1 shows the housing stocks by house type from the old and new estimates. While the total number of households in 1980 has only been increased by 0.6%, the split among house types shows greater changes. Most important, the number of multifamily households has been increased by nearly 6%. The estimate of total households in 2000 has been lowered by 8%.

We adjusted the total housing stock in 1980 to obtain agreement with the 1980 Census. The rates of retirement of single family and multifamily houses are now independent, namely 0.5%/yr for single family and 1.0%/yr for multifamily. We have taken the projection of housing starts (except mobile homes) from the MASTER model.[25] Overall, the number of housing starts, formerly in the range of 2.0-2.2 million units per year has been diminished to values typically in the range 1.6-1.8 million per year after 1984.

2. Energy cost projections.

The last decade has seen dramatic changes in expectations regarding energy costs. For that reason, the assumed energy price projections have been altered repeatedly. The original assumptions for the appliance standards analysis involved a range of values.[8] The effect of the change in assumptions is to expect less efficiency improvement in electrical appliances, and more efficiency improvement in fossil-fueled appliances, than with the old energy costs. The annual real fuel price increases, including the expected and low and high bounds, are shown in Table 2.

3. Income projections.

The expected increases in real income were previously based on per capita estimates. The older estimates[8] were optimistic, and have not been borne out by recent experience. In addition to using a newer projection, with lower growth expected in income per capita, the definition of the input variable has been changed to income per household. The new income projection is affected by changes in the number of persons per household. If income per capita is constant, but there are fewer persons per household in future, then income per household declines. Currently, we assume 1.2%/year real growth in income per household after 1985.

4. Engineering Analysis.

For the Consumer Products Efficiency Standards analysis, the Department of Energy commissioned a compilation of engineering designs available in the marketplace in 1978 for each appliance.[26] Updates[27,10] to that analysis include some products available in 1980. The complete data set is used to derive the relationship between equipment purchase cost and unit energy consumption for each end-use and fuel. The resulting curves extend to higher efficiencies than previous studies, allowing for greater efficiency improvements, with or without government policy.

We developed an aggregation procedure for combining data for different classes of products, e.g. manual defrost and frost-free refrigerators. [28] The procedure involves grouping the design options from each class according to the expected percent change in unit energy consumption (UEC). Then the shipment-weighted average of the classes provides equipment cost and unit energy consumption data points for each product type (e.g., refrigerators). The aggregate data points (one data point for each group) are weighted by the number of primary data points in the group.* This method was designed to extract as much information as possible, yet simplify the representation to a single curve for each product type.

* For example, two designs of frost-free refrigerators attain decreases in UEC of 10 and 25%, respectively, while 2 designs of manual-defrost units attain 15 and 25% savings. Then the designs achieving 25% savings are grouped together when calculating design changes for the product type, refrigerators. Each of the other points comprise a group with a weight of 1, while the group with a 25% lower UEC carries a weight of 2.

The DOE-sponsored work failed to characterize advanced technologies, that is, those not already in production. We used engineering estimates to partially compensate; but the uncertainty in equipment cost increases at higher efficiencies.

5. Recent efficiency trends.

During the public comments on proposed appliance efficiency standards, trade associations and some manufacturers provided a record of equipment efficiency improvements since 1972. We have included in the model the changes in design that have been reported. Projections of future efficiencies are based upon the decision processes of the past, applied to engineering estimates of expected future designs.

6. Projected floor area per house.

The older projections, extrapolating from historic trends, predicted floor area per new house in the year 2005 20% above the 1977 average house size. In view of the recent cessation of the trend toward larger houses[29], we have assumed that floor area per new house (within each house type) remains constant. Of course, the average floor area across the entire housing stock will continue to change, reflecting changes in the composition of the stock, e.g., the percent of all households that are single family.

MODEL SPECIFICATION CHANGES

This section includes descriptions of ten major methodological changes that we made to the ORNL model. We describe each change by comparing the old method with the new, including estimates of the effect of the change on critical outputs. We discuss the overall effect of all the changes in the Results section.

1. Efficiency of new appliances

The ORNL model projects future equipment efficiencies from a base year starting point. The improvements to the model are:

1) Recognize the initial difference between the efficiency of a new appliance and the one it replaces.

2) Include data on recent efficiency trends (through 1981 for many products), and begin projection after the last year of available data on efficiency of new units.

3) Replace the algorithm for forecasting future appliance efficiencies. The new approach is based on a detailed analysis of market behavior from 1972 to 1981.

The ORNL model contained the assumption that, in the initial year of a simulation (in this case 1977), the efficiency of a new appliance was the same as the efficiency of the average unit already in use. With the passage of time and with increases in energy costs, manufacturers are providing, and consumers are purchasing, appliances with higher efficiencies. The disparity between the efficiency of a new unit and the unit it replaces will be increasingly significant when estimating future energy consumption. Figure 2 shows the relative efficiency improvements over the last decade. In the old method, the 1978 new unit would have been assigned an energy consumption equal to that of the 1977 stock unit.

The effect of the first two changes is illustrated in Figure 3. The electricity consumption of the average refrigerator in use in 1977 was 1726 kwh/year in all cases. Before any changes were made, the model forecast decreasing energy consumption due to design improvements, so that a new refrigerator in 2005 used only 1210 kwh/year (Figure 3, OLD METHOD). The first change, distinguishing between the energy use of new and stock units in 1977, reduced the energy consumption of a new refrigerator in 1978 by 15% to 1473 kwh/year, and in 2005 by 14% to 1040 kwh/year (Figure 3, CHANGE 1). The second change, utilizing recent efficiency data, reduces energy consumption in 1981 an additional 18%, from 1453 kwh/yr (after the first change) to 1190 kwh/yr for a new refrigerator. In 2005, a 12% decrease in energy consumption per unit occurs, from 1040 to 915 kwh/yr (Figure 3, CHANGE 2).

The market behavior algorithm has been replaced. The original formulation was theoretical, since data on appliance efficiencies were not available. Recent work at LBL using data made available during the Department of Energy analysis of proposed Consumer Product Efficiency Standards indicates that the original formulation, assuming an inverse relationship between unit energy consumption and energy price, forecasts higher efficiency improvements than observed in the market in the past 10 years. Appliance efficiencies have improved, but not by as much as had been forecast. What appears to be relatively constant is the discount rate implicit in the market's appliance efficiency choice.[30] In most cases, the efficiency increases have only kept pace with rising energy costs, and do not yet indicate any change in the market decision-making process toward placing more emphasis on energy conservation. Since the decision process with regard to efficiency seems to have been hardly affected at all by the substantial increases in energy costs over the last 10 years, the new methodology retains that decision process into the future.

