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# Residential HVAC Data, Assumptions and Methodology

# for End-Use Forecasting with EPRI-REEPS 2.1

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**ABSTRACT**

This report details the data, assumptions and methodology for end-use forecasting of space conditioning energy use in the U.S. residential sector. Space conditioning end-uses include Heating, Ventilation and Air Conditioning (HVAC). Our analysis uses the modeling framework provided by the HVAC module in the Residential End-Use Energy Planning System (REEPS), which was developed by the Electric Power Research Institute (McMenamin et al. 1992). This modeling framework treats space conditioning separately from appliances such as refrigerators or water heating due to the complex physical and economic interactions that characterize HVAC systems, and because space conditioning is the most significant end-use of residential energy in the United States. Space conditioning accounts for approximately 30% of electricity consumption, 70% of natural gas consumption and 90% of oil consumption in the U.S. residential sector. In terms of primary energy, space conditioning represents over half of all energy consumption in residences (EIA 1993).

This report is primarily methodological in nature, taking the reader through the entire process of developing the baseline residential space conditioning end-use models. Analysis steps documented in this report include: defining the thermal shell characteristics, gathering technology and market data for HVAC equipment and systems, developing cost data for the various components of the thermal shell and HVAC systems, and specifying decision models (both the functional form and equation parameters) to forecast future purchase decisions by households. Our implementation of the REEPS 2.1 modeling framework draws on the extensive technology, cost and market data assembled by LBL for the purpose of analyzing federal energy efficiency standards. The resulting residential HVAC forecasting model offers a flexible and accurate tool for analyzing the effect of policies at the national and north/south levels.

## FOREWORD AND ACKNOWLEDGMENTS

This project was undertaken at Lawrence Berkeley Laboratory (LBL) under the direct supervision of Jonathan Koomey, and with the guidance of James E. McMahon and Mark D. Levine. The purpose of this work is to create a well-documented end-use forecasting model for the residential sector, and to use that model to analyze national policies affecting the efficiency and patterns of energy use in the U.S.

The work adopts the modeling framework of the Residential End-Use Energy Planning System (REEPS) developed for the Electric Power Research Institute (EPRI). This report is one of a series of three reports documenting the residential sector end-use forecasting project using EPRI-REEPS 2.1, which is the most recent version of the computer software. The first report in the series summarizes the model framework and inputs, and presents the results of the baseline forecast for each end-use (LBL-34044). The other two reports detail the data, assumptions and methodology for the two distinct groups of end-uses in the residential sector. This report (LBL-34045), the second in the series, covers the space conditioning end-uses of Heating, Ventilating and Air Conditioning (HVAC) while the third report (LBL-34046), covers appliances, including water heating, refrigerators, freezers, clothes washers, clothes dryers, dishwashers, lighting and cooking.

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## 1. INTRODUCTION

This report details the data, assumptions and methodology for end-use forecasting of space conditioning energy use in the U.S. residential sector. Space conditioning end-uses include Heating, Ventilation and Air Conditioning (HVAC). Our analysis uses the modeling framework provided by the HVAC module in the Residential End-Use Energy Planning System (REEPS), which was developed by the Electric Power Research Institute (McMenamin et al. 1992). This modeling framework treats space conditioning separately from appliances such as refrigerators or water heating due to the complex physical and economic interactions that characterize HVAC systems. The appliance end-uses are discussed in a separate report (Hwang et al. 1994). The HVAC end-use represents the most significant area of residential energy consumption in the United States. Space conditioning accounts for approximately 30% of electricity consumption, 70% of natural gas consumption and 90% of oil consumption in the U.S. residential sector. In terms of primary energy, space conditioning represents over half of all energy consumption in residences (EIA 1993). Both the complexity and the sheer magnitude of energy consumption in this end-use suggest that space conditioning must be ascribed an important role in any residential sector policies or programs aimed at improving energy efficiency and/or reducing energy consumption. The baseline forecast using the REEPS model described here is presented in a separate report (Koomey et al. 1994a).

Engineering-economic models such as REEPS offer a means of assessing future trends in energy consumption at the end-use level under differing assumptions, scenarios or policies. Such models attempt to characterize the long-term structure and patterns of energy consumption in homes. They are called end-use forecasting models because they generally include considerable end-use detail. They rely on data regarding the building stock, the equipment available for supplying energy services, and historical patterns of end-use energy consumption in homes. For HVAC analysis, which is the focus of this report, engineering data on the building thermal shell and energy-using equipment are combined with economic parameters regarding purchase and usage of the equipment. At the national level, these end-use forecasting models facilitate the analysis of energy conservation programs and policy initiatives that are widely applicable and broad in their scope, such as residential appliance standards (US DOE 1989b, US DOE 1990, US DOE 1993) and national energy policy initiatives (EIA 1990). Utilities rely on end-use forecasting models in order to assess market trends for new technologies (McMenamin et al. 1992) and in the development of Demand-Side Management (DSM) programs (Hummel and McMenamin 1992).

This report details the supporting data, model parameters, and methodology for HVAC models developed for use with REEPS 2.1. In Section 2 we outline the HVAC modeling framework provided by REEPS and the end-use structure and assumptions we adopted for this analysis. In Section 3, we define the thermal shell characteristics, which serve as the starting point for the analysis of heating and cooling demand. In Section 4, we explain the technology and market data for HVAC equipment and systems. Section 5 includes the development of cost data and functions for the various components of the thermal shell and HVAC systems. Section 6 details the development of the various decision models used to forecast future purchase decisions by households, including the functional form and the parameters estimated for the models. Section 7 outlines areas for future work which are important to end-use forecasting for space conditioning, but could not be included in the model due to data and time limitations. In Section 8 we summarize and conclude the report.

## 2. MODEL STRUCTURE AND ASSUMPTIONS

In this section of the report we outline the REEPS modeling framework and the assumptions and data structure we have adopted in configuring the HVAC model. In Section 2.1, we describe the general features of residential end-use forecasting and the particular features of the REEPS modeling framework, emphasizing those aspects relevant to the HVAC model. In Section 2.2, we explain the methodology for structuring the HVAC model and some of the conventions we adopted in setting up the model. In Section 2.3, we provide an overview of the data sources we used to develop the structure, inputs and parameter estimates for the HVAC model. In Section 2.4, we discuss some of the potential applications of the model in analyzing impacts of government policies, utility programs, changes in technology development and adoption, and economic scenarios.

### 2.1. REEPS Modeling Framework

The basic assumptions and structure of residential end-use forecasting are quite similar across both different modeling frameworks and different end-uses (Johnson et al. 1992). The household is considered the fundamental unit for energy consumption. The physical housing stock is defined by its thermal properties, while energy-using equipment is described by variables such as size (or capacity) and efficiency. Macroeconomic and demographic variables that change over time include the housing stock, household size, fuel prices and household income. Technology data characterize the existing and/or future stock of equipment and allow the formulation of functional relationships to use in the forecast. Consumer data describe ownership patterns for equipment and appliances, generally segmented by housing type. Consumer attitudes toward energy efficiency investments are typically characterized by parameters that represent economic tradeoffs between purchase price and operating cost. Market shares are estimated for each technology or fuel for a given end-use or energy service and the models adjust these market shares over time as households purchase equipment.

The EPRI-REEPS model is one of several prominent end-use forecasting models that have been developed since the mid-1970s. One of the earliest residential end-use forecasting models was developed at Oak Ridge National Laboratory (Hirst and Carney 1978). This model was later modified at the Lawrence Berkeley Laboratory (McMahon 1987) for the analysis of residential appliance standards. REEPS has been used since the early 1980s both as a tool for national policy analysis and subsequently as an analytical tool for electric utilities to forecast long-term residential energy demand (EPRI 1982). The first version of the model, REEPS 1.0, relied on an econometric/micro simulation approach to estimate energy consumption for a given sample of households (Cowing and McFadden 1984). The newest version of the model, REEPS 2.1, is quite different in that it provides the user with a generalized modeling framework rather than attempting to simulate a particular set of households. As a result, REEPS 2.1 does not have the theoretical foundation and household-specific data enumeration offered by the micro simulation approach in REEPS 1.0 (Cowing 1992).

This latest version of REEPS incorporates the basic features of residential end-use forecasting into a generalized modeling framework in which the user has considerable control over the algorithms and model structure (McMenamin et al. 1992). All REEPS users work within a common software framework, which allows them to focus on the substantive aspects of the analysis and avoid potential programming errors introduced by changes in the software source code. This framework provides greater flexibility over more traditional models which are "hardwired" for particular formulations of residential sector energy use. Rather than relying on a fixed set of equations and/or parameters, the user can precisely specify the equations used to forecast future equipment and housing characteristics. Both the functional form and parameters included in these equations are open to modification by the user. This enables modeling of a wide range of scenarios and policies at varying levels of disaggregation without ever changing the computer program itself. This improved modeling flexibility, however, brings with it considerably more responsibility on the part of the user in configuring the input data. Each distinct set of data and parameters results in a different model, with the result that there can be considerable variation in the forecast results even when exogenous variables remain the same. In effect, the "model" consists of the structure, data, and algorithms developed by the user, with the REEPS computer program itself as a modeling shell that imparts a higher level structure and consistency to the analysis.

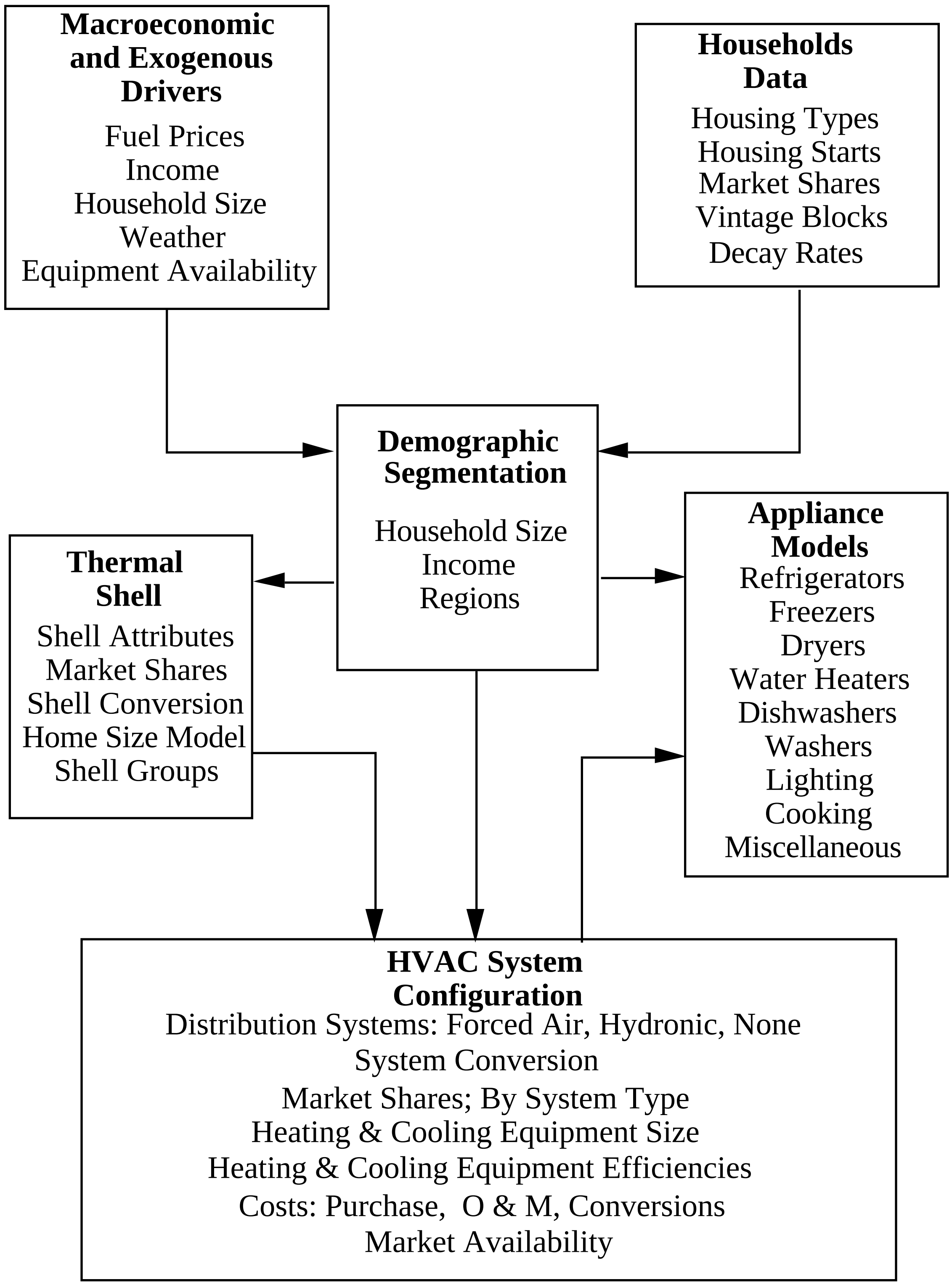
REEPS 2.1 provides a distinct modeling component for the space conditioning end-uses, with the capability to model heating, ventilation and air conditioning (HVAC). The HVAC module in REEPS derives its higher-level structure from other input variables shown in Figure 2.1. Exogenous variables include macroeconomic projections such as income and household size, along with other external parameters needed by the model. Fuel price projections are implemented as exogenous time series for each fuel and rate class used in the model. Households data allow the user to forecast changes to the housing stock based on separate decay rates for each housing type and vintage block. Demographic segmentation divides the HVAC market into different segments based on household characteristics such as income or household size, allowing purchase decisions to be differentiated between the segments. These other input sets precede the specification of the HVAC model itself because they define important elements of the HVAC model structure, such as the housing types specified in the Households module. Data from these input sets are used as drivers in forecasting the size, characteristics, and usage of the space conditioning equipment and housing stock. In general, REEPS uses data in the form of an average value within a market segment (house type, income, etc.), rather than a distribution of values that would more closely approximate the actual situation. This data structure could potentially introduce aggregation bias into the forecasts, which the user may attempt to minimize by dividing the market into smaller segments (thus the average values input to REEPS represent fewer houses).