Figure 3 (CHANGE 3) shows the results for refrigerators. The new algorithm for market behavior has no effect on energy consumption of new refrigerators until 1982, when the projection begins. However, for the later part of the projection period (after 1985), energy consumption of new units is higher than with the old market behavior projection. In 2005, the unit energy consumption is 980 kwh/yr. This value is 19% lower than the original projection (Figure 3, OLD METHOD) with none of the three changes affecting unit energy consumption, but 7% higher than the projection using the old model with recent efficiencies (Figure 3, CHANGE 2).

The largest effect of the three changes (about 20-25% reduction in energy consumption) occurs for refrigerators, freezers, and ranges/ovens. Moderate effects (5-10%) occur for clothes dryers, and room and central air conditioners.

2. Construction practices in new houses

Just as new appliances are more efficient than those already in use, new houses are constructed in such a way as to reduce their space conditioning energy requirements relative to old houses. While measured data on the energy consumption of new houses are more difficult to obtain, the characteristics of new houses are known from national surveys.[31] Such characteristics include: thicknesses of ceiling, wall, and floor insulation, the number of glazings, floor area, and window area. We used a physical model of heat transfer in a house (DOE-2.1 Building Energy Analysis Program[32]) to determine the annual energy consumptions for heating and for cooling, based on the characteristics of the house. We made corrections for changes in the floor area of the house, efficiency of the heating system, and usage patterns in addition to, and separate from, this calculation.

The effect of the change[33] is to decrease energy consumption in new single-family homes with gas central space heating by 11%, and by 13% in single-family homes heated with electricity or heating oil. In multifamily homes, the decrease in space heating energy is 13% for electrically heated units, and 8-9% for gas and oil heated units. For mobile homes, the new assumption implies 60% lower space heating requirements in electrically heated units, and 25% decrease in gas and oil heated units.

While some secondary effects occur in efficiency choice and usage behavior as a result of the new thermal integrity assumptions, the overall effect is simply to lower the estimate of space heating energy requirements in new dwellings throughout the projection period. Air conditioning energy consumption is decreased 2% in single-family homes, 3% in multifamily, and 7% in mobile homes.

3. Appliance retirements

The original ORNL model distinguished between purchase of appliances each year for new houses and for installation in existing houses. Most of the latter are replacements of appliances that have reached the end of their useful service life. The original formulation used an exponential retirement function, equivalent to retiring each year a constant percentage of the existing appliances of each age. Since the most recently purchased appliances will not soon require replacement, this assumption is poor, especially in a population that is growing at a significant rate.

The general solution to this problem involves keeping track of the vintages, or age distribution, of all the appliances, and replacing them at appropriate intervals after their year of original purchase. This vintaging approach requires a more complex computer model, and a significant increase in computation time, but provides a more accurate representation of the turnover of appliances.

We found data on retirement functions[34] that give the percent of appliances that retire during each year after original purchase. Figure 4 gives a comparison of the retirement function and the exponential assumption that it replaced. While the old formula retired about 5.1% of the existing appliances each year, regardless of their age, the new formulation retires no refrigerators until they are 12 years old.* (Presumably, many refrigerators are sold as second-hand items, but continue to function under new ownership.) Also, the old formula allowed a number of very old refrigerators to go on operating for 40 years, while the new approach eliminates refrigerators older than 26 years.

Figure 5 illustrates the effect of these changes on estimates of installations of central air conditioners, excluding heat pumps, in existing houses. The use of a vintaging approach achieves two purposes: 1) eliminating the erroneous early retirement of young appliances; retirements in early years of the projection are therefore lower in the new method; 2) capturing the wave-like rise and fall of replacement sales, reflecting the aging of units purchased during peak economic and housing construction periods.

The change decreases shipments for most products. This effect arises in two ways: 1) the revised lifetimes are longer, causing slower turnover of appliance stocks; and 2) the change in shape of the retirement function means that fewer appliances retire soon after purchase. (The second effect would balance out over time, with greater retirements of older appliances, if the

* The change in form of the retirement function is an improvement, but additional research is proposed to refine the shape. We suspect that data limitations, not reality, gave the results that all refrigerators survive a minimum of 12 years.

lifetimes were the same in the two cases, and if overall market growth stopped.)

4. Energy use of retiring appliances.

The old method accounted for the energy use of retiring appliances by retiring the energy use of the average unit in stock at the time. This was inaccurate, since units of several ages retire in any given year and the older retirees are likely to consume more energy (be less efficient) than newer models. In the new model, the retirees retain the unit energy consumption appropriate for their vintage. That is, the energy use of surviving stock is calculated each year as a function of the unit energy consumption for each vintage unit, and the number of units of that vintage that survive.

This change decreases the estimated energy consumption in future years. Since the greater portion of retiring appliances are older than the average appliance in stock, the new method assigns lower efficiencies to the retirees. As a consequence, the average efficiency of surviving appliances is higher than before. With higher efficiencies, the appliances consume less energy. Together with replacement of the retirement functions, the effect of this change is to decrease energy consumption in 2005 by 5% for refrigerators, relative to the old forecast.

5. Appliance Price Deflators

Another new feature is the ability to adjust the real purchase price of equipment each year of the forecast. Changes in the real price per unit may occur as technologies for the manufacture of a product evolve, or as economies of scale are realized. Different changes in the real price over time may be applied to different products and fuel types.

Projections used for the analysis of Consumer Products Efficiency Standards indicated decreasing real prices for most appliances.[35] While the effect of this change is to provide an additional capability in the model, the quantitative effect on residential energy consumption is negligible. Caution must be used when exercising this option, since extreme changes in projected real prices of competitors (e.g., if electric water heaters become more expensive while gas water heaters become much less expensive) will lead to changes in purchase decisions (in this case, toward more purchases of gas water heaters at the expense of the market share of electric water heaters). Such results are believable only if the relative equipment price forecasts are credible.

6. Explicit treatment of heat pumps.

The old model subsumed heat pumps under electric central space heating and central air conditioning. In previous analyses, standards were applied to central air conditioning without separating out the unregulated heat pumps.[8] This meant an overestimate of the energy savings and provided no mechanism for including a different standard for heat pumps. In the new model, heat pumps are treated explicitly.

The new model calculates the saturation of electric central space heating as before, in competition with gas, oil, and other heating systems. Then, it determines the fraction of electric central space heating installations that are heat pumps, as a function of relative operating costs (electric forced air vs. heat pumps) and changes in electricity cost. Next, it determines the fraction of air conditioning installations that are central units, as before. Then, it subtracts the number of heat pump installations from the total central air conditioning installations to determine the number of regulated central air conditioner installations. No standards have been proposed or analyzed for heat pumps yet.

To include heat pumps explicitly involved additional data. We estimated exogenously the efficiency of heat pumps for heating. The projected cooling efficiencies of heat pumps, calculated in the base case, were not affected by the standards. We also estimated the initial saturation of heat pumps and the coefficients for the fraction of central electric space heating installations that are heat pumps.

The effect of the change is to decrease the estimated energy consumption for regulated central air conditioners. (Heat pumps account for about 25% of the energy consumption and costs of central air conditioning systems over the projection period.) The more important effect is to provide a methodology that can separate heat pumps from conventional central air conditioners. The method adopted is a first approximation, and more work is needed in this area.

7. Distribution of efficiencies.

Both the ORNL model and the LBL model project an average efficiency for new appliances purchased each year in the base case. In the standards case, the models differ. Early analyses of appliance efficiency standards[8] assumed the 1978 distribution (number of shipments in each range of efficiencies) to be static for all time. We calculated the average efficiency in the presence of Consumer Product Efficiency Standards (CPES) exogenously by applying the CPES level to the 1978 distribution. Thus, the average efficiency in the presence of standards was assumed to be constant in all future years, unless exceeded by the average efficiency in the base case.

In the LBL model, the 1978 distribution of efficiencies[36] is moved each year in the standards case so that the average efficiency agrees with the base case projection. The distribution is expressed in efficiencies as a fraction of the average, so that broadening of the distribution also occurs. To obtain the average efficiency in the standards case, all shipments with efficiencies less than the standard are assumed to be upgraded to the standard. Those with efficiencies at or above the standard are unaffected. Then we calculated the shipment-weighted average from the adjusted distribution.

The new method has the advantages that: 1) the distribution of efficiencies changes in a way consistent with the change in the average efficiency; 2) the effect of the standard level diminishes with time, as the base case efficiencies move to or beyond the standards. Whereas in the old model the efficiency level in the standards case was a function of the standard level and of the 1978 distribution of efficiencies, the efficiency level in the new method is a function of the standard level and a distribution that changes over time; 3) standards can be applied to individual classes of appliances.

The change has no effect on the base case projection. However, the change causes the estimate of energy consumption in the policy case (for Consumer Product Efficiency Standards) to decrease. Applying a standard to a moving distribution of efficiencies produces a higher average efficiency than applying the same standard to a fixed distribution. That is, the effect of the policy is greater than before, since the policy case no longer ignores the greater-than-standard efficiencies occurring in the base case.

8. Purchase cost/energy use formulation.

The old model used a 3-parameter fit to the data from the Engineering Analysis to obtain the continuous function of purchase cost to unit energy consumption.[5] Similar curve fits could be obtained, having different values for two of the three parameters. Since these parameters were important for calculating life cycle costs and aggregate implicit discount rates, the ambiguity was a problem.[30]

The solution in the new method is to use a 2-parameter formulation, which provides unambiguous values for the two parameters, and provides good fits to the data points.[28] Consequently, the shape of the purchase cost/energy use curves changed slightly for some products.

Changes to the Engineering Analysis data base are discussed above (Data Changes, section 4). These also contributed to changes in the shapes of the purchase cost/energy use curves under discussion here. No calculation has been made of the effect of changing the formulation on projected energy consumption, but we expect that the effect is small.

9. Twelve End-Uses.

The old model considered only nine end-uses, including the regulated products. The new model considers total residential energy consumption, composed of 12 end-uses: central space heating, room space heating, room air conditioners, central air conditioners, heat pumps, water heaters, refrigerators, freezers, ranges and ovens, dryers, lighting, and miscellaneous. (The new end-uses are heat pumps, lighting, and miscellaneous.) Lighting and miscellaneous had been considered in even older versions of the old model, but to the exclusion of dryers and room space heaters, since the total number of end-uses had been fixed. Separating heat pumps from central air conditioners eliminates the overcounting of savings for a policy applied only to non-heat pump air conditioners, and permits consideration of different standard levels for heat pumps and conventional central air conditioners.

Another important change involves reformatting the inputs, such that one set of inputs is defined for use with all end-uses (such as housing starts), while additional sets of input are defined specific to each end-use. The new model has been generalized so that it is now easy to analyze subsets or the full set of end-uses as desired.

10. Graphical output.

We added the capability of obtaining graphical output for most of the key outputs. The pictorial presentation,[10,11] as opposed to tabular, facilitates analysis of large amounts of data, and is particularly useful when analyzing trends over time. Among the graphs that can be produced are: total residential energy consumption over time, fuel prices over time, efficiency trends over time, and residential purchases of appliances by type over time. Some graphs illustrate the difference between two sets of results, usually a base case and a policy case: energy savings over time, net present benefit by end-use (bar graph), efficiency of new units over time, and percent energy savings by end-use by house type over time.

RESULTS

The data changes result in lower energy consumption estimates due to smaller housing stock, more expensive fossil fuels, less increase in income, smaller houses, and more efficient appliances.

The effects of methodological changes are illustrated here. All comparisons in the following discussion are between the old and new methods, both using the same updated data base. The direction and magnitude of the individual changes are indicated in the Methods section above. The effects of some of the individual changes are large, but the overall effect is smaller because: 1)

The aggregate energy consumption reflects the average effect over all end-uses; only a few of the end-uses show the extreme changes, while others show small or no change. 2) Since not all the changes are in the same direction, the net effect involves some cancellation of individual effects. 3) There are strong feedbacks built into the simulation. For example, assuming more efficient furnaces causes the model to project decreased investments in insulation and increased usage, both effects subtracting from the gross savings expected from the efficiency change alone. This section considers the overall impact of the changes taken together, not the sum of the impacts of the individual changes.

In fact, the data changes moved the model results away from agreement with recorded data, and the net effect of the methodological changes is to largely balance the effect of the data changes. The overall result then is reasonable agreement with recorded aggregate measures of residential energy consumption. Of course, the recorded measures must be evaluated carefully. For example, there is considerable apparent disagreement between the model and reported heating oil consumption, but the cause is unclear, since the reported oil consumption data are incomplete.

In what follows, we concentrate on projected national residential energy consumption in the years 1977-1982 and 2000, and on end-use energy consumption.