## 2.2. HVAC Model Structure

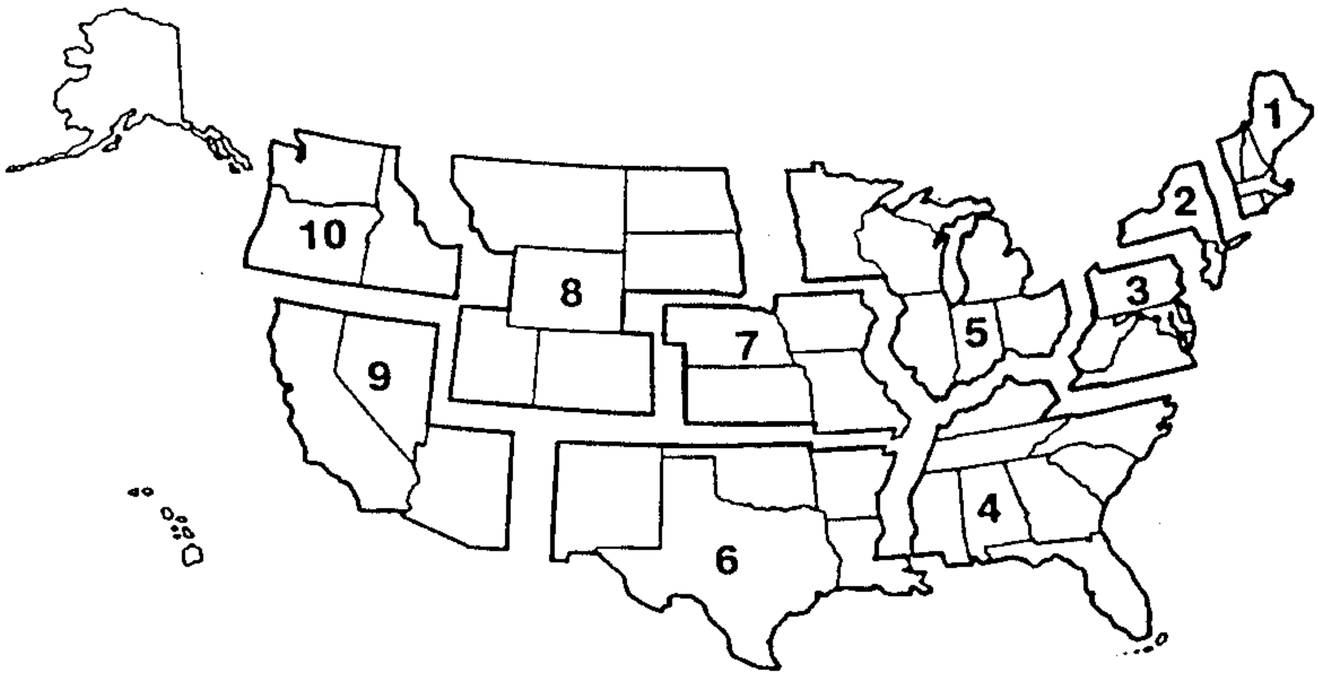
In forecasting energy consumption for space conditioning in U.S. residences, some level of regional disaggregation is desirable due to the wide differences in climate and the associated heating and cooling requirements. However, regional disaggregation is often not possible because detailed data such as that required to describe the technology characteristics of heating and cooling equipment is often not available at the regional level. Moreover, regional segmentation is not easily accomplished in REEPS, partially because most users of REEPS are utilities who need not be concerned with climate differences. Consequently, we chose an intermediate level of regional disaggregation, North and South, as used in a recent analysis of conservation potential in the U.S. residential sector (Koomey et al. 1991a). As illustrated in Figure 2.2, the North consists of Federal regions 1, 2, 3, 5, 7, 8 and 10 while the South consists of Federal regions 4, 6 and 9. This requires two distinct "implementations" of REEPS, which can then be aggregated to yield national results. Our regional breakup allows us to capture climate-related characteristics of heating and cooling without stretching the modeling framework beyond what current data can support. At the same time, we have adopted a methodology throughout the analysis which is independent of the number of regions, so that the framework could include more regions if more detailed data became available at the regional level.

While regional disaggregation should yield more accurate modeling results, there are certain modeling applications that do not allow the time to set-up and run the regional models. For these quick response situations, we have developed a national (one-region) REEPS HVAC model. The structure and inputs to this model are documented in Appendix H. In general, the structure and data sources used in the national model are identical to the regional models.

**Figure 2.1: Relationships among REEPS Input Sets**



## Figure 2.2: Map of Regions Used in REEPS HVAC Model




**Region 1**
**New England**
Connecticut (CT)
Maine (ME)
Massachusetts (MA)
New Hampshire (NH)
Rhode Island (RI)
Vermont (VT)

**Region 2**
**New York/**
**New Jersey**
New Jersey (NJ)
New York (NY)

**Region 3**
**Mid Atlantic**
Delaware (DE)
District of Columbia (DC)
Maryland (MD)
Pennsylvania (PA)
Virginia (VA)
West Virginia (WV)

**Region 4**
**South Atlantic**
Alabama (AL)
Florida (FL)
Georgia (GA)
Kentucky (KY)
Mississippi (MS)
North Carolina (NC)
South Carolina (SC)
Tennessee (TN)

**Region 5**
**Midwest**
Illinois (IL)
Indiana (IN)
Michigan (MI)
Minnesota (MN)
Ohio (OH)
Wisconsin (WI)

**Region 6**
**Southwest**
Arkansas (AR)
Louisiana (LA)
New Mexico (NM)
Oklahoma (OK)
Texas (TX)

**Region 7**
**Central**
Iowa (IA)
Kansas (KS)
Missouri (MO)
Nebraska (NE)

**Region 8**
**North Central**
Colorado (CO)
Montana (MT)
North Dakota (ND)
South Dakota (SD)
Utah (UT)
Wyoming (WY)

**Region 9**
**West**
Arizona (AZ)
California (CA)
Hawaii (HI)
Nevada (NV)

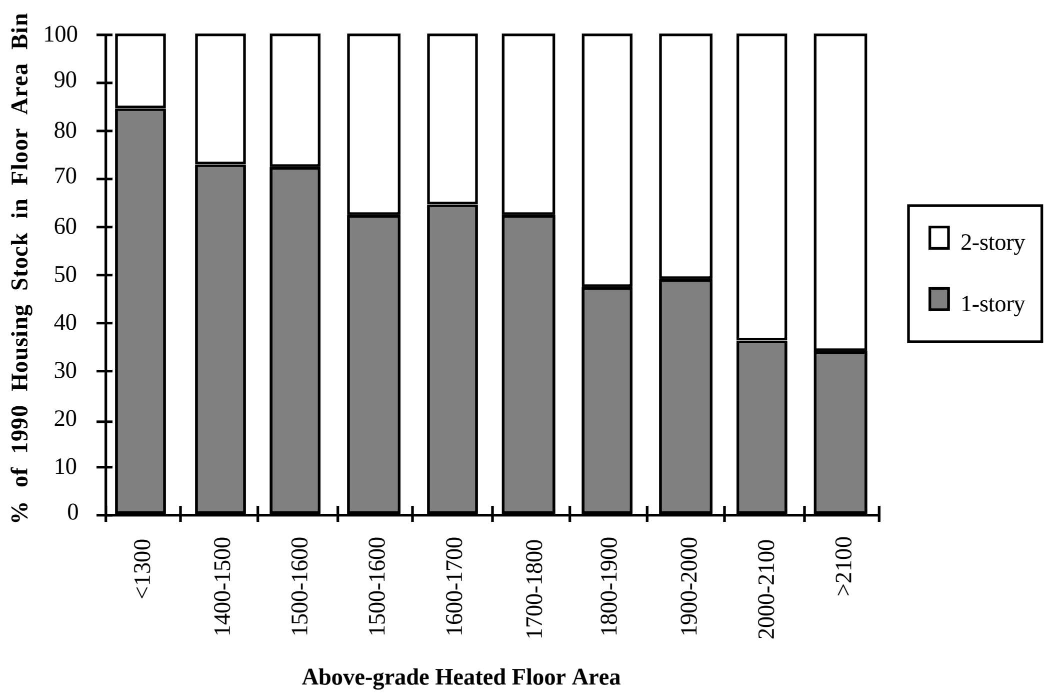
**Region 10**
**Northwest**
Alaska (AK)
Idaho (ID)
Oregon (OR)
Washington (WA)

South Region is defined as Federal Regions 4, 6, and 9.

North Region is defined as Federal Regions 1, 2, 3, 5, 7, 8, and 10

This analysis distinguishes between four housing types: small single-family homes, large single-family homes, multifamily homes, and manufactured homes. Each housing type has characteristic HVAC-system energy consumption and market behavior. We separated the two types of single-family homes by using 1800 square feet heated floor area as the dividing line between large and small homes.[1] The distinction between small and large single-family homes is an important one, for a number of reasons. First, REEPS does not model the building dimensions of new homes separately from existing homes. We know, however, that homes being built today are substantially larger on average than existing homes. Therefore, we divide single-family homes by floor area so that the small category better describes existing homes, while the large category better describes new homes. Second, larger homes are generally 2-story homes, which have different thermal characteristics than 1-story homes of the same floor area. Furthermore, as Figure 2.3 shows, 1800 square feet is roughly the break point for single-family construction practices in the U.S. More than 50% of homes in each category larger than 1800 square feet are 2-story homes while more than 50% of homes in each category smaller than 1800 square feet are 1-story.[2] Finally, the heating and cooling requirements are different for large and small homes, with the result that the economics of choosing among HVAC systems and thermal shells is also quite different. We can thus capture this market effect in our model.

**Figure 2.3: Shares of 1-Story and 2-Story Single-Family Homes by Heated Floor Area**




Source: 1990 RECS (EIA 1993).

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[1] We consider only the above-grade heated area, based on RECS data, to exclude basements from the calculation of floor area. The dividing point has also been chosen because the median heated floor area for new construction in the base year of 1990 is approximately 1800 square feet (ASE et al. 1991). Note that the national model described in Appendix H does not distinguish between large and small single-family house types.

[2] Split-level homes and homes with more than 2 stories are treated as 2-story homes, although these make up a small percentage of all homes.

The HVAC model has four types of inputs: (1) thermal shell configurations; (2) HVAC technologies and systems characteristics; (3) HVAC equipment size, usage, and cost models; and (4) decision models for purchases of equipment and thermal shells. The thermal shell prototypes are configured using either whole-house U-values to represent thermal integrity or by specifying the U-values of the building components such as windows and ceilings. We chose the latter approach. The technologies to be defined include heating and cooling equipment and distribution systems. These technologies are then grouped into HVAC systems. The decision models are the basis of REEPS' forecasting capabilities, and can be of two types: reduced-form or logit choice models. The reduced-form models are used to forecast average values for important properties of technologies and systems that change over time, such as cost, size, efficiency or usage. The logit choice equations estimate the market shares of technologies over time based on a user-specified utility function. The main part of this report devotes a section to each of these four components of the HVAC model.

### 2.3. Data Sources

The REEPS 2.1 modeling framework is data intensive, requiring data at the household level as well as detailed data on the characteristics of HVAC equipment and thermal shells. The primary source of data for our analysis is the 1990 Residential Energy Consumption Survey (RECS) conducted by the Energy Information Administration (EIA 1989, EIA 1992, EIA 1993). For data on heating and cooling equipment, we rely on annual records provided by trade groups on the shipments, efficiency and in certain cases the size (capacity or volume) of the equipment (AHAM 1991, ARI 1991, GAMA 1992). For cost data, we draw on published cost estimates of the R.S. MEANS company (R.S. MEANS Co. 1991b, R.S. MEANS Co. 1991c) and engineering-cost data developed by the ADM corporation (ADM 1987). For thermal shell data, we use estimates of prototype population characteristics for single-family buildings (Ritschard et al. 1992), multifamily buildings (Ritschard and Huang 1989), and manufactured homes (Koomey et al. 1991a). For new homes, we used survey data by state from the National Association of Home Builders (NAHB 1989). Other miscellaneous sources provided data where it was not available from these main sources.

### 2.4. Potential Applications

Within the HVAC module of REEPS 2.1, the user can model a variety of policies and impacts. Future market conditions and policies can be modeled by modifying relevant parameters, data structure, functional equations or control data. For instance, new technologies can be defined to satisfy markets or areas of demand that are expected to develop. Table 2.1 lists some of the impacts that can be modeled and the policy handles available for this purpose. We group these according to the major building component to which they apply: the thermal shell, heating and cooling equipment, or distribution systems. Policies can also be modeled through exogenous variables, such as fuel prices, that pertain to any end-use and can be modified directly in the input sets. The list in Table 2.1 is by no means exhaustive; the policies that can be modeled are limited to some extent only by the imagination of the modeler or policy analyst.

## 3. THERMAL SHELL

The thermal shell of a building refers to its physical properties with respect to the flow and distribution of heat, without considering the occupants or their behavior. The REEPS model provides two alternative methods for configuring thermal shells to represent the physical characteristics of the residential building stock. One option is a whole-house U-value index, in which each discrete thermal shell is characterized by a single heat-load (heating) multiplier and a single heat-gain (cooling) multiplier. The second option is a multiple-attribute approach in which the user builds the thermal shell prototypes within the REEPS model by defining specific attributes representing important thermal components, such as windows and ceilings. The user then chooses the appropriate number of levels or values for each attribute, such as insulation levels (R-values) in the case of walls or ceilings. Weighting factors are then calculated for each housing type to represent the contribution of each attribute to the whole-house heat gain and heat loss, according to its relative surface area and heat transfer properties. The user then "builds" a set of packages or prototypes by choosing combinations of different attribute levels to represent the thermal shells to be used in the model. The heat gain and heat loss multipliers for the shell are a linear combination of the specific attributes using the weighting factors.

**Table 2.1: Policy Handles in EPRI-REEPS HVAC Module**

| Area of Impact | Policy Handle |
|---|---|
| THERMAL SHELL | |
| Building efficiency standards | Set "Legal Availability" of specific shells |
| Energy-Efficient Mortgages | Decision model of thermal shell investments |
| Rebates for thermal shell upgrades | Adjust cost of specific shell components |
| Regional/Utility promotion of retrofits | Change rates of thermal shell retrofits |
| Investment Tax Credits | |
| Low-Interest loans | Decision model for retrofits |
| Energy Doctor | Adjust purchase cost of thermal shells |
| Energy Audits | Add shell components and options |
| Incentives to Builders/Developers | Add thermal shell specifications |
| New building/shell technologies | |
| Passive solar design/landscaping/shading | |
| | |
| HEATING/COOLING EQUIPMENT | |
| Efficiency Standards | Change efficiency choice equation |
| New technologies | Add technologies to HVAC model |
| Efficiency Rebates | Adjust cost-efficiency parameter |
| Early retirement/replacement | Develop HVAC Conversion model |
| Investment Tax Credits | Change decision model parameters |
| Energy Doctor | Adjust operating cost or efficiency |
| "Golden Carrot" Programs | Cost/Market Availability |
| Technology Procurement | Change market share model |
| Labeling/Information Dissemination | Change efficiency choice model |
| Economies-of-scale | Set technology cost multipliers |
| Changing Market Structure | Adjust market shares |
| Federal Energy Management | Segment Federal building stock |
| HVAC Contractor Incentives | Change cost equations |
| Research and Development | Adjust cost multipliers |
| Patent Law | Adjust "market availability" |
| Trade/Imports/Exports | |
| Gas Availability | Set fuel availability variable for Gas |
| | |
| DISTRIBUTION SYSTEMS | |
| Efficiency Standards | Configure new distribution systems |
| New technologies | Change distribution system cost |
| Efficiency Rebates | Conversion of distribution systems |
| Early retirement/replacement | |
| | |
| ENERGY PRICES | |
| Taxes | Change fuel prices in desired years |
| energy taxes | |
| carbon tax | |

This analysis employs the multiple-attribute approach in order to lend a better physical interpretation to the model and to facilitate a more disaggregated analysis of thermal shell efficiency investments. In this section, we describe the methodology used to develop the thermal shell data and building prototypes for the two regions. Section 3.1 describes the thermal shell attributes and the components they represent in our analysis. In Section 3.2, we provide data on the building dimensions for the various housing types and the manner in which they are used as weighting factors in calculating the whole-building heating and cooling loads. In Section 3.3, we use combinations of the attributes to define a set of thermal shell packages representing the housing stock of each region. Section 3.3 also develops the market shares of these shell packages for existing and new homes of each housing type and shell group. In Section 3.4, we detail our estimates of the purchase price for shell attributes in new construction. These price estimates are designed to be used in decisions about thermal shell purchases as a means of comparing the economic tradeoffs between higher purchase price and lower operating cost due to lower heating and/or cooling requirements.

## 3.1. Thermal Shell Components

We use six components in this analysis to represent the thermal shells. The physical characteristics of each component are used to specify thermal integrity levels. Table 3.1 lists the levels of each component and their U-values, along with shading coefficients for windows. These components correspond to specific attributes in the REEPS modeling framework and are used to determine the heat gain and loss characteristics of each thermal shell package. The South prototypes have a slab foundation because this is the predominant foundation design in that region. The foundation attribute levels for the South in Table 3.1 refer to the thickness and depth of insulation applied to the slab. In the north, the predominant foundation is an unheated basement, for which the foundation attribute levels in Table 3.1 refer to basement (underfloor) insulation. The attribute levels for ceilings and walls refer to insulation R-values. The infiltration levels are based on the number of Air Changes per Hour (ACH). For windows, we use seven window types, ranging from single-glazed windows to superwindows, and assume a wood frame is used for all types. The last four of these window types represent new technologies that have appeared on the market in the past 5-10 years and are expected to gain market share as their purchase price declines with increasing production volumes (Frost et al. 1993). The residual loads are used to represent heating and cooling load effects (such as internal gains) not attributed to the shell components.

We use building energy simulations to determine the heating and cooling loads associated with the various thermal shells. Building energy simulations require weather input data for specific cities. We used a population-weighted climate-averaging program (Andersson et al. 1986) to determine the most representative weather conditions for each region. The weather of Chicago, IL was found to approximate the weather of the northern region while the weather of Charleston, SC approximates the weather for the southern region. We have estimated the thermal shell heating and cooling loads using normalized component loads adopted from a database of DOE-2 thermal simulation model runs (Huang et al. 1987a). The simulations assumed a constant thermostat setpoint of 70°F for heating (without thermostat setback at night) and 78°F for cooling, and included typical internal gains. Appendix A gives the normalized component loads for the North and South regions.

We use the shell components in Table 3.1 as specific attributes in the thermal shell framework of the REEPS HVAC module. Building loads are calculated directly from the normalized component loads for heating and cooling. For a given level of an attribute, such as R-7 insulation for ceilings, the normalized component loads give the heating and cooling loads in kBtu per square foot of ceiling per year.

| Table 3.1: Thermal Shell Components, U-values and Shading Coefficients | | | | |
|---|---|---|---|---|
| **Component** | **Construction** | **U-Value** | **SC** | **Construction Assumptions** |
| Ceiling | R00 | 0.2470 | | Uninsulated ceiling below attic |
| | R07 | 0.0928 | | R07 insulated ceiling below attic |
| | R11 | 0.0682 | | R11 insulated ceiling below attic |
| | R19 | 0.0460 | | R19 insulated ceiling below attic |
| | R22 | 0.0389 | | R22 insulated ceiling below attic |
| | R30 | 0.0293 | | R30 insulated ceiling below attic |
| | R38 | 0.0235 | | R38 insulated ceiling below attic |
| | R49 | 0.0185 | | R49 insulated ceiling below attic |
| | R60 | 0.0152 | | R60 insulated ceiling below attic |
| Wall | R00 | 0.2241 | | Uninsulated 2x4 wood frame wall |
| | R07 | 0.1051 | | R07 insulated 2x4 wood frame wall |
| | R11 | 0.0881 | | R11 insulated 2x4 wood frame wall |
| | R13 | 0.0693 | | R13 insulated 2x4 wood frame wall |
| | R19 | 0.0600 | | R19 insulated 2x6 wood frame wall |
| | R27 | 0.0427 | | R19 insulated 2x6 wood frame wall with insulated sheathing |
| | R34 | 0.0322 | | R19 insulated 2x6 wood frame wall with insulated sheathing |
| Windows | 1.0-gla | 1.10 | 0.90 | Wood Frame, 80% glass, single clear glass |
| | 2.0-gla | 0.48 | 0.66 | Wood Frame, 80% glass, double clear glass, 0.5" air space |
| | 3.0-gla | 0.30 | 0.61 | Wood Frame, 80% glass, triple clear glass, 0.5" air space |
| | 2-gla loE | 0.36 | 0.59 | Wood Frame, 80% glass, low emissivity film |
| | 2-gla loEAr | 0.30 | 0.59 | Wood Frame, 80% glass, low emissivity film, argon fill |
| | Spectrally Sel. | 0.36 | 0.44 | Wood Frame, 80% glass, spectrally selective double glazing |
| | Superwindow | 0.20 | 0.51 | Wood Frame, 80% glass, 2 glazings & suspended low-E film. |
| | Heat Mirror | 0.29 | 0.39 | Wood Frame, 80% glass, 2 glaz. & suspended heat mirror film. |
| Floors (crawl or unheated basement) | R00 | 0.2137 | | Uninsulated 2x10 floor over basement or crawl space |
| | R11 | 0.0693 | | R11 insulated 2x10 floor over basement or crawl space |
| | R19 | 0.0471 | | R19 insulated 2x10 floor over basement or crawl space |
| | R30 | 0.0328 | | R30 insulated 2x10 floor over basement or crawl space |
| | R38 | 0.0295 | | R38 insulated 2x10 floor over basement or crawl space |
| | R49 | 0.0201 | | R49 insulated 2x10 floor over basement or crawl space |
| Slab | R-0 | 0.4752 | | Uninsulated Slab |
| | R-5 2ft | 0.2505 | | Exterior vertical slab insulation to depth and R-value listed |
| | R-10 2ft | 0.2107 | | Exterior vertical slab insulation to depth and R-value listed |
| | R-5 4ft | 0.1983 | | Exterior vertical slab insulation to depth and R-value listed |
| | R-10 4ft | 0.1380 | | Exterior vertical slab insulation to depth and R-value listed |
| Heated Basement | R-0 | 1.6717 | | Uninsulated basement wall |
| | R-5 4ft | 0.8348 | | Ext. vertical basement wall insul. to depth and R-value listed |
| | R-10 4ft | 0.6734 | | Ext. vertical basement wall insul. to depth and R-value listed |
| | R-5 8ft | 0.6655 | | Ext. vertical basement wall insul. to depth and R-value listed |
| | R-10 8ft | 0.4468 | | Ext. vertical basement wall insul. to depth and R-value listed |

Source: Huang et al. (1987a)
1) SC = Shading Coefficient
2) For windows, "80% glass" means that 80% of the gross window area is glass (remainder is frame and sash material). Window U-values are for whole window.
3) Koomey et al. (1994b) describe window technologies in more detail.

One should note that our approach to calculating building loads differs from the approach suggested in the REEPS model documentation.[3] The suggested methodology is based on the

[3] See pages HV-9-12 in the REEPS User's guide (EPRI 1990) for a more detailed description of this methodology, based on the Manual J method of calculating heat gains and losses. The Manual J method (ACCA 1975) develops a whole-house U-value by averaging the component U-values using component weights (component areas modified to account for non-conductive heat transfer). This method is similar to the equipment sizing method presented by ASHRAE (1993). The Manual J method is less accurate than building simulations because it does not explicitly account for complex phenomena such as radiative transfer or thermal mass.

Manual J method (ACCA 1975) which estimates building loads based on a whole-house weighted average U-value. On the other hand, the DOE-2 building simulation model, from which we derived the normalized loads, can incorporate physical interactions that the imputed weights cannot. By using an explicit physical specification of the building components, building simulations achieve a better representation of the heating and cooling characteristics than approaches which rely on an index of thermal integrity or a whole house U-value (Johnson and Hanford 1992). The use of specific attributes and building components is also important in analyzing the economics of consumer decisions about thermal shells.

## 3.2. Building Characteristics

We developed a set of data on the dimensions of buildings for each of the two regions and each of the four housing types: small single-family, large single-family, multifamily and manufactured homes, as given in Table 3.2. These building dimensions determine the shell component weighting factors described in the previous section.

**Table 3.2: REEPS Input Building Characteristics**

| | **North Region** | | | | **South Region** | | | |
|---|---|---|---|---|---|---|---|---|
| *Housing Type:* | Small Single-Family | Large Single-Family | Multi-family | Manu-factured Homes | Small Single-Family | Large Single-Family | Multi-family | Manu-factured Homes |
| Number of Stories | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| Foundation Type | Unheated Basement | | | | Slab | | | |
| *Component Dimensions (square feet)* | | | | | | | | |
| Conditioned Floor Area | 1227 | 2892 | 1074 | 1207 | 1336 | 2562 | 1056 | 1195 |
| Ceiling | 1227 | 1446 | 479 | 1207 | 1336 | 2562 | 490 | 1195 |
| Walls | 1002 | 2349 | 476 | 993 | 1051 | 1785 | 480 | 987 |
| Windows | 147 | 347 | 73 | 145 | 160 | 307 | 48 | 143 |
| Infiltration | 1227 | 2892 | 1074 | 1207 | 1336 | 2562 | 1056 | 1195 |
| Foundation Area | 1227 | 1446 | 31 | 1207 | 1336 | 2562 | 31 | 1195 |
| Foundation Perim. (lin. ft.) | 144 | 169 | | 142 | 151 | 262 | | 141 |
| 1990 Stock (millions) | 23.6 | 10.6 | 15.1 | 2.5 | 19.1 | 7.1 | 9.5 | 3.7 |

Sources: Single-family: 1990 RECS (EIA 1993); Multifamily: Ritschard and Huang (1989); Manufactured Homes: Census Bureau C-25 report (US Bureau of the Census 1991). Housing Stock from 1990 Census (US Bureau of the Census 1992).
Notes: 1) Multifamily component area is for an average apartment unit among several types of MF buildings.
2) Wall area assumes 8 foot wall height and is net of windows.
3) Stock split between large and small single-family based on 1990 RECS for SF detached.

Note that REEPS does not distinguish between stock homes and new construction based on building dimensions. Rather, the vintage of buildings is distinguished by thermal integrity level, which is specified through the shell package market shares described in Section 3.3. We have used floor areas for new homes, because floor area mainly affects the new-home decision models. This will not bias the calculation of energy usage for existing homes in REEPS because the usage equation for existing homes is calibrated to the existing-home UECs at the beginning of forecast execution. For small single-family, a 1-story home is used in both north and south regions. For large single-family, a 2-story home is used in the north while a one-story home is used in the south, according to the predominant type in each region. The heated floor areas for small single-family and large single-family homes were derived from the 1990 RECS based on the average above-grade (excluding basements) heated floor area for single-family homes below and above 1800 square feet, respectively. These data are averages for homes in the RECS sample built between 1980 and 1990. For multifamily buildings, the dimensions are averaged across several different configurations of apartment units because the location of a unit within the building is important in determining the apartment-unit load (Ritschard and Huang 1989). Generally, the apartment buildings we modeled are between 2 and 4 stories, with a combination of middle and end units. Manufactured home dimensions are based on average floor areas for new mobile homes shipped in 1990 (US Bureau of the Census 1991), and a width of 28 feet, which is a common truss width.

The heating and cooling loads for a given set of attributes (constituting a single prototype) are linear functions of the component loads and are scaled by weighting factors based on the building dimensions:

$$\text{Load (MMBtu)} = \sum_i (W_i * NL_i) + \text{Residual Load} \qquad (3.1)$$

$W_i$ is the weighting of component *i* and $NL_i$ is the normalized heating or cooling load for component *i*. For infiltration, the weight is the total above-grade conditioned or heated floor area. For slab foundations, the weight is the perimeter of the slab. For all other components, the weight is simply the area in square feet of the component.

## 3.3. Thermal Shell Packages

Having defined the shell component attributes and weighting factors, we now build a set of prototypes for each region by choosing "packages" of the components which are representative of housing practices in each region. These prototypes can then be used to describe the composition of the existing housing stock and the expected composition in new housing construction. These packages determine the design usage of space conditioning equipment based on a given package's heating and cooling loads calculated using Equation 3.1. We choose a total of twelve such packages for each region, ranging from completely uninsulated to extremely well-insulated homes with component levels that are currently available on the market.

Tables 3.3-N and 3.3-S list the thermal shell packages for the north and south regions, respectively, listed in order of increasing thermal integrity and thus decreasing heat load. The main differences between the packages are their ceiling and wall insulation, which generally have the largest effect on overall heating and cooling loads. Rather than defining all possible combinations, which would result in unnecessary proliferation of shell packages, we have chosen this limited set of packages to represent the distribution of thermal integrity in each region. The packages are selected sensibly, in that we do not pair high levels of ceiling insulation with low levels of wall insulation, for example. We use packages 1-8 in each region to describe existing homes and packages 3-9 to describe new homes. Packages 10-12 are intended as the high-end options for thermal shell choices in future years. The packages are generally the same for both regions, with the following exceptions. First, since the foundations are different in the north and south prototypes, the foundation insulation levels in the packages differ somewhat. Second, we chose Superwindows for packages 10-12 in the north to minimize heat loss while the same packages in the south include Heat Mirrors to minimize solar gain. Finally, the insulation levels are higher in some packages in the north than in the south as might be expected due to the differences in heating requirements and as current practice suggests (NAHB 1989).

To develop the market shares of these thermal shells in the existing housing stock, we used the 1990 RECS along with estimates of prototype populations for single-family homes (Ritschard et al. 1992), multifamily homes (Ritschard and Huang 1989) and manufactured homes (Koomey et al. 1991a). The RECS data allowed us to break out small and large single-family homes and to assess insulation categories and windows for the four housing types. We followed a similar procedure in developing the market shares for new homes, but based our analysis on the subset of homes in the 1990 RECS which were built in the 1980s. We included estimates of current construction practice for each housing type (Hanford et al. 1994) where market share data for a given shell package were missing or inadequate. The resulting market share data are shown in Tables 3.4-N and 3.4-S for existing homes and Tables 3.5-N and 3.5-S for new homes.