1. Historical national residential energy consumption

A comparison of the revised projection with observed energy consumption trends in the United States in recent years is encouraging. Table 3 shows the model estimates for 1977-1982 compared with data from the Energy Information Administration (EIA)[38], American Gas Association[39], and Edison Electric Institute[40]. The agreement for aggregate energy consumption is within 8 percent. The best agreement is for electricity, where the model results range from 1 to 7 percent high (1979 to 1982). Much of the difference can be explained by a difference in definitions of the residential sector. The model is based upon the housing stock, obtained from Census data; however, utilities routinely treat mass-metered apartment buildings as commercial accounts. Therefore, an overestimate by the model, which includes apartments, on the order of 4% was expected. The same problem for gas could account for the model being 5% high.

The initialization of the model provides estimates of electricity and gas consumption that are 7 and 5 percent high in 1977. After accounting for the mass-metered apartments, the electricity estimate is about 3% high and the gas estimate is in agreement with reported values. In 1982, the model estimates for gas and electricity are 1% above reported. The growth in electricity consumption appears to be underestimated, while the decline in gas consumption is overestimated.

The most serious disagreement is with oil consumption. The source of the reported data is EIA's survey of fuel oil dealers[41]. Again, apartments are classified in the commercial sector. An alternative source of oil consumption is the RECS survey[42], which provides an estimate of 1.62 Q for 1980. Correcting for weather gives a value of 1.53 Q, which is 9% higher than the first estimate. The model result is 24 percent over the EIA estimate in 1979, up to 45% over EIA in 1981. However, the model result is 40% high in 1980 (EIA data) or 28% compared to the RECS data. The marked decline in reported oil consumption from 1979 to 1981 is underestimated by the model. It appears from the reported consumption, if the 1979 data are complete, that a marked change in consumption occurred after the 1979 price shock. The model fails to forecast this change in consumption. The data for 1979 should be checked for completeness, and the possibility that usage behavior (including thermostat settings) could account for the change should be explored.

In summary, the model agrees to within 8% with reported electricity and gas consumption over the period 1977-1982. There is serious disagreement for oil, with particular concern in both the model and in the reported value for accuracy in characterizing oil consumption by apartment buildings.

2. Projections for the year 2000.

The new method provides estimates that are lower for all fuels than the old method, using the same exogenous inputs (Table 4). The absolute magnitude of the difference increases over time. For electricity, the difference in 1980 is 0.08 Q, while in 2000 it is 0.12 Q, representing decreases of 1% in both years. For natural gas, there is no difference between the projections of the old and new models in 1980, but a difference of 0.40 Q (11%) in 2000. For oil, the difference is 0.10 Q (5%) in 1980, and 0.24 Q in 2000 (17%). For fossil fuels, the relative magnitude of the difference between the projected energy consumption by old and new methods increases over time, as the absolute amount consumed declines. For electricity, the absolute amount consumed increases over time, and the relative difference between methods remains nearly constant at 1%.

3. End use energy consumption

The small change between electricity consumption projections by the old and new methods masks much larger underlying changes for specific end-uses. For example, in the year 2000, refrigerators consume 26% less electricity in the new projection than in the old method, but this is largely offset by increased electricity consumption for water heating.

The methodological changes reduce total fuel consumption for most end-uses, except for water heaters and miscellaneous (Table 5). The largest changes in 2000 are decreases in the annual energy consumption of refrigerators (26%), freezers (22%), and cooking (19%). Decreases are also seen for air conditioning (9%), central space heating (5%), clothesdryers (4%), and room space heaters (1%).

Lighting is unchanged, while miscellaneous shows an increase (1%), as does water heating (8%). The change for water heating involves higher market penetration for electric water heaters than previously predicted. This change in fuel choice dominates the improved efficiencies obtained for fossil-fueled water heaters. Additional analysis is needed on the market share elasticities to support this result, particularly in light of the recent availability of heat-pump water heaters.

CONCLUSIONS

Residential energy consumption is a major component of national energy consumption, and plays an important role in making new electricity-generating plants necessary. Although there are many components of residential energy consumption, specifically different end-uses, fuels, and types of households, the ability to anticipate likely trends is necessary for good planning by electric utility companies, governmental policy-makers, and other resource planners. This paper describes major improvements made to an existing computer model for simulating future residential energy demand.

The most important improvements include: accounting for the improvements in efficiency of residential appliances in recent years; a forecasting scheme derived from 10 years of market behavior regarding efficiency choice; estimation of the replacement market from historical purchase data; and reformulation of the relationship between purchase cost of equipment and efficiency. In addition, the usefulness of the model for policy analysis has been enhanced by those changes and by incorporating a distribution of efficiencies for equipment; more comprehensive treatment of end-uses by the addition of heat pumps; and implementation of graphical output.

Improvements have been made in the data base for housing starts, appliance efficiency, thermal characteristics of buildings, appliance shipments for residential sale, appliance saturations, and unit energy consumption. The net effect of all the improvements is substantial agreement with observed energy consumption in recent years.

The revised model provides a more complete picture, including total residential energy, broken down by end-use and fuel type. The significant distinctions in the list of end-uses are the separation of room heaters from central heaters, heat pumps from conventional central air conditioners, and clothesdryers from miscellaneous.

In addition, the measurements of policy effects involving comparisons between two sets of results from the model - energy savings, consumer costs, net present value - are more readily obtained without hand calculations, and in some cases are better defined to avoid unintentional misinterpretations.

The model can use data on efficiencies of new appliances as they become available, and can base projections on purchasing patterns derived from the most recent year of data. Similarly, data on thermal characteristics of new buildings can be incorporated, keeping pace with developments in the construction industry. Since the entire data base has been reformatted, it is now easy to isolate one or more end-uses and to perform analyses on end-uses of interest without incurring the costs of repetitive analyses of the complete set.

A great deal of work remains to be done before a completely satisfactory model of residential energy consumption is obtained. Among the major difficulties of this deterministic model is the failure to quantify the uncertainty in its estimates. Second, the market share elasticities are based on cross-sectional data almost 15 years old. A reestimation is long overdue. Third, the end-use forecasts should include shipments of each class of appliance (e.g., top-mount frost-free vs. manual defrost refrigerator/freezers). Fourth, further elucidation of the roles played by various actors in the market to determine appliance efficiencies is necessary. Although we have characterized the market as a whole, we are particularly interested in a better understanding of manufacturers' decision processes, and those of distributors, retailers, builders, landlords, and other purchasers.