**Table 3.3-N: North Region Thermal Shell Packages**

| Package | Component | | | | |
|---|---|---|---|---|---|
| | Ceiling | Walls | Windows | Infiltration (ACH) | Foundation (Unheated Basement) |
| 1 | R-0 | R-0 | 1-G | 0.8 | R-0 |
| 2 | R-7 | R-0 | 1-G | 0.7 | R-0 |
| 3 | R-11 | R-7 | 1-G | 0.7 | R-0 |
| 4 | R-19 | R-7 | 2-G | 0.55 | R-11 |
| 5 | R-22 | R-11 | 2-G | 0.55 | R-11 |
| 6 | R-30 | R-13 | 2-G | 0.55 | R-11 |
| 7 | R-30 | R-13 | 2GLeA | 0.55 | R-11 |
| 8 | R-38 | R-19 | 2GLeA | 0.4 | R-11 |
| 9 | R-49 | R-19 | 2GLeA | 0.4 | R-19 |
| 10 | R-38 | R-19 | Superwindow | 0.4 | R-19 |
| 11 | R-49 | R-27 | Superwindow | 0.4 | R-19 |
| 12 | R-60 | R-34 | Superwindow | 0.4 | R-30 |

**Table 3.3-S: South Region Thermal Shell Packages**

| Package | Component | | | | |
|---|---|---|---|---|---|
| | Ceiling | Walls | Windows | Infiltration (ACH) | Foundation (Slab) |
| 1 | R-0 | R-0 | 1-G | 0.8 | R-0 |
| 2 | R-7 | R-0 | 1-G | 0.7 | R-0 |
| 3 | R-11 | R-7 | 1-G | 0.7 | R-0 |
| 4 | R-19 | R-7 | 2-G | 0.7 | R-0 |
| 5 | R-22 | R-11 | 2-G | 0.55 | R-5,2 |
| 6 | R-30 | R-13 | 2-G | 0.55 | R-5,2 |
| 7 | R-30 | R-13 | 2GLeA | 0.55 | R-5,2 |
| 8 | R-38 | R-19 | 2GLeA | 0.4 | R-5,2 |
| 9 | R-38 | R-19 | 2GLeA | 0.4 | R-10,2 |
| 10 | R-38 | R-19 | Heat Mirror | 0.4 | R-10,2 |
| 11 | R-49 | R-27 | Heat Mirror | 0.4 | R-10,2 |
| 12 | R-60 | R-34 | Heat Mirror | 0.4 | R-5,4 |

1) ACH = Air Changes per Hour
2) See Table 3.1 for more extensive description of component levels.
3) Foundation insulation in the north is underfloor insulation, in the south slab-edge insulation.

REEPS allows the user to group thermal shells into "shell groups" for the purpose of defining thermal shell market shares. These shell groups are differentiated by HVAC equipment type, thus one or more HVAC systems are assigned to each shell group. One could specify a distinct thermal shell group for each HVAC system, but this would needlessly repeat heating/cooling profiles which are already quite similar. We separated single-family homes into five shell group categories based on heating and/or cooling system: Heat Pumps, Electric Heating, Gas Furnace/Central Air, Fuels, and Other.

**Table 3.4-N: North Region Thermal Shell Shares for Existing Homes (% of Shell Group) (Screen HV-3f.1)**

| ***House Type*** | **Small Single-Family** | | | | | **Large Single-Family** | | | | | **MF** | **MH** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Shell Group*** | **HP** | **Elec** | **NG/CA** | **Fuels** | **Other** | **HP** | **Elec** | **NG/CA** | **Fuels** | **Other** | **All** | **All** |
| Package | | | | | | | | | | | | |
| 1 | | | | 0.3% | | | | | 1% | | | |
| 2 | 4% | 3% | 7% | 20% | 14% | | 11% | 8% | 20% | 6% | 36% | 20% |
| 3 | 3% | 6% | 9% | 7% | 5% | 8% | 11% | 3% | 6% | 3% | 36% | 7% |
| 4 | 14% | 14% | 34% | 37% | 22% | 32% | 22% | 31% | 29% | 29% | 25% | 24% |
| 5 | 24% | 56% | 41% | 32% | 45% | 43% | 48% | 36% | 42% | 32% | 4% | 29% |
| 6 | 26% | 11% | 3% | 3% | 5% | 5% | 4% | 4% | 1% | 9% | | 20% |
| 7 | 26% | 8% | 5% | 2% | 9% | 11% | 4% | 17% | 1% | 10% | | |
| 8 | 3% | 2% | | | | | | 2% | | 10% | | |
| 9 | | | | | | | | | | | | |
| 10 | | | | | | | | | | | | |
| 11 | | | | | | | | | | | | |
| 12 | | | | | | | | | | | | |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| 1990 Stock (thousands) | 563 | 2,510 | 4,621 | 13,078 | 3,328 | 203 | 673 | 2,698 | 5,588 | 839 | 13,906 | 2,845 |

**Table 3.4-S: South Region Thermal Shell Shares for Existing Homes (% of Shell Group) (Screen HV-3f.1)**

| ***House Type*** | **Small Single-Family** | | | | | **Large Single-Family** | | | | | **MF** | **MH** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Shell Group*** | **HP** | **Elec** | **NG/CA** | **Fuels** | **Other** | **HP** | **Elec** | **NG/CA** | **Fuels** | **Other** | **All** | **All** |
| Package | | | | | | | | | | | | |
| 1 | 2% | 12% | 8% | 12% | 7% | | 10% | 4% | 5% | | | |
| 2 | 7% | 11% | 3% | 8% | 6% | | | 5% | 20% | | 7% | 5% |
| 3 | 15% | 13% | 26% | 32% | 8% | 25% | 15% | 24% | 40% | 14% | 41% | 28% |
| 4 | 1% | 11% | 6% | 8% | 8% | 7% | 10% | 5% | 0% | | 44% | 68% |
| 5 | 52% | 39% | 42% | 37% | 40% | 29% | 60% | 37% | 22% | 38% | 9% | |
| 6 | 18% | 14% | 9% | 3% | 25% | 16% | 6% | 10% | 0% | 5% | | |
| 7 | 6% | | 7% | | 5% | 18% | | 15% | 13% | 42% | | |
| 8 | | | | | | 6% | | 1% | | | | |
| 9 | | | | | | | | | | | | |
| 10 | | | | | | | | | | | | |
| 11 | | | | | | | | | | | | |
| 12 | | | | | | | | | | | | |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| 1990 Stock (thousands) | 2,533 | 3,435 | 4,759 | 8,660 | 3,256 | 1,131 | 1,163 | 3,136 | 1,586 | 603 | 10,510 | 2,366 |

(1) MF = Multifamily, MH = Manufactured Home.
(2) HP = Heat Pump, Elec = Electric Heat, NG/CA = Natural Gas Furnace/Central Air, Fuels = Oil and Gas, Other = LPG and Misc.
(3) Sources: 1990 RECS (EIA 1993), Ritschard et al. (1992), Ritschard and Huang (1989).

We estimated only one distribution for multifamily homes and one for manufactured homes, since these house types have less variation in thermal integrity and make up a less significant fraction of the housing stock. This breakout captures the effect of differences in the vintage of homes and equipment between the groups, and similarities in the economic characteristics of heating/cooling within each group. The "Heat Pump" shell group represents only those homes whose main heating systems are heat pumps. The "Electric" shell group includes homes heated by built-in (baseboard-type) electric units or by central electric furnaces. The "Gas Furnace/Central Air" shell group includes only those homes with central gas warm-air furnaces and central air conditioning. The "Fuels" shell group includes homes heated by gas and oil technologies other than centrally air-conditioned homes with natural gas furnaces. The "Other" shell group includes homes heated with LPG or with miscellaneous fuels such as wood, coal or kerosene. In this segmentation, homes with LPG heating are included in the Other shell group because we wanted to separate natural gas and LPG-heated homes to account for piped-gas availability, and LPG homes tend to be rural and therefore more similar to the homes with Other fuels (kerosene, wood, etc.). The breakout of the Heat Pump and Gas Furnace/CAC shell groups is significant because these two options predominate in current construction, together accounting for over half of all HVAC systems in 1990 (US Bureau of the Census 1991).

**Table 3.5-N: North Region Thermal Shell Shares for New Homes (% of Shell Group) (Screen HV-4e)**

| ***House Type*** | **Small Single-Family** | | | | | **Large Single-Family** | | | | | **MF** | **MH** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Shell Group*** | **HP** | **Elec** | **NG/CA** | **Fuels** | **Other** | **HP** | **Elec** | **NG/CA** | **Fuels** | **Other** | **All** | **All** |
| Package | | | | | | | | | | | | |
| 1 | | | | | | | | | | | | |
| 2 | | | | | | | | | | | | |
| 3 | 5.1% | 9.8% | | 1.5% | 1.7% | | | 2.6% | 5.5% | | 19.6% | 11.4% |
| 4 | 0.0% | 0.0% | 5.2% | 0.0% | 0.0% | 15.5% | | 0.0% | 0.0% | | 5.3% | 2.3% |
| 5 | 0.0% | 3.7% | 0.0% | 15.9% | 0.0% | 0.0% | | 0.0% | 0.0% | | 7.0% | 17.6% |
| 6 | 79.9% | 53.5% | 62.8% | 44.8% | 66.6% | 75.3% | 100.0% | 49.0% | 67.6% | 15.5% | 68.1% | 62.9% |
| 7 | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | | 0.0% | 0.0% | 0.0% | | 0.0% |
| 8 | 15.1% | 33.0% | 32.1% | 37.8% | 31.7% | 9.1% | | 48.4% | 26.9% | 84.5% | | 5.7% |
| 9 | | | | | | | | | | | | |
| 10 | | | | | | | | | | | | |
| 11 | | | | | | | | | | | | |
| 12 | | | | | | | | | | | | |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

**Table 3.5-S: South Region Thermal Shell Shares for New Homes (% of Shell Group) (Screen HV-4e)**

| ***House Type*** | **Small Single-Family** | | | | | **Large Single-Family** | | | | | **MF** | **MH** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Shell Group*** | **HP** | **Elec** | **NG/CA** | **Fuels** | **Other** | **HP** | **Elec** | **NG/CA** | **Fuels** | **Other** | **All** | **All** |
| Package | | | | | | | | | | | | |
| 1 | | | | | | | | | | | | |
| 2 | | | | | | | | | | | | |
| 3 | 25.7% | 59.0% | 22.3% | 34.6% | 21.4% | 15.5% | 74.0% | 18.4% | | 11.2% | 82.6% | 44.7% |
| 4 | 2.7% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | | 0.0% | 0.0% | 44.0% |
| 5 | 54.6% | 22.1% | 23.4% | 17.2% | 4.3% | 66.1% | 0.0% | 14.2% | | 28.2% | 9.6% | 11.3% |
| 6 | 17.0% | 18.8% | 54.3% | 48.2% | 74.3% | 18.4% | 26.0% | 67.4% | 100.0% | 60.6% | 7.8% | |
| 7 | | | | | | | | | | | | |
| 8 | | | | | | | | | | | | |
| 9 | | | | | | | | | | | | |
| 10 | | | | | | | | | | | | |
| 11 | | | | | | | | | | | | |
| 12 | | | | | | | | | | | | |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 101% | 100% | 100% | 100% | 100% | 100% |

(1) MF = Multifamily, MH = Manufactured Home.
(2) HP = Heat Pump, Elec = Electric Heat, NG/CA = Natural Gas Furnace/Central Air, Fuels = Oil and Gas, Other = LPG and Misc.
(3) Sources: 1990 RECS (EIA 1993), Ritschard et al. (1992), Ritschard and Huang (1989).
(4) New homes are 1980-90 vintage in RECS.

The shell group market shares in Tables 3.5-N&S are bimodal or discontinuous for certain shell groups, which may be due to several factors. First, the thermal integrity of new residential construction may in reality exhibit a bimodal distribution because the market is segmented into low-end "builder" homes and high-quality "custom" homes. Second, due to the discrete nature of the REEPS shell packages and the RECS thermal shell variables, it is possible to have significant changes in shell package assignment with only a small change in the RECS value. This is exacerbated by the fact that the RECS variables for insulation and window characteristics do not allow one to precisely determine the insulation value of these shell components (i.e., the discrete variables have few possible values). Finally, in some cases, such as large single-family fuel-heated homes in the South, the RECS 1980-1990 vintage sample size is very small, leading to discontinuous distributions (or all sample points in one shell package). The problem of small sample sizes should not affect the aggregate forecast results, however, because these house types represent a very small part of the new building stock.

### 3.4. New Home Thermal Shell Prices

The purchase prices of thermal shell components are required in the REEPS model to quantify the economic choices consumers face when selecting the thermal integrity level for a new home. We estimated these prices from a regional database of conservation measure prices for new single-family buildings (Koomey et al. 1991b) and data on window prices for emerging technologies (Koomey et al. 1994b). The REEPS model requires these prices to be specified per square foot of floor area, thus we have normalized all prices using building dimensions for new two-story and one-story homes, with the resulting estimates shown in Table 3.6. The prices also account for regional price differences, as reported in Koomey et al. (1991b).

We do not present prices for existing home thermal shell retrofits because REEPS allows only one set of thermal shell prices. When the thermal shell retrofit module is activated in REEPS, the model uses new home component prices to model the price of shell retrofits. REEPS also constrains thermal shell prices to be constant for all housing types. In new construction, we believe that this is a reasonably accurate portrayal of the market. For shell retrofits, however, prices can vary substantially between housing types, leading to potentially inaccurate modeling of thermal shell retrofit decisions. It is not possible to overcome these limitations without changing the REEPS computer code.

## 4. EQUIPMENT DATA AND MARKET SHARES

The REEPS HVAC model permits the user to define and configure equipment and distribution systems for the space conditioning end-uses. The equipment modeling structure is quite general and can apply to any type of heating and/or cooling equipment, such as heat pumps or natural gas furnaces. The user may define as many equipment technologies as appropriate by specifying each equipment type's technical characteristics such as the fuel used, equipment lifetime, size or capacity, and average efficiency. For this analysis, we modeled ten heating and three cooling technologies. The heating technologies are: natural gas furnaces, oil furnaces, LPG furnaces, electric furnaces, oil boilers, natural gas boilers, electric heat pumps, gas room, electric room and other. The "Other" category for equipment corresponds to the "Other" category for fuels, which include miscellaneous fuels such as wood, coal and kerosene. The cooling technologies are: heat pumps, unitary central air, and room air conditioners. We further differentiate the cooling equipment into primary -- unitary central air and heat pumps -- and secondary -- room air conditioners. This distinction is important because it simplifies the cooling equipment choice model (homeowners choose only among primary equipment options), and room air conditioners are often present in homes with central cooling and thus properly should be considered a "secondary" cooling system. Distribution systems include hydronic, forced-air and "none" in our model. The combination of a heating technology, cooling technology and distribution system define a discrete HVAC system in REEPS, so that these systems are tracked independently throughout the course of the model. Instead of treating the three space conditioning end-uses separately (heating, ventilation, and air conditioning), this characterization captures some of the physical and economic relationships among them.

| **Table 3.6: New Home Shell Component Prices ($1990/sq. ft. of floor area) (Screen HV-5d.1)** | | | | | |
|---|---|---|---|---|---|
| **Component Descriptions** | **Component Level** | **North (Chicago)** | | **South (Charleston)** | |
| | | **1-story** | **2-story** | **1-story** | **2-story** |
| **Ceiling** | R-0 | 0.00 | 0.00 | 0.00 | 0.00 |
| *ceiling insulation* | R-7 | 0.22 | 0.11 | 0.20 | 0.10 |
| *R-value* | R-11 | 0.35 | 0.17 | 0.31 | 0.15 |
| | R-19 | 0.49 | 0.24 | 0.46 | 0.23 |
| | R-22 | 0.54 | 0.27 | 0.51 | 0.25 |
| | R-30 | 0.67 | 0.33 | 0.64 | 0.32 |
| | R-38 | 0.83 | 0.41 | 0.84 | 0.42 |
| | R-49 | 1.04 | 0.52 | 1.02 | 0.51 |
| | R-60 | 1.22 | 0.61 | 1.21 | 0.61 |
| **Wall** | R-0 | 0.00 | 0.00 | 0.00 | 0.00 |
| *wall insulation* | R-7 | 0.18 | 0.21 | 0.17 | 0.20 |
| *R-value* | R-11 | 0.29 | 0.33 | 0.27 | 0.31 |
| | R-13 | 0.33 | 0.38 | 0.32 | 0.37 |
| | R-19 | 0.48 | 0.55 | 0.46 | 0.53 |
| | R-27 | 1.03 | 1.18 | 1.03 | 1.18 |
| | R-34 | 1.22 | 1.40 | 1.22 | 1.40 |
| **Slab Edge Insul.** | R-0 | n/a | n/a | 0.00 | 0.00 |
| *perimeter R-value* | R-5 2ft | n/a | n/a | 0.29 | 0.15 |
| *and depth* | R-5 4ft | n/a | n/a | 0.37 | 0.19 |
| | R-10 2ft | n/a | n/a | 0.57 | 0.30 |
| | R-10 4ft | n/a | n/a | 0.74 | 0.38 |
| **Floor Insulation** | R-0 | 0.00 | 0.00 | 0.00 | 0.00 |
| | R-11 flr | 0.42 | 0.21 | 0.39 | 0.19 |
| *underfloor R-value* | R-19 flr | 0.65 | 0.32 | 0.60 | 0.30 |
| | R-30 flr | 0.80 | 0.40 | 0.73 | 0.36 |
| | R-38 flr | 0.90 | 0.45 | 0.82 | 0.41 |
| | 0.8 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Infiltration** | 0.7 | 0.00 | 0.00 | 0.00 | 0.00 |
| ACH | 0.55 | 0.19 | 0.13 | 0.18 | 0.13 |
| | 0.4 | 0.38 | 0.26 | 0.36 | 0.25 |
| **Windows** | 1.0-gla | 0.00 | | 0.00 | |
| *no. of panes/design* | 2.0-gla | 0.39 | | 0.34 | |
| | 2-gla loE | 0.64 | | 0.56 | |
| | 2-gla loEAr | 0.71 | | 0.62 | |
| | Spectrally Sel. | 0.53 | | 0.46 | |
| | Superwindow | 2.29 | | 2.00 | |
| | Heat Mirror | 1.07 | | 0.93 | |

(1) Sources: Koomey et al. (1991b), Koomey et al. (1994b). Costs are for single-family homes.
(2) Costs normalized using average floor area for new homes: 1500 sq. ft. for 1-story, and 2200 sq. ft. for 2-story.
(3) REEPS model uses 2-story costs in north and 1-story costs in south.

For each technology the REEPS model requires five types of data, discussed in Sections 4.1-4.4. The data include: vintage blocks for the existing equipment stock, equipment lifetimes, average capacity or size for each housing type, average efficiency of new equipment, and the unit energy consumption (UEC) by housing type. The lifetimes and vintage blocks are used to track purchases and retirements of equipment throughout the course of the forecast period. The capacity of equipment is used to determine its purchase price in future years and to calculate average usage or utilization over the course of a heating or cooling season. The UEC provides a calibration value for the energy consumed by each technology in a given housing type. The average efficiency of new equipment provides a calibration value for the efficiency choice of new and replacement equipment. The user also defines HVAC systems and inputs market shares for these systems in new and existing homes, which we discuss in Section 4.5. Although room air conditioners are not a primary equipment type in our model formulation and thus do not require the same extensive input data as the other primary options, we report the above data for room air conditioners as well, for the sake of completeness.

## 4.1. Vintage Blocks

The vintage of equipment refers simply to the year or group of years in which it was purchased. REEPS allows the user to configure vintage blocks for each type of heating and cooling equipment. The vintage block data developed for this study are shown in Tables 4.1-N&S.

**Table 4.1-N: North Region HVAC Equipment Vintage Blocks**
(% of heating or cooling equipment type of given age in 1990)

| End-Use | Technology | <2YR | 2-4YR | 5-9YR | 10-19YR | >20YR | Total |
|---|---|---|---|---|---|---|---|
| **Heating** (Screen HV-3b.3) | | | | | | | |
| | Electric Furnace | 1% | 10% | 18% | 65% | 6% | 100% |
| | Gas Furnace | 9% | 17% | 18% | 29% | 27% | 100% |
| | Oil Furnace | 10% | 18% | 16% | 23% | 34% | 100% |
| | LPG Furnace | 21% | 22% | 18% | 24% | 16% | 100% |
| | Electric Heat Pump | 9% | 31% | 26% | 32% | 3% | 100% |
| | Gas Hydronics | 11% | 9% | 13% | 27% | 41% | 100% |
| | Oil Hydronics | 9% | 13% | 15% | 21% | 42% | 100% |
| | Electric Room | 7% | 5% | 18% | 39% | 30% | 100% |
| | Gas Room | 9% | 7% | 12% | 36% | 36% | 100% |
| | Other Equipment | 7% | 22% | 32% | 28% | 11% | 100% |
| **Cooling** (Screen HV-3e.3) | | | | | | | |
| | Central Air | 13% | 23% | 19% | 35% | 10% | 100% |
| | Electric Heat Pump | 9% | 21% | 37% | 33% | 0% | 100% |
| | Room Air | 13% | 25% | 28% | 27% | 7% | 100% |

**Table 4.1-S: South Region HVAC Equipment Vintage Blocks**
(% of heating or cooling equipment type of given age in 1990)

| *End-Use* | *Technology* | <2YR | 2-4YR | 5-9YR | 10-19YR | >20YR | Total |
|---|---|---|---|---|---|---|---|
| **Heating** (Screen HV-3b.3) | | | | | | | |
| | Electric Furnace | 5% | 10% | 26% | 48% | 10% | 100% |
| | Gas Furnace | 7% | 11% | 23% | 35% | 24% | 100% |
| | Oil Furnace | 5% | 15% | 19% | 24% | 38% | 100% |
| | LPG Furnace | 18% | 16% | 28% | 30% | 9% | 100% |
| | Electric Heat Pump | 13% | 21% | 42% | 20% | 4% | 100% |
| | Gas Hydronics | 10% | 17% | 9% | 23% | 42% | 100% |
| | Oil Hydronics | 0% | 0% | 0% | 31% | 69% | 100% |
| | Electric Room | 10% | 21% | 20% | 24% | 26% | 100% |
| | Gas Room | 5% | 8% | 16% | 23% | 48% | 100% |
| | Other Equipment | 10% | 30% | 27% | 26% | 8% | 100% |
| **Cooling** (Screen HV-3e.3) | | | | | | | |
| | Central Air | 12% | 16% | 29% | 33% | 10% | 100% |
| | Electric Heat Pump | 10% | 27% | 40% | 20% | 3% | 100% |
| | Room Air | 11% | 21% | 34% | 27% | 7% | 100% |

(1) Source: 1990 RECS (EIA 1993).
(2) Heat Pump vintage shares exclude heating-only heat pumps.

For each vintage block, the user must estimate the average efficiency of currently installed equipment and the share of the total stock it represents. The vintage blocks are used to account for changes in the stock efficiency due to retirements and replacements of equipment. Vintage blocks can also be used as a means of correlating equipment vintages with the vintages of the buildings themselves, which are also retired, although at a much slower rate. We used data from the 1990 RECS to develop five vintage blocks for each equipment type in each region. We estimated the efficiency for a given equipment type and vintage block by using the Shipment-Weighted Energy Factors (SWEFs) for the years 1970-1990, as provided by several trade groups which track this data for their members (AHAM 1991, ARI 1991, GAMA 1992). For early years such as 1970-72 in which the data were sometimes not available, we substituted the SWEF from the nearest available year.

The regional specification of vintage blocks (as opposed to using the same vintage blocks for both regions) can have an important effect on the model results in cases where existing equipment is substantially different than new equipment. There are several reasons for these differences. First, new construction has historically been concentrated in one region or another during a particular period. In our regional breakdown, housing construction has been concentrated in the south in the past decade, so that a greater percentage of equipment in the south is newer and hence more efficient. Second, some types of equipment are much more popular in one region than another, such as oil furnaces in the north, and the vintage blocks reflect this equipment's particular regional vintages rather than the national average vintages. Finally, some types of equipment have had slower rates of adoption in one region than another so that the vintage profiles are quite different. This is the case with heat pumps, which have been adopted much more slowly in the north compared to the south and thus on average are newer in the north. Appendix B contains the full specification of vintage blocks for each equipment type.

### 4.2. HVAC Equipment Lifetimes

The lifetime of equipment determines both when replacement equipment will be needed in the course of the forecast and also the life-cycle cost of equipment given a finite equipment lifetime. We used field estimates of equipment lifetime parameters (Lewis and Clarke 1990), as shown in Table 4.2.

**Table 4.2: HVAC Equipment Lifetime Estimates**

| | | Equipment Lifetimes (Years) | | |
|---|---|---|---|---|
| **End-Use** | **Technology** | **Minimum** | **Average** | **Maximum** |
| **Heating** (Screen HV-2b.2) | Electric Furnace | 20 | 22.5 | 25 |
| | Gas Furnace | 15 | 17.5 | 20 |
| | Oil Furnace | 15 | 17.5 | 20 |
| | Electric Heat Pump | 10 | 12.5 | 15 |
| | Gas Hydronics (boiler) | 20 | 25 | 30 |
| | Oil Hydronics (boiler) | 20 | 25 | 30 |
| | Electric Room | 15 | 17.5 | 20 |
| | Gas Room | 15 | 17.5 | 20 |
| | Other Equipment | 10 | 12.5 | 15 |
| **Cooling** (Screen HV-2c.2) | Central Air | 11 | 13.5 | 16 |
| | Electric Heat Pump | 10 | 12.5 | 15 |
| | Room Air | 10 | 12.5 | 15 |

(1) Source: Lewis and Clarke (1990).

Decay of equipment occurs when it reaches the end of its useful lifetime. It is modeled by a decay function that removes some portion of the stock of equipment each year and replaces it with new equipment. In the REEPS HVAC module, the user specifies maximum and minimum equipment lifetimes, and the equipment stock decays linearly between those two points. For example, consider a certain technology having a minimum lifetime of 5 years and a maximum lifetime of 15 years. For a stock of equipment purchased in a given year, say 1986, 100% will survive until the minimum lifetime is reached in 1991. Each year between 1991 and the maximum lifetime in 2001, 10% of the stock will decay and need to be replaced. After 2001, none of the stock purchased in 1986 will remain.

### 4.3. HVAC Equipment Capacity and Efficiency Data

The output capacity of space conditioning equipment refers to its capability to deliver heating or cooling energy under normal operating conditions. Energy input ($Q_{in}$) and energy output ($Q_{out}$) for heating and cooling equipment are often measured in thousand Btu per hour (kBtuh). The rated efficiency of space conditioning equipment incorporates its tested performance over an average heating or cooling season under specified conditions, thereby accounting for cycling and other performance features of the equipment not captured by the steady-state efficiency. Efficiency is generally measured with Annual Fuel Utilization Efficiency (AFUE) for fuels and Seasonal Energy Efficiency Ratios (SEER) for heat pumps and central air conditioning. The one exception to this convention is room air conditioners, whose efficiency is measured by the steady-state Energy Efficiency Ratio (EER), because these equipment tend to operate at full load nearly the whole time they are operated. We obtained data on the capacity and efficiency of manufacturers' shipments of heating and cooling equipment from reports and equipment catalogs produced by the relevant trade organizations (AHAM 1991, ARI 1991, GAMA 1992, Hydronics Institute 1992). The efficiency definitions and units are shown in Table 4.3 along with the average capacity and efficiency. Efficiency of electric heating equipment is assumed to be 100%. The efficiency levels cited do not include duct losses. The data are for the most recent year available.

**Table 4.3: New HVAC Equipment Characteristics**

| End-Use | Technology | Efficiency Units | 1992 Federal Standard | 1990 SWEF | 1990 Avg. Size (kBtuh) |
|---|---|---|---|---|---|
| **Heating** | | | (Screen:) | (HV-4c) | (HV-3b.1) |
| | Electric Furnace | None | | | not applicable |
| | Gas Furnace | AFUE | 78.0 | 75.8 | 90.1 |
| | Oil Furnace | AFUE | 78.0 | 80.3 | 101.3 |
| | Electric Heat Pump | HSPF | 6.8 | 7.03 | 34.2 |
| | Gas Hydronics (boiler) | AFUE | 80.0 | 79.6 | 104.2 |
| | Oil Hydronics (boiler) | AFUE | 80.0 | 84.0 | 107.2 |
| | Electric Room | None | | | not applicable |
| | Gas Room | AFUE | 65.0 | 67.0 | 38.5 |
| | Other Equipment | AFUE | 78.0 | 70.0 | 80.0 |
| **Cooling** | | | (Screen:) | (HV-4d) | (HV-3e.1) |
| | Central Air | SEER | 10.0 | 9.24 | 34.6 |
| | Electric Heat Pump | SEER | 10.0 | 9.41 | 34.2 |
| | Room Air | EER | 9.0 | 8.73 | 10.8 |

(1) Sources: AHAM (1991), ARI (1991), GAMA (1992), Hydronics Institute (1992).
(2) Data for gas and oil equipment are from 1991 shipments.
(3) SWEF = Shipment Weighted Energy Factor; kBtuh = Thousand Btu per hour.
(4) AFUE=Annual Fuel Utilization Efficiency; EER=Energy Efficiency Ratio; HSPF=Heating Seasonal Performance Factor; SEER=Seasonal Energy Efficiency Ratio.
(5) Heating equipment size is input capacity (Qin), cooling equipment (including heat pump) is output (Qout).

REEPS also requires data on the average capacity of HVAC equipment in the base year, disaggregated by house type. We developed these data using the same manufacturer shipment data described above, and then allocated the shipments to particular house types using the thermal loads from Section 3 and the equipment sizing factors that are shown in Section 5.1. The average capacities are shown in Tables 4.4-N and 4.4-S.