Fifth, specification of the number and effectiveness of retrofit measures taken on existing houses is now exogenous to the model. Sixth, while the model framework can now support retirement functions for appliances, we would like to reevaluate the current input assumptions, which are based on the only study of this phenomenon of which we are aware. Seventh, all end uses have been treated as independent and this is a bad assumption. The "waste" heat generated by most electrical appliances serves as an internal heating source. Changes to appliance efficiencies will therefore influence space conditioning energy consumption. Eighth, additional data is needed to characterize the likely penetration of advanced technologies into homes within the time horizon of the forecast period. Ninth, weaknesses in the data base for multifamily and mobile homes should be corrected.

Tenth, maintenance costs of appliances should be considered. Eleventh, the model should be disaggregated further into types of households (by income, owner/renter, geographic location, etc.) to allow assessment of regional issues, equity of policies, and aggregation error. Twelfth, some attention should be given to differentiating energy costs for each end-use. For example, electric space heating and water heating are commonly given lower rates than average, through rate categories and through declining block rates. Thirteenth, equipment capacities should be explicitly modeled. The sizes of air conditioners and refrigerators have changed over time, and should be expected to vary in the future. Fourteenth, a correction should be made for the migration of new home construction toward milder climates over time. This will effect equipment capacities, heating and cooling loads, water heating load, and possibly usage.

The original modeling effort at ORNL was innovative, given the lack of end-use data at the time. The work described here represents part of the effort needed to take advantage of data that have become available since that time. In the course of converting the ORNL model to the LBL Residential Energy Model, we have begun to tune the model to the next higher level of detail, including appliance efficiencies, market behavior in efficiency choice, and appliance retirements. While it is important that the aggregate totals are coming into closer agreement with recorded consumption, even greater changes are seen in the individual components of demand. The result has been increased success both in the replication of reported energy consumption and in enhanced capabilities and usefulness of the model for policy analysis.

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Table 1. Stock of Occupied Residential Buildings
(Millions of Households)

	Building Type	1980	1985	1990	1995	2000
OLD ESTIMATE:						
	Single family	51.9	55.8	59.3	62.4	65.1
	Multifamily	24.3	27.5	30.4	32.5	34.5
	Mobile homes	3.7	4.5	5.4	6.1	6.9
	Total	79.9	87.8	95.1	101.0	106.5
NEW ESTIMATE:						
	Single family	50.8	53.5	56.4	59.6	62.6
	Multifamily	25.7	27.0	28.3	29.3	30.2
	Mobile homes	3.8	4.3	4.8	5.1	5.4
	Total	80.4	84.5	89.5	94.1	98.2

Table 2. Annual Real Increases in Residential Energy Price and Household Income

	ENERGY PRICE SCENARIOS		
ELECTRICITY	Low	Reference	High
1983-2005	0.0	1.0	2.0
NATURAL GAS	Low	Reference	High
1983-1985	5.0	9.0	12.0
1986-1990	2.0	5.0	7.0
1991-2005	1.0	3.0	5.0
HEATING OIL	Low	Reference	High
1983-1985	0.0	3.0	5.0
1986-1990	0.0	4.0	6.0
1991-1995	0.0	3.0	5.0
1996-2005	0.0	2.5	5.0
OTHER FUELS		Reference	
1983-1985	*	1.5	*
1986-1990	*	7.3	*
1991-1995	*	5.9	*
1996-2000	*	4.5	*
2001-2005	*	3.7	*
HOUSEHOLD INCOME		Reference	
1983-1985	*	1.8	*
1986-2005	*	1.2	*

* Low and high scenarios were not estimated for this variable.

Table 3. U.S. Residential Energy Consumption, 1977-1982
Projections by Old and New Model, and Reported Consumption
(Quads)[a]

Fuel	Data Source	1977	1978	1979	1980	1981	1982
Electricity[b]	Old Model	7.83	7.96	8.24	8.51	8.66	8.76
	New Model	7.83	7.93	8.19	8.43	8.57	8.67
	Reported(EEI)[c]	7.34	d	7.96	8.13	8.41	8.56
Natural gas	Old Model	5.17	5.23	5.23	5.12	5.02	4.86
	New Model	5.17	5.23	5.23	5.12	5.00	4.83
	Reported(AGA)[c]	4.94	d	4.97	4.80	4.73	4.76
Heating oil	Old Model	2.18	2.25	2.22	2.06	1.91	1.83
	New Model	2.18	2.22	2.15	1.96	1.80	1.70
	Reported(EIA)[c]	d	d	1.74	1.40	1.24	d
	Reported(RECS)[c]	d	d	d	1.53	1.26	d

a 1 Quad = 10^{15} Btu
b 1 kwh = 11500 Btu
c Normalized to remove variations due to weather.
d Missing value.
AGA American Gas Association
EEI Edison Electric Institute
EIA Energy Information Administration
RECS Residential Energy Consumption Surveys

Table 4. Residential energy consumption in 2000.
(Quadrillion Btu)

	Model		Percent
	Old	New	Change
Electricity(a)	12.35	12.23	-1
Natural gas	3.58	3.18	-11
Heating oil	1.40	1.16	-17
Other fuels	0.28	0.19	-32
Total	17.63	16.76	-4

a Primary energy: 1 kwh = 11500 Btu.

Table 5. Residential end-use energy projected for the year 2000.
(Quadrillion Btu, Primary Energy)

	Method		Percent
	Old	New	Change
Central space heating	4.97	4.72	-5
Water heating	3.33	3.58	+8
Room space heating	1.55	1.53	-1
Miscellaneous	1.44	1.46	+1
Air conditioning	1.49	1.35	-9
Refrigeration	1.47	1.09	-26
Lighting	1.05	1.05	0
Cooking	1.17	0.95	-19
Clothesdrying	0.71	0.68	-4
Freezing	0.45	0.35	-22

FIGURE CAPTIONS

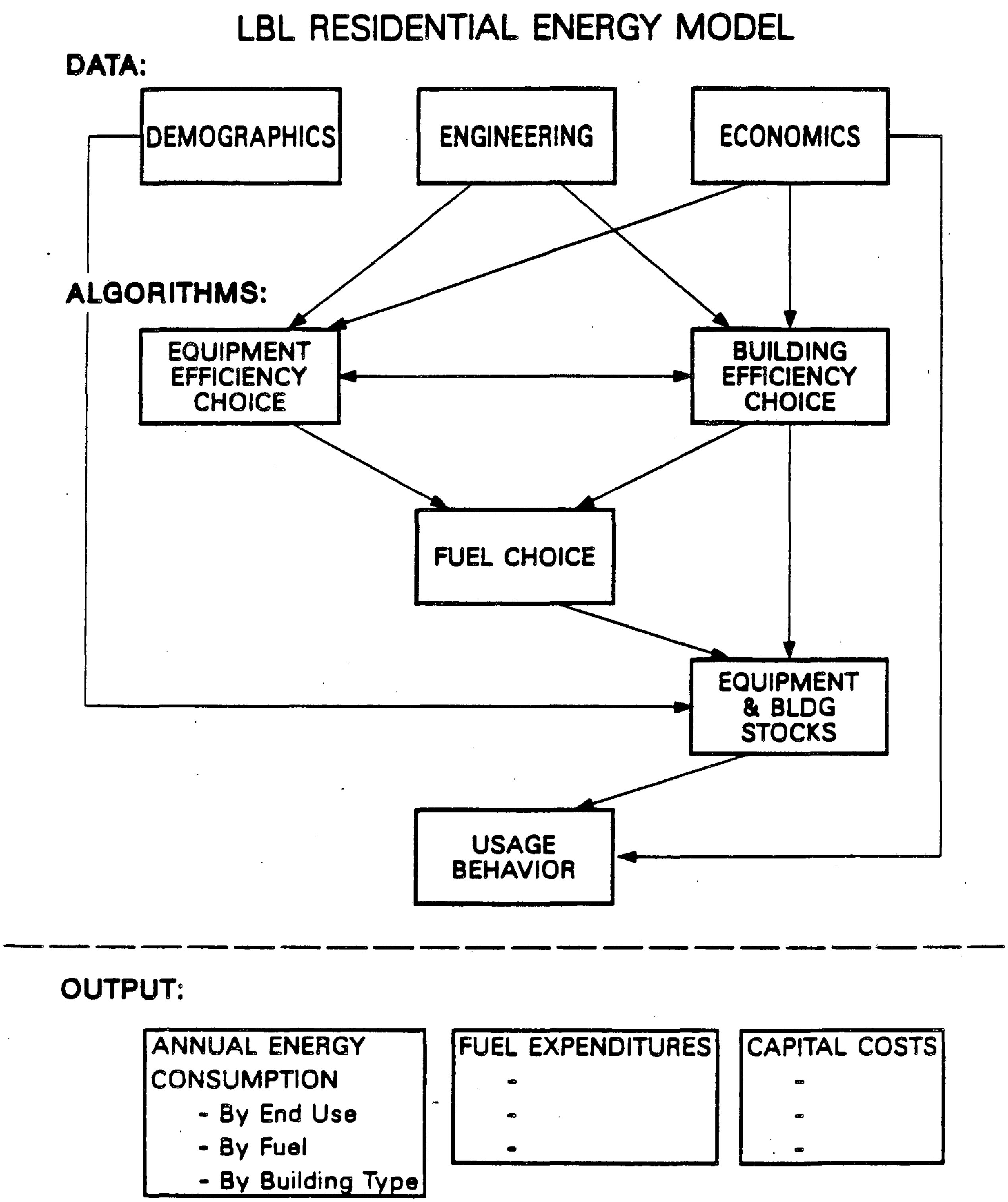
Figure 1. Flow diagram showing major components of the Lawrence Berkeley Laboratory (LBL) Residential Energy Model.

Figure 2. Percent improvement in average energy efficiency of new appliances since 1972.

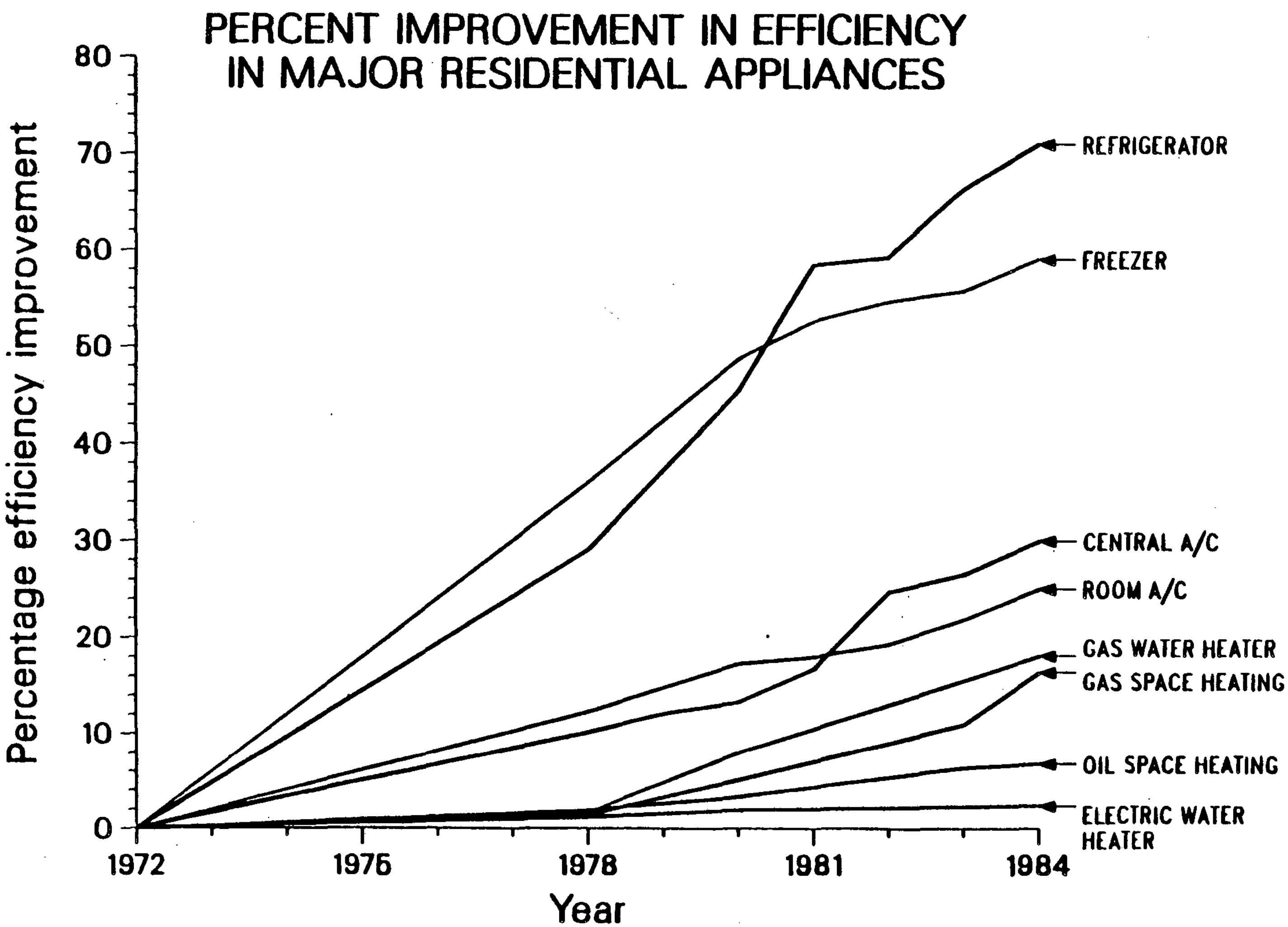
Figure 3. Alternative forecasts of energy consumption of new refrigerators, showing successive modifications to the model.