**Table 4.4-N: North Region 1990 HVAC Equipment Average Capacity (kBtu/hour)**

| End-Use | Technology | SSF | LSF | MF | MH |
|---|---|---|---|---|---|
| Heating (Screen HV-3b.1) | | | | | |
| | Electric Furnace | 40 | 80 | 21 | 60 |
| | Gas Furnace | 60 | 100 | 50 | 80 |
| | LPG Furnace | 60 | 100 | 50 | 80 |
| | Oil Furnace | 35 | 120 | 60 | 90 |
| | Electric Heat Pump | 24 | 48 | 18 | 24 |
| | Gas Hydronics | 80 | 120 | 50 | 100 |
| | Oil Hydronics | 100 | 150 | 50 | 100 |
| | Electric Room | 35 | 50 | 25 | 35 |
| | Gas Room | 40 | 60 | 35 | 40 |
| | Other Equipment | 30 | 45 | 25 | 30 |
| Cooling (Screen HV-3e.1) | | | | | |
| | Central Air | 36 | 24 | 22 | 26 |
| | Electric Heat Pump | 36 | 24 | 22 | 26 |
| | Room Air | 13 | 11 | 10 | 10 |

**Table 4.4-S: South Region 1990 HVAC Equipment Average Capacity (kBtu/hour)**

| End-Use | Technology | SSF | LSF | MF | MH |
|---|---|---|---|---|---|
| Heating (Screen HV-3b.1) | | | | | |
| | Electric Furnace | 30 | 50 | 20 | 30 |
| | Gas Furnace | 50 | 80 | 30 | 60 |
| | LPG Furnace | 50 | 80 | 30 | 60 |
| | Oil Furnace | 60 | 90 | 40 | 70 |
| | Electric Heat Pump | 18 | 48 | 18 | 24 |
| | Gas Hydronics | 70 | 100 | 40 | 80 |
| | Oil Hydronics | 80 | 120 | 40 | 80 |
| | Electric Room | 15 | 30 | 15 | 20 |
| | Gas Room | 20 | 40 | 20 | 20 |
| | Other Equipment | 20 | 35 | 15 | 20 |
| Cooling (Screen HV-3e.1) | | | | | |
| | Central Air | 24 | 48 | 18 | 24 |
| | Electric Heat Pump | 24 | 48 | 18 | 24 |
| | Room Air | 10 | 14 | 8 | 10 |

(1) Capacity values are based on manufacturer shipment data, disaggregated by house type using the loads from Section 3 and sizing parameters from Section 5.1.

We also obtained data on the distribution of size and efficiency within manufacturers' annual shipment totals, for either 1990 or 1991, which are documented in Appendix C. We had no data for either central electric furnaces or electric room heaters. As the three-dimensional graphs in Appendix C illustrate, the efficiency distribution of shipments is generally not uniform for all equipment sizes (i.e., some sizes of equipment have efficiency distributions that are skewed toward high or low efficiency models). There are many reasons for these differences, such as physical design constraints, differences in the cost-effectiveness of marginal improvements in efficiency, market niches occupied by different sizes of equipment, and the types of buildings in which particular equipment sizes are generally installed. Although we empirically observe that equipment efficiency varies with capacity, the REEPS model assumes for the sake of simplicity that efficiency is independent of capacity. Nevertheless, the simplified efficiency distributions are important for sizing equipment and modeling efficiency choice.

## 4.4. Unit Energy Consumption Estimates

Estimates of unit energy consumption (UEC) are important drivers in the HVAC model because they determine the basic trend of energy consumption and are used to calibrate usage equations for each type of equipment. UECs are specified for each region, housing type and each type of heating and cooling equipment, as shown in Tables 4.5-N and 4.5-S.

**Table 4.5-N: North Region 1990 Stock Average Unit Energy Consumption Estimates**

| End-Use | Technology | Units | SSF | LSF | MF | MH |
|---|---|---|---|---|---|---|
| **Heating** (Screen HV-3b.5) | | | | | | |
| | Electric Furnace | kWh | 9,300 | 21,000 | 8,700 | 8,000 |
| | Gas Furnace | kBtu | 81,400 | 112,200 | 58,300 | 66,100 |
| | LPG Furnace | kBtu | 61,500 | 64,000 | 51,300 | 46,400 |
| | Oil Furnace | kBtu | 67,900 | 105,800 | 59,300 | 52,600 |
| | Electric Heat Pump | kWh | 6,900 | 14,000 | 4,000 | 6,300 |
| | Gas Hydronics | kBtu | 94,400 | 143,700 | 61,400 | 66,100 |
| | Oil Hydronics | kBtu | 94,000 | 138,100 | 54,600 | 52,600 |
| | Electric Room | kWh | 8,700 | 19,000 | 8,000 | 7,400 |
| | Gas Room | kBtu | 75,700 | 119,800 | 71,600 | 76,800 |
| | Other Equipment | kBtu | 18,000 | 17,800 | 26,300 | 36,400 |
| **Cooling** (Screen HV-3e.5) | | | | | | |
| | Central Air | kWh | 1,500 | 3,100 | 1,200 | 1,400 |
| | Electric Heat Pump | kWh | 1,700 | 3,800 | 1,200 | 1,500 |
| | Room Air | kWh | 430 | 820 | 370 | 470 |

**Table 4.5-S: South Region 1990 Stock Average Unit Energy Consumption Estimates**

| End-Use | Technology | Units | SSF | LSF | MF | MH |
|---|---|---|---|---|---|---|
| **Heating** (Screen HV-3b.5) | | | | | | |
| | Electric Furnace | kWh | 4,900 | 8,000 | 3,700 | 4,500 |
| | Gas Furnace | kBtu | 42,900 | 57,600 | 25,900 | 40,600 |
| | LPG Furnace | kBtu | 28,600 | 36,800 | 12,300 | 21,800 |
| | Oil Furnace | kBtu | 40,900 | 57,900 | 35,600 | 45,300 |
| | Electric Heat Pump | kWh | 4,100 | 6,900 | 2,100 | 1,500 |
| | Gas Hydronics | kBtu | 71,300 | 126,000 | 31,700 | 40,600 |
| | Oil Hydronics | kBtu | 69,700 | 106,200 | 57,500 | 45,300 |
| | Electric Room | kWh | 2,800 | 4,500 | 1,900 | 2,300 |
| | Gas Room | kBtu | 36,000 | 62,300 | 16,200 | 30,400 |
| | Other Equipment | kBtu | 11,800 | 9,600 | 6,000 | 26,800 |
| **Cooling** (Screen HV-3e.5) | | | | | | |
| | Central Air | kWh | 3,000 | 4,200 | 1,900 | 2,300 |
| | Electric Heat Pump | kWh | 3,200 | 4,400 | 1,900 | 2,400 |
| | Room Air | kWh | 1,400 | 2,100 | 1,000 | 1,300 |

(1) Sources: 1990 RECS (EIA 1993) for fuel heating equipment. Tables B.7 and B.8 of Hanford et al. (1994) for electric heating and cooling equipment. The UEC values reported by Hanford were translated into small and large single-family using the average heating and cooling loads for the thermal shell groups in this report.
(2) SSF = Small Single-Family, LSF = Large Single-Family, MF = Multifamily, MH = Manufactured Home.
(3) UECs for hydronic systems in manufactured homes are assumed to be the same as gas furnaces.
(4) Cooling UECs for Heat Pumps exceed CAC UEC due to greater number of heat pumps in warm climates.

The UECs for this analysis are drawn from the 1990 RECS consumption estimates[4] for fuel-fired heating equipment (EIA 1993), and a compilation of utility survey data (Hanford et al. 1994) for electric heating and cooling equipment. The measurement units for UECs are kilowatt-hours (kWh) for electric and thousands of BTUs (kBTUs) for fuels. REEPS also permits the user to separately consider the energy consumption resulting from secondary heating and cooling and electricity used by ventilation fans. As mentioned earlier, we treat room air conditioners as secondary equipment, because the REEPS model allows simpler accounting of their energy use in this way. We do not make use of the secondary heating option because it is too difficult to correlate secondary consumption with the main heating equipment.

### 4.5. HVAC Equipment Market Shares

We now define feasible HVAC systems based on combinations of the heating and cooling equipment and the distribution systems defined in the preceding sections. These cross-tabulations between heating and cooling systems account for physical and economic dependencies among the heating and cooling equipment types. The REEPS HVAC module allows the user to group the systems using any criteria such as cooling type or distribution system. We adopt a simple framework in which systems with and without central air conditioning form the basis of the system types. We considered all possible combinations of heating and cooling equipment but chose only those with 1% or more market share in either region, resulting in sixteen discrete HVAC systems. This specification of system type also allows the decision models to be estimated using a nested logit approach, in which the decision is modeled as two levels: the upper level is a choice of central cooling and the lower level is a choice of heating equipment. We will discuss the nested logit decision model in Section 6.3.

We developed market share data for the sixteen HVAC systems, differentiated by existing and new homes and by each of the four housing types, as shown in Tables 4.6-N&S and 4.7-N&S. These market share data are used in REEPS both to allocate households to the different HVAC systems and to calibrate the decision model for new homes. The market share data for existing buildings are from the 1990 RECS (EIA 1993) while market share data for new buildings were developed by cross-tabulating the RECS data for 1980s vintage homes with the census data for 1990 construction (US Bureau of the Census 1991).

In addition, REEPS requires data on the market share of secondary cooling equipment – room air conditioners – in the housing stock in order to forecast the saturation of these units. For use in REEPS, these data are disaggregated according to the presence and type of central cooling equipment. Table 4.8 shows the market share of room air conditioners for both the north and south regions.

Each combined heating and cooling HVAC system is associated with one of the five shell groups (HP, Elec, NG/CA, Fuels, Other) defined in Section 3.3. The association of HVAC equipment and shell groups allows for more accurate modeling of important interactions between the equipment characteristics and the building heating and cooling loads. The shell groups, in turn, include a distribution of thermal integrity levels by assigning market shares to the thermal shell packages, as described in Section 3.3.

[4]The 1990 RECS consumption values are based on billing data at the household level, which are then disaggregated into component end-uses by means of a conditional demand analysis model. Thus, although based on measured data, the RECS UEC values should properly be considered estimates rather than "pure" measured (sub-metered) data.

| **Table 4.6-N: North Region Existing Homes HVAC System Shares in 1990 (Screen HV-3a.1)<br>(% of house-type with given HVAC system)** | | | | | |
|---|---|---|---|---|---|
| **System No.** | **Cooling/Heating Combination** | **Housing type** | | | |
| | | **SSF** | **LSF** | **MF** | **MH** |
| 1 | Central Air/Electric Furnace | 1.2% | 1.8% | 7.0% | 6.3% |
| 2 | Central Air/Gas Furnace | 19.2% | 27.0% | 8.6% | 18.3% |
| 3 | Central Air/LPG Furnace | 1.2% | 1.5% | 0.0% | 2.6% |
| 4 | Central Air/Oil Furnace | 1.2% | 2.2% | 0.2% | 1.2% |
| 5 | Central Air/Gas Hydronics | 0.6% | 1.4% | 0.7% | 0.0% |
| 6 | Central Air/Oil Hydronics | 0.9% | 4.3% | 0.3% | 0.0% |
| 7 | Central Air/Other | 0.6% | 0.7% | 0.0% | 0.0% |
| 8 | Electric Heat Pump | 2.3% | 2.2% | 1.7% | 0.8% |
| 9 | No Central Air/Gas Furnace | 27.2% | 20.3% | 14.1% | 22.5% |
| 10 | No Central Air/LPG Furnace | 3.4% | 1.9% | 0.3% | 12.8% |
| 11 | No Central Air/Oil Furnace | 8.5% | 5.2% | 2.1% | 6.1% |
| 12 | No Central Air/Gas Hydronics | 7.0% | 11.0% | 31.4% | 0.0% |
| 13 | No Central Air/Oil Hydronics | 5.9% | 11.1% | 16.1% | 0.0% |
| 14 | No Central Air/Electric Room | 9.2% | 4.9% | 13.0% | 12.9% |
| 15 | No Central Air/Gas Room | 3.0% | 0.4% | 3.4% | 0.4% |
| 16 | No Central Air/Other | 8.6% | 4.1% | 1.1% | 16.1% |
| | Totals | 100.0% | 100.0% | 100.0% | 100.0% |

| **Table 4.6-S: South Region Existing Homes HVAC System Shares in 1990 (Screen HV-3a.1)<br>(% of house-type with given HVAC system)** | | | | | |
|---|---|---|---|---|---|
| **System No.** | **Cooling/Heating Combination** | **Housing type** | | | |
| | | **SSF** | **LSF** | **MF** | **MH** |
| 1 | Central Air/Electric Furnace | 9.1% | 13.3% | 26.1% | 7.4% |
| 2 | Central Air/Gas Furnace | 21.0% | 41.2% | 19.2% | 6.8% |
| 3 | Central Air/LPG Furnace | 0.8% | 1.7% | 0.2% | 12.5% |
| 4 | Central Air/Oil Furnace | 1.6% | 1.2% | 0.0% | 0.0% |
| 5 | Central Air/Gas Hydronics | 0.0% | 0.8% | 0.5% | 0.0% |
| 6 | Central Air/Oil Hydronics | 0.0% | 0.0% | 0.0% | 0.0% |
| 7 | Central Air/Other | 1.0% | 2.0% | 0.0% | 0.9% |
| 8 | Electric Heat Pump | 11.2% | 14.8% | 11.0% | 3.1% |
| 9 | No Central Air/Gas Furnace | 12.9% | 11.2% | 5.1% | 23.7% |
| 10 | No Central Air/LPG Furnace | 5.4% | 2.3% | 0.0% | 18.2% |
| 11 | No Central Air/Oil Furnace | 2.2% | 1.0% | 0.2% | 3.2% |
| 12 | No Central Air/Gas Hydronics | 0.8% | 0.6% | 3.5% | 0.0% |
| 13 | No Central Air/Oil Hydronics | 0.2% | 1.5% | 0.7% | 0.0% |
| 14 | No Central Air/Electric Room | 6.0% | 2.0% | 12.2% | 13.4% |
| 15 | No Central Air/Gas Room | 20.6% | 4.6% | 18.9% | 3.3% |
| 16 | No Central Air/Other | 7.2% | 1.8% | 2.4% | 7.5% |
| | Totals | 100.0% | 100.0% | 100.0% | 100.0% |
| Source: 1990 RECS (EIA 1993). | | | | | |

| **Table 4.7-N: North Region New Homes HVAC System Shares (Screen HV-4a)<br>(% of house-type with given HVAC system)** | | | | | |
|---|---|---|---|---|---|
| **System No.** | **Cooling/Heating Combination** | **Housing type** | | | |
| | | **SSF** | **LSF** | **MF** | **MH** |
| 1 | Central Air/Electric Furnace | 10.0% | 0.0% | 16.5% | 8.2% |
| 2 | Central Air/Gas Furnace | 26.6% | 68.9% | 41.3% | 28.7% |
| 3 | Central Air/LPG Furnace | 0.6% | 0.6% | 0.0% | 4.9% |
| 4 | Central Air/Oil Furnace | 0.0% | 0.0% | 0.0% | 0.0% |
| 5 | Central Air/Gas Hydronics | 0.0% | 1.1% | 0.0% | 0.0% |
| 6 | Central Air/Oil Hydronics | 0.0% | 1.2% | 0.0% | 0.0% |
| 7 | Central Air/Other | 0.3% | 0.4% | 0.0% | 0.0% |
| 8 | Electric Heat Pump | 19.0% | 8.3% | 13.0% | 0.0% |
| 9 | No Central Air/Gas Furnace | 18.8% | 3.8% | 2.6% | 23.1% |
| 10 | No Central Air/LPG Furnace | 0.5% | 1.0% | 1.7% | 14.0% |
| 11 | No Central Air/Oil Furnace | 3.2% | 1.2% | 0.0% | 4.0% |
| 12 | No Central Air/Gas Hydronics | 1.1% | 3.4% | 16.5% | 0.0% |
| 13 | No Central Air/Oil Hydronics | 8.4% | 8.4% | 2.4% | 0.0% |
| 14 | No Central Air/Electric Room | 6.1% | 1.1% | 6.1% | 1.0% |
| 15 | No Central Air/Gas Room | 0.0% | 0.0% | 0.0% | 0.0% |
| 16 | No Central Air/Other | 5.5% | 0.5% | 0.0% | 16.1% |
| | Totals: | 100% | 100% | 100% | 100% |