Figure 4. Percent survivors of a cohort of refrigerators, as a function of years since original purchase. Comparison of old (exponential) and new (MTSC) formulations.

Figure 5. Forecasts of replacement purchases of central air conditioners, without (OLD FORECAST) and with (NEW FORECAST) historical purchase and retirement data. (After 1990, data are displayed only every fifth year. Annual data would give a more sinusoidal shape in NEW FORECAST.)

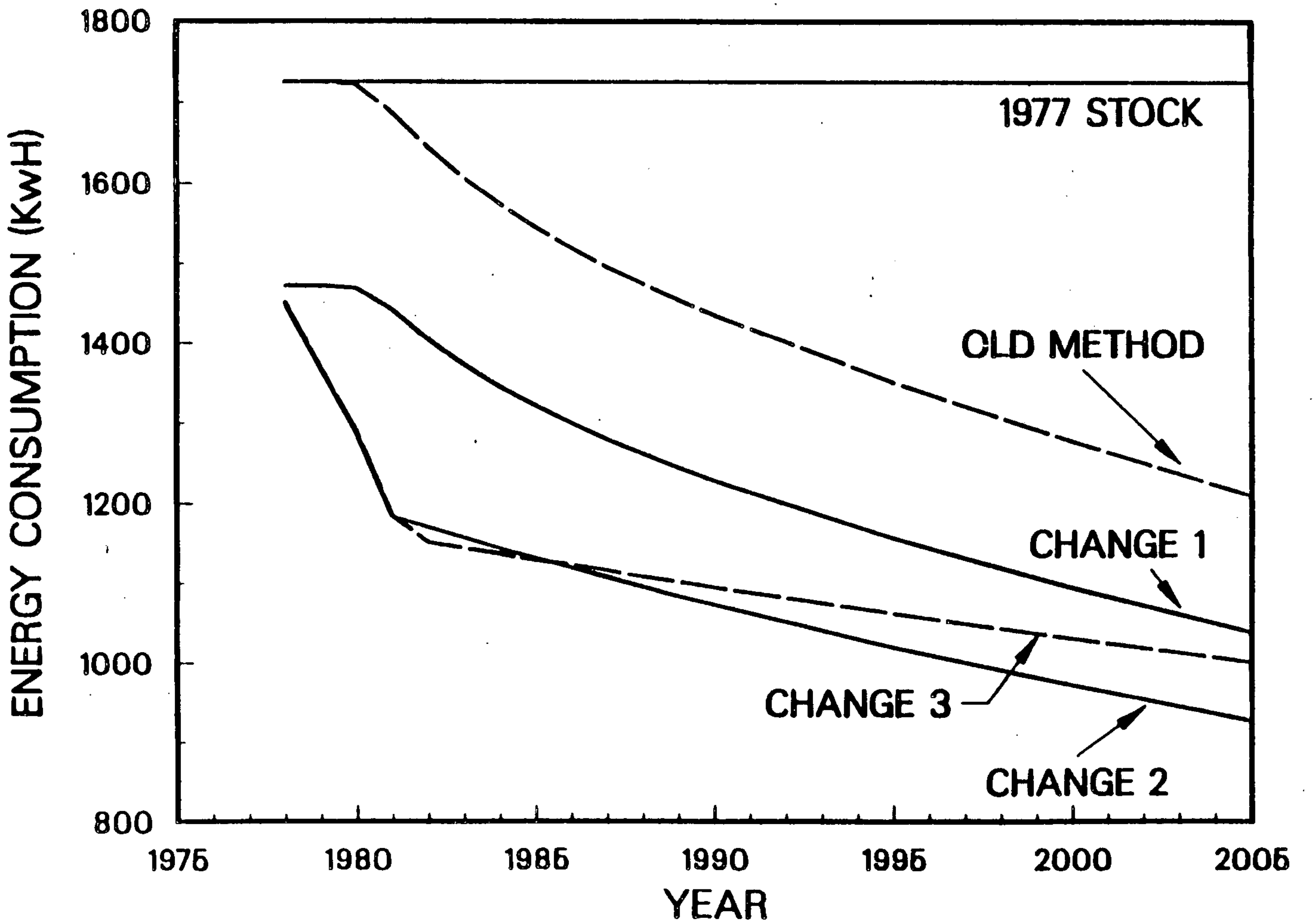


XCG 8412-13510


PERCENT IMPROVEMENT IN EFFICIENCY
IN MAJOR RESIDENTIAL APPLIANCES
Percentage efficiency improvement
0
10
20
30
40
50
60
70
80
1972
1975
1978
1981
1984
Year
REFRIGERATOR
FREEZER
CENTRAL A/C
ROOM A/C
GAS WATER HEATER
GAS SPACE HEATING
OIL SPACE HEATING
ELECTRIC WATER HEATER