| **Table 4.7-S: South Region New Homes HVAC System Shares (Screen HV-4a)<br>(% of house-type with given HVAC system)** | | | | | |
|---|---|---|---|---|---|
| **System No.** | **Cooling/Heating Combination** | **Housing type** | | | |
| | | **SSF** | **LSF** | **MF** | **MH** |
| 1 | Central Air/Electric Furnace | 11.8% | 5.8% | 21.6% | 15.0% |
| 2 | Central Air/Gas Furnace | 30.8% | 59.4% | 18.5% | 5.4% |
| 3 | Central Air/LPG Furnace | 0.4% | 1.1% | 1.0% | 24.5% |
| 4 | Central Air/Oil Furnace | 0.0% | 0.0% | 0.0% | 0.0% |
| 5 | Central Air/Gas Hydronics | 0.0% | 0.0% | 0.0% | 0.0% |
| 6 | Central Air/Oil Hydronics | 0.0% | 0.0% | 0.0% | 0.0% |
| 7 | Central Air/Other | 1.4% | 1.1% | 0.0% | 2.3% |
| 8 | Electric Heat Pump | 38.5% | 25.5% | 35.6% | 6.5% |
| 9 | No Central Air/Gas Furnace | 7.4% | 4.2% | 10.6% | 23.2% |
| 10 | No Central Air/LPG Furnace | 1.3% | 0.0% | 0.0% | 17.0% |
| 11 | No Central Air/Oil Furnace | 0.0% | 0.0% | 0.0% | 3.9% |
| 12 | No Central Air/Gas Hydronics | 0.0% | 0.5% | 0.0% | 0.0% |
| 13 | No Central Air/Oil Hydronics | 0.0% | 0.0% | 0.0% | 0.0% |
| 14 | No Central Air/Electric Room | 4.7% | 1.5% | 8.5% | 1.0% |
| 15 | No Central Air/Gas Room | 0.9% | 0.0% | 3.6% | 1.0% |
| 16 | No Central Air/Other | 3.0% | 0.8% | 0.6% | 0.0% |
| | Totals: | 100% | 100% | 100% | 100% |

Source: 1990 RECS homes built 1980 to 1990 (EIA 1993); 1990 C-25 report (US Bureau of the Census 1991).
(1) SF and MF shares are based on C-25 data. RECS used for weighting of SSF and LSF, and MF equipment types.
(2) MH electric and gas room heating shares have been limited to ≤1% based on conversations with MH manufacturers (Boghosian 1994). The RECS shares (in excess of 1%) for these heating types have been allocated to other non-CAC heating systems.

| Table 4.8: Room Air Conditioner Market Shares in 1990 Stock Homes (Screen HV-3c.4) (% of central cooling-type with RAC) | | | | | |
|---|---|---|---|---|---|
| **Region** | **Central Cooling System** | **Housing type** | | | |
| | | **SSF** | **LSF** | **MF** | **MH** |
| North | Central Air | 4.0% | 8.4% | 4.2% | 4.1% |
| | Heat Pump | 0.0% | 13% | 0.0% | 0.0% |
| | No Central Air | 42% | 44% | 52% | 37% |
| South | Central Air | 8.7% | 10% | 0.0% | 7.4% |
| | Heat Pump | 3.8% | 3.0% | 0.0% | 0.0% |
| | No Central Air | 54% | 49% | 41% | 53% |
| Source: 1990 RECS (EIA 1993). | | | | | |

## 5. EQUIPMENT SIZE, USAGE AND PRICE MODELS

The usage and size of HVAC equipment are modeled through structural equations in REEPS. Usage for space conditioning equipment is specified in units of kWh per year for electric equipment and kBtu per year for fuels. The first section describes the development of the model to estimate equipment sizing. The second section presents the Unit Energy Consumption data for each region and the equations to forecast equipment usage. The third section presents heating and cooling equipment prices, while the fourth section presents distribution system prices.

### 5.1. Equipment Size Models

Usually, equipment is sized according to the peak load of a building rather than the annual load[5]. To investigate the relationship between the peak and annual heating and cooling loads, we used the DOE-2 building energy simulation model to develop thermal loads for a set of prototypes in each region. The prototypes differed in thermal integrity due to varying levels of insulation, infiltration, and so forth. Based on the calculated peak and annual loads of the prototypes, we developed a simple linear relationship between peak load and annual load for each region with the following form:

$$P_{irh} = b_{rh} + m_{rh} * L_{irh} \quad (5.1)$$

where $P_{irh}$ = predicted peak for prototype *i*, region *r* and housing type *h* (kBtuh),
$b_{rh}$ = estimated intercept term for peak equation,
$m_{rh}$ = estimated slope with respect to the heating or cooling load,
$L_{irh}$ = calculated annual load for prototype *i*, region *r* and housing type *h* (kBtu).

We use a linear relationship of this form for all four housing types. We used single-family prototypes in estimating the parameters for single-family homes and manufactured homes, and multifamily prototypes to estimate the relationship for multifamily homes. Table 5.1 gives the resulting linear parameters for the determination of peak load for heating and cooling in the two regions, along with the $r^2$ for the regression. The data and regression lines for the peak heating and cooling estimation are provided in Appendix D for the two regions and two housing types (mobile homes are treated the same as single-family homes for the purpose of equipment sizing).

The high $r^2$ for heating suggests that the relationship between annual and peak heating loads is quite strong, while the lower $r^2$ for cooling shows that a linear relationship does not describe all the variation in peak cooling load. Peak cooling loads are more dependent than peak heating

[5]The one exception is room air conditioners, which are usually not sized in relation to the whole-house load, but rather to provide a fixed quantity of cooling at peak periods.

loads on local extreme weather conditions, such as humidity, and on building geometry. Peak cooling loads can even be higher in a northern city such as Chicago than in a southern city such as Charleston. This means that there may be more uncertainty and variability in the sizing of cooling equipment. Thus while the heating parameters provide fairly robust estimates of peak loads for the two regions and the various prototypes, the parameters for cooling provide only rough estimates of the building peaks. The issue of sizing has important ramifications for the performance and cost of heating and cooling equipment under the design conditions of the assumed thermal shell. We will address some of these issues in Sections 6 and 7.

**Table 5.1: Regression Results for Peak Load as a Function of Annual Load**

| **Heating** | **slope (kBtuh/kBtu)** | **intercept (kBtuh)** | **rsquare** |
|---|---|---|---|
| North Single-Family | 0.423 | 7.917 | 0.99 |
| North Multi-Family | 0.356 | 6.451 | 0.96 |
| South Single-Family | 0.662 | 8.563 | 1.00 |
| South Multi-Family | 0.564 | 7.321 | 0.90 |
| **Cooling** | | | |
| North Single-Family | 2.176 | 5.481 | 0.87 |
| North Multi-Family | 1.568 | 3.251 | 0.65 |
| South Single-Family | 1.838 | -11.447 | 0.76 |
| South Multi-Family | 1.642 | -8.321 | 0.53 |

(1) Peak Load = intercept + slope*(Annual Load).
(2) The regressions are based on DOE-2 results with thermal shell packages of varying thermal integrity.
(3) kBtuh = 1000 Btu per hour.
(4) The equations describe a generalized relationship between increased building-shell thermal integrity (or annual load) and peak load, but do not necessarily describe peak design load.

Besides being sized to meet the peak load, equipment is usually oversized to account for uncertainty in equipment performance and operating conditions that will actually be encountered once installed. Thus, to develop accurate sizing estimates we need to determine the degree to which equipment is typically oversized. In the absence of detailed capacity data from heating and cooling equipment installations, we must select the appropriate equipment size for each prototype in order to determine the average relationship between the peak loads of the prototypes and the size distribution of the shipments. We define two sets of criteria in correlating shells with equipment sizes. The first is to attempt to match, where possible, the size distribution of the shipments themselves. The second criterion is to choose a set of sizing parameters such that the average size of the "sized" shells is equal to the average size in the shipment data itself. This latter criterion is actually a linear programming problem formulated as follows:

$$\text{Minimize } [S_g - \Sigma (Z_{gh} * P_{igh} * W_{igh})] \quad (5.2)$$

such that:

$$\Sigma (Z_{gh} * P_{igh} * W_{igh}) - S_g > 0$$

$$z_L < Z_i < z_H \quad \forall\, i$$

where $P_{igh}$ = the predicted peak for shell *i* and housing type *h* for technology *g*,
$W_{igh}$ = the share for shell *i* and housing type *h* for technology *g*,
$Z_{gh}$ = the sizing factor for technology *g* and housing type *h*,
$S_g$ = the shipment-weighted size for technology *g*,
$(z_L, z_H)$= bounds on the sizing criteria.

Application of this algorithm resulted in the sizing criteria shown in Tables 5.2-N and 5.2-S for the two regions. We had no data on the size of electric heating equipment, thus we chose the sizing for electric equipment based on typical practice (EPRI 1987).

**Table 5.2-N: North Region Equipment Sizing Parameters**

| Heating | SSF | LSF | MF | MH |
|---|---|---|---|---|
| Electric Furnace | 1.83 | 1.83 | 1.66 | 1.81 |
| Gas Furnace | 2.13 | 2.13 | 1.89 | 2.07 |
| Oil Furnace | 2.22 | 2.22 | 2.04 | 2.18 |
| Electric Heat Pump | 1.46 | 1.46 | 1.53 | 1.62 |
| Gas Hydronics | 2.41 | 2.41 | 2.01 | n/a |
| Oil Hydronics | 2.43 | 2.43 | 2.32 | n/a |
| Electric Room | 1.79 | 1.79 | 1.66 | 1.72 |
| Gas Room | 1.63 | 1.63 | 1.66 | 1.61 |
| Other Equipment | 2.03 | 2.03 | 1.95 | 2.01 |
| **Cooling** | | | | |
| Central Air | 1.03 | 1.03 | 0.84 | 1.07 |
| Electric Heat Pump | 1.46 | 1.46 | 1.03 | 1.42 |
| Room Air | 0.71 | 0.71 | 0.51 | 0.68 |
| No Air | | | | |

**Table 5.2-S: South Region Equipment Sizing Parameters**

| Heating | SSF | LSF | MF | MH |
|---|---|---|---|---|
| Electric Furnace | 1.66 | 1.66 | 1.51 | 1.63 |
| Gas Furnace | 1.98 | 1.98 | 1.88 | 2.04 |
| Oil Furnace | 2.06 | 2.06 | 1.91 | 2.12 |
| Electric Heat Pump | 1.51 | 1.51 | 1.36 | 1.46 |
| Gas Hydronics | 2.36 | 2.36 | 1.83 | n/a |
| Oil Hydronics | 2.45 | 2.45 | 1.71 | n/a |
| Electric Room | 1.81 | 1.81 | 1.64 | 1.58 |
| Gas Room | 1.43 | 1.43 | 1.52 | 1.34 |
| Other Equipment | 1.74 | 1.74 | 1.99 | 1.83 |
| **Cooling** | | | | |
| Central Air | 0.96 | 0.96 | 0.83 | 0.89 |
| Electric Heat Pump | 1.07 | 1.07 | 1.04 | 0.87 |
| Room Air | 0.58 | 0.58 | 0.61 | 0.72 |
| No Air | | | | |

(1) Developed from thermal shell characteristics in 1990 RECS, peak load estimation relation, and data on the size of recent shipments of the various equipment types (AHAM 1991, ARI 1991, GAMA 1992).
(2) A sizing parameter of 1.0 implies that the size of the equipment is exactly sufficient to meet the peak load, while a sizing parameter of 1.80 implies that the capacity of the equipment is 80% larger than required to exactly meet peak load.

In actual practice, sizing factors vary considerably. One sizing study in Cleveland, Ohio, showed sizing parameters ranging from 1.0 to 7.0 (Dewerth 1991). Sizing of equipment may also depend on the energy conservation behavior of household occupants, such as night thermostat setback. Some analyses have shown that a northern climate, the required equipment capacity for such scenarios may be greater than 3 times the peak load given constant thermostat setpoint (Hedrick et al. 1991). The equipment sizing model we estimate for REEPS is a combination of the peak load relationships from Table 5.1 and the equipment sizing parameters from Tables 5.2-N&S.

One must bear in mind several methodological observations about the algorithms and criteria used in sizing HVAC equipment. First, the sizing is based on our two-region modeling framework. A different number of regions would likely result in a rather different set of sizing parameters. Second, the sizing is based on the prototypes presented earlier in this report. A different set of prototypes, even with the same two regions (climates) could also result in different sizing parameters. Third, the methodology is aimed at calibrating two independent sets of data, namely the equipment size data and the thermal shell data, rather than predicting what the sizing will be for particular installations. While these distinctions limit the applicability of the sizing criteria to actual practice, the results are appropriate within the modeling framework because they maintain internal consistency among the components of the analysis -- namely the shells, housing types and technology specifications.

## 5.2. Unit Energy Consumption and Usage Models

In future years, the UECs must be updated to reflect changes in important parameters such as the building loads, fuel prices and the efficiency of new equipment. The analyst enters an equation for usage to specify these relationships. We chose the following form for this equation:

$$UEC_{ghs} = \left(\frac{k_{gh}}{\eta_s}\right) * \left(\frac{L_{ghs}}{E_g}\right) * (P_g)^{\varepsilon} \tag{5.3}$$

where
$UEC_{ghs}$ = UEC for technology $g$, housetype $h$ and HVAC system $s$,
$L_{ghs}$ = Heating or cooling load,
$P_g$ = Fuel price for technology $g$,
$\varepsilon$ = usage elasticity with respect to fuel price,
$k_{gh}$ = calibration multiplier,
$\eta_s$ = distribution system efficiency,
$E_g$ = equipment efficiency for technology $g$.

The usage equation is calibrated against the base year UECs (Tables 4.4-N&S) to yield the calibration multipliers $k_{gh}$ for each technology $g$ and housing type $h$.