XCG 858-386

ANNUAL ENERGY USE PER NEW REFRIGERATOR



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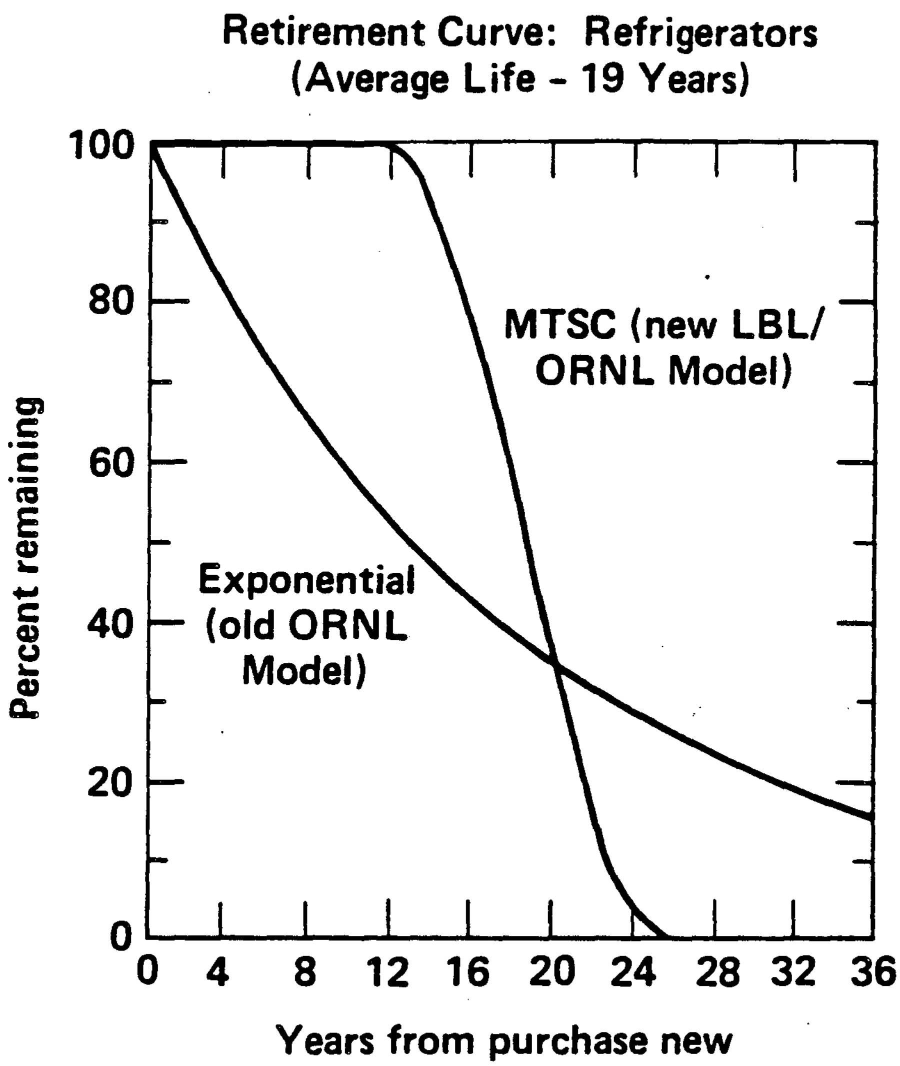
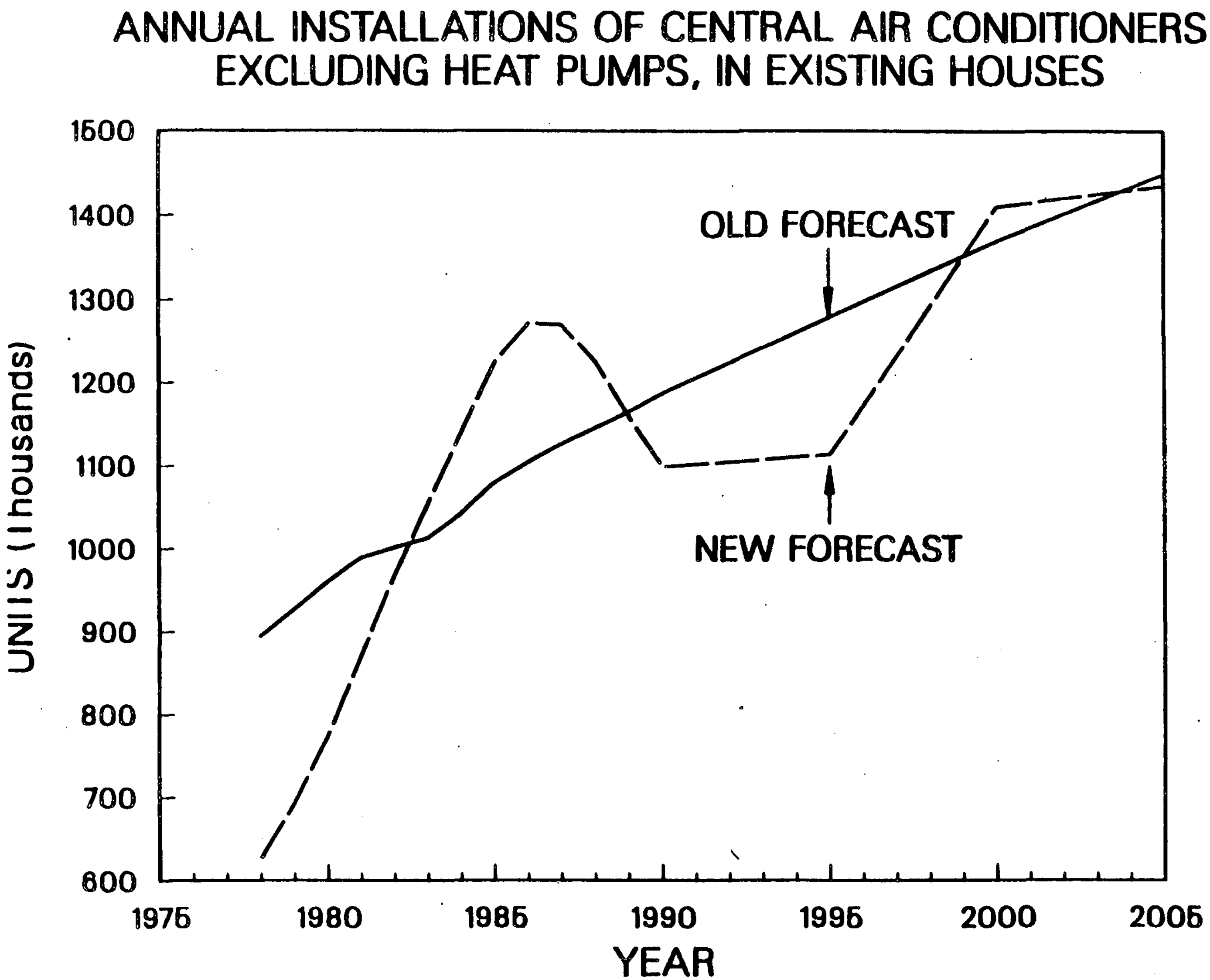

Retirement Curve: Refrigerators
(Average Life - 19 Years)
100
80
60
40
20
0
Percent remaining
0 4 8 12 16 20 24 28 32 36
Years from purchase new
MTSC (new LBL/
ORNL Model)
Exponential
(old ORNL
Model)

XBL 824-8891


ANNUAL INSTALLATIONS OF CENTRAL AIR CONDITIONERS
EXCLUDING HEAT PUMPS, IN EXISTING HOUSES
1500
1400
1300
1200
1100
1000
900
800
700
600
UNITS (Thousands)
OLD FORECAST
NEW FORECAST
1975
1980
1985
1990
1995
2000
2005
YEAR

XCG 861-7050