## 5.3. Heating and Cooling Equipment Prices

In the REEPS model, the purchase price of heating and cooling equipment is explicitly calculated for use in the new home equipment decision model. The purchase price of heating and cooling technologies is assumed to vary over time as a function of size and efficiency, relative to the base year. If we assume that t=0 represents the base-year, then the equation has the following functional form:

$$PP_t = ( b + m * [S_t - S_0] ) * \left(\frac{C_t}{C_0}\right) * \left(\frac{E_t}{E_0}\right)^{\varepsilon} \tag{5.4}$$

where
$PP_t$ = equipment purchase price in year $t$,
$b$ = price at the base year size $S_0$ and efficiency $E_0$,
$m$ = price slope with respect to size,
$S_t$ = equipment size in year $t$,
$C_t$ = exogenous price multiplier for year $t$ ,
$E_t$ = marginal (new equipment) efficiency in year $t$,
$\varepsilon$ = elasticity of price with respect to efficiency,
$S_0$ = equipment size in base year,
$C_0$ = exogenous price multiplier in base year,
$E_0$ = marginal (new equipment) efficiency in base year.

As Equation 5.4 shows, the purchase price of equipment is assumed to vary linearly with size, and the equation reflects the parametric form of a line, anchored to the base size $S_0$. The average efficiency $E_t$ is for 1991 shipments, which is the first year of new purchases in the model. The base price $b$ gives the price of equipment at the base year size and efficiency. The slope describes the increase in price corresponding to a unit increase in size, measured in kBtuh. Price is related to efficiency via the elasticity parameter ε, which gives the percentage change in price corresponding to a percentage change in efficiency. The exogenous parameter $C_t$ is used as a price multiplier to allow the cost of a particular type of equipment to be reduced (or increased) in future years. One possible use of the parameter would be for a technology which is not yet mature, so that its price can be reduced as the technology nears full-scale production.

We used construction industry field estimates for cost data on heating and cooling equipment of different sizes (R.S. MEANS Co. 1991b, R.S. MEANS Co. 1991c) to estimate the parameters $b$ and $m$ in Equation 5.4. We used engineering-economic data for varying efficiency options (ADM 1987) in order to estimate the parameter $\varepsilon$ for each type of equipment. Since the data came from two independent sources, we combined the data to produce a single set of parameters for the functions. Since we are interested in the installed purchase price of equipment (the price to the consumer), we assumed that each installation involved a main contractor and an HVAC subcontractor. We fit a linear regression for the price-size data and a non-linear regression for the price-efficiency data based on Equation 5.4. The details of these calculations along with the data and regression lines are given in Appendix E. Table 5.3 shows the resulting parameters for all equipment types and the regression $r^2$ for the linear portion of the equation. No goodness-of-fit is provided for the non-linear regression because unlike linear regression, there would be no unique metric for this purpose.

### 5.4. Distribution System Prices

Distribution systems generally represent a substantial portion of the price of central heating and cooling systems; therefore the price of distribution systems is an important factor in the REEPS decision models. In our framework, there are two types of distribution systems, hydronic and forced-air. We developed prices for both types of systems based on engineering analysis of duct insulation prices (Andrews and Modera 1991) and construction field estimates (R.S. MEANS Co. 1991a). REEPS requires a linear relationship between distribution system price and floor area of the house $A_h$. We chose 1800 square feet as the base size for the linear equation since it is the dividing line between small and large homes (see Section 2.2). The regression parameters we estimated are shown in the following equation for distribution system price:

$$\textit{Forced-Air Systems:}\quad \text{Price} = \$2998 + 0.842 * (A_h - 1800) \tag{5.5}$$

$$\textit{Hydronic Systems:}\quad \text{Price} = \$3508 + 1.485 * (A_h - 1800) \tag{5.6}$$

Equations 5.5 and 5.6 yield the purchase price of the distribution system for a house of any floor area $A_h$. The distribution system costs are part of the total HVAC system prices and are therefore included when comparing the prices of different systems to determine future market shares, as will be discussed in Section 6.3.

**Table 5.3. Parameters for New Single-Family HVAC Equipment Price Functions**

| End-use | Technology | | Fuel | | Base Price ($1990) | Base Capacity (Output) (kBtu/hr) | Base Efficiency | Efficiency Units | Price Slope ($/kBtuh) | Efficiency Elasticity |
|---|---|---|---|---|---|---|---|---|---|---|
| Heating | Furnace | FRN | Electric | E | 1165 | 65 | 100 | AFUE | 7.6 | n/a |
| Heating | Furnace | FRN | Gas | G | 1280 | 80 | 77.2 | AFUE | 7.9 | 1.44 |
| Heating | Furnace | FRN | Oil | O | 1837 | 100 | 80.3 | AFUE | 7.4 | 3.91 |
| Heating | Hydronic | H2O | Gas | G | 2102 | 120 | 79.6 | AFUE | 8.1 | 2.73 |
| Heating | Hydronic | H2O | Oil | O | 2735 | 120 | 84.6 | AFUE | 9.1 | 3.14 |
| Heating | Room | RM | Electric | E | 1085 | 20 | 100 | AFUE | 35.8 | n/a |
| Heating | Room | RM | Gas | G | 822 | 30 | 70.0 | AFUE | 14.8 | 0.15 |
| Heating | Room | RM | Oil | O | 1837 | 100 | 75.0 | AFUE | 7.4 | 1.95 |
| Cooling | Central Air | CAC | Electric | E | 2097 | 36 | 9.24 | SEER | 31.8 | 0.76 |
| Cooling | Heat Pump | HP | Electric | E | 3449 | 36 | 9.41 | SEER | 60.0 | 0.46 |
| Cooling | Room AC | RAC | Electric | E | 522 | 12 | 8.73 | EER | 27.9 | 1.50 |

The Purchase Price of Equipment is a function of Capacity and Efficiency according to the following equation:

Price = (b + m*[C-C1])*(E/E1)^eff

where:

b = Price at Base Capacity and Efficiency ($)
m = Price Slope ($/kBtu/hr)
C = Equipment Capacity (Output, kBtu/hr)
C1 = Base Capacity (Output, kBtu/hr)
E = Equipment Efficiency
E1 = Base Efficiency
eff = Elasticity of price with respect to efficiency

(1) Heat pump (HP) costs are based on data for split systems. Hydronic (H2O) costs are based on data for hot water boilers. Electric room (E RM) costs are based on data for electric baseboards, with increasing capacity from adding additional baseboards.
(2) Base cost, capacity, and cost vs. capacity relationship from MEANS 1992 residential and mechanical cost data (R.S. MEANS Co. 1991b, R.S. MEANS Co. 1991c). Converted to 1990$ using the producer price index. Costs include installation but not thermal distribution system.
(3) Cost vs efficiency relationship from ADM (1987). Converted to 1990$ using the producer price index.
(4) Base efficiency and capacity are not necessarily the typical efficiency and capacity of current units, and are only used as a reference point for cost purposes.
(5) HP base unit HSPF is 7, and this parameter scales more or less linearly with SEER. The relationship is not exact, but it is roughly accurate.

**Valid Ranges for Equipment Cost Functions**

| End-use | System | Technology | Heating Fuel | Output Capacity (kBtuh) | | Efficiency | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Lower | Upper | Lower | Upper | Units |
| Heating | Forced Air | Furnace | Electric | 30 | 131 | n/a | n/a | n/a |
| Heating | Forced Air | Furnace | Gas | 42 | 160 | 62 | 92 | AFUE |
| Heating | Forced Air | Furnace | Oil | 55 | 200 | 80 | 91 | AFUE |
| Heating | Hydronic | HW Boiler | Gas | 80 | 203 | 68 | 90 | AFUE |
| Heating | Hydronic | HW Boiler | Oil | 109 | 236 | 82 | 89 | AFUE |
| Heating | Room | Baseboard | Electric | 8 | 38 | n/a | n/a | n/a |
| Heating | Room | Furnace | Gas | 18 | 50 | 73 | 80 | AFUE |
| Heating | Room | Heater | Oil | 24 | 94 | 64 | 87 | AFUE |
| Cooling | Forced Air | Central Air | Electric | 24 | 60 | 7.0 | 14.1 | SEER |
| Cooling | Forced Air | Heat Pump | Electric | 18 | 60 | 6.8 | 14.7 | SEER |
| Cooling | Room | Room Air | Electric | 6 | 21 | 9.3 | 13.5 | EER |

## 6. DECISION MODELS

Consumers must make several decisions regarding the purchase or upgrading of heating and cooling equipment. In residential end-use forecasting, these decisions are generally grouped according to the system being purchased and the relevant energy efficiency attributes of that system. The HVAC model of REEPS actually has three distinct types of decision models corresponding to three types of consumer choices. The first is efficiency choice, which refers to the level of efficiency chosen by the consumer for a particular type of heating or cooling equipment. The second is the choice of a particular HVAC system, based in this analysis on the combinations detailed in Section 4. The third type of consumer choice is the decision of thermal shell package for new homes, using the packages we defined in Section 3.3. These decisions are of course related to each other and, in the course of the forecast, REEPS iterates to bring the decision models together in a consistent fashion (McMenamin et al. 1992).

We developed decision models for the first two of these types of decisions. These models are based on the theory that consumers make tradeoffs between purchase price and operating expense in their purchase decisions. This tradeoff is captured through explicit calculation of a utility function for each type of equipment and/or housing type. The utility functions are used in a multinomial logit framework to represent consumer choice and forecast market shares. In the following sections, we describe the methodology used to develop the decision models and present the estimated parameters for these decision models. Section 6.1 outlines the general framework for all three decision models in REEPS and shows the calculation of the two basic attributes -- purchase price and operating expense -- to be used in each model. Section 6.2 explains the methodology and results for the efficiency choice model parameters. Section 6.3 details the estimation of market share parameters for HVAC systems in new homes. Section 6.4 discusses the market share analysis for thermal shell choice.

### 6.1. Decision Model Framework

The multinomial logit model for the decision models is derived from the theory of "qualitative (or "discrete") choice analysis." We use a standard model of consumer choice, involving the implicit tradeoff between present purchase price and future operating expense (Train 1986). Confronted with *j* discrete purchase options, a consumer selects the option that maximizes utility as a function of purchase price (PP) and operating expense (OC), as well as other factors. If one assumes a linear utility function (which is a standard practice), then the utility of option *j* can be represented as:

$$U_j=\beta_1 PP_j+\beta_2 OC_j + \alpha_j \qquad \forall \ j \tag{6.1}$$

where $\beta_1$, $\beta_2$ and $\alpha_j$ are unknown parameters to be estimated. In this specification, utility is presumed to decrease with an increase in either cost, so that $\beta_1$ and $\beta_2$ are expected to be negative. The constant $\alpha_j$ is supposed to account for those attributes of option *j* that affect the consumer's decision but are unobserved. In this model, the ratio of the two parameters $\beta_1$ and $\beta_2$ represents the marginal rate of substitution between the two elements of purchase price and operating expense, commonly interpreted as the implicit discount rate *r* if the devices or systems are assumed to have infinite lifetime:

$$\frac{\beta_1}{\beta_2} = r. \tag{6.2}$$

If the devices or systems have a finite lifetime of *T* years, we can interpret the parameters similarly by calculating the value of *r* that satisfies the following relationship:

$$\frac{\beta_1}{\beta_2} = \frac{r}{[1-(1+r)^{-T}]}. \tag{6.3}$$

We report the implicit discount rate for each decision model estimated in this analysis. These discount rates are provided mainly as an intuitive interpretation of the logit parameters and should be used with caution if transferred to other consumer choice models, such as life-cycle cost minimization models.

The utility function in Equation 6.1 is used to predict the shares or probabilities of particular options in a given year *t* based on the standard multinomial logit formulation:

$$\text{Probability of Ownership}^{t}_{h,j} = \frac{\exp(U_{h,j})}{\sum_{j'} \exp(U_{h,j'})} \qquad (6.4)$$

where *h* is the housing type, *j* is the option of interest, *j'* is the set of all options, and *U* is the "utility function" or "desirability index" in any given year *t*. For the reader interested in more detail on the nature of qualitative choice analysis and its implications for decisions on investments in energy efficiency, we have provided a detailed discussion in Appendix G.

Accurate estimation of the parameters $\beta_1$, $\beta_2$ and $\alpha_j$ requires detailed price data on purchase decisions at the individual or household level. Unfortunately such data do not typically exist at the national level. One option is to use data collected at the regional level on individual purchase decisions, such as utility data collected from rebate programs. Another option is to use aggregate and averaged national data to characterize overall market outcomes. We choose the option of basing our analyses on aggregate national-level data, and we segment the data accordingly. We develop price estimates using the price parameters from Section 5 for HVAC equipment, distribution systems and the thermal shell.

In actual practice, there exist many other relevant attributes in these decisions beyond operating expense and purchase price. The practices and recommendations of contractors in the HVAC market will certainly have a significant effect on the choices made. The clarity with which the products are displayed or advertised will impact the ability of consumers to determine the cost tradeoffs involved. The occupancy patterns and conservation behavior of the households can alter their operating expenses. The pricing strategies of manufacturers may result in considerable variation in the prices of more efficient equipment. Such complexities can be explicitly included in the model by adding additional $\beta_j$ terms, or can be implicitly represented by the $\alpha_j$ term in Equation 6.1. The standard practice in discrete choice analysis, however, is to exclude these additional factors due to a lack of data with which to estimate them. We adopt this practice in this analysis, excluding all other factors besides purchase price and operating expense. In doing so, we conduct our analyses *as if* the market behaves according to this simple tradeoff[6]. Thus we are able to make explicit our assumptions concerning the behavior of the market for energy efficiency. The two-attribute model (Equation 6.1 without the $\alpha_j$ term) becomes a proxy for the more complex workings of the marketplace. Fortunately, heating and cooling equipment have no real frills like some appliances and their value is generally based on the ability to reliably deliver heating or cooling services at lowest cost. This suggests that the two-parameter HVAC decision models offer a reasonable depiction of the marketplace (Ruderman et al. 1987).

[6] In our framework, the "consumer" or "decision maker" does not refer to specific purchasers or types of purchasers such as a homeowner or contractor, but instead represents the behavior of the market for HVAC equipment in the aggregate, with some segmentation by housing type. Consequently the consumer represents that economic agent who best characterizes the market for each equipment and/or system type considered.

## 6.2. Efficiency Choice

In the residential forecasting framework, households face decisions about what level of efficiency they choose for a given type of equipment -- a choice that could be influenced by many factors. These factors include the design heating or cooling load of the building, the current fuel prices, the number of people in the household, and the expected conservation practices of the household. The REEPS HVAC module currently does not model these HVAC equipment efficiency choices in the same way as the REEPS appliance model -- with discrete efficiency options for HVAC equipment and a logit efficiency choice model to forecast market shares. Rather, *average* efficiency levels are forecast for each HVAC equipment type, based on an exogenous time series of average efficiency values (driven by Federal appliance standards) modified by a fuel price elasticity, as shown in Equation 6.5:

$$\text{Eff}_g^t = \text{ExogEff}_g^t \times \left(\text{FuelPrice}^t\right)^{\varepsilon g} \tag{6.5}$$

where *Eff* is the forecast efficiency of equipment type, $g$, in year, $t$, *ExogEff* is an exogenous time series of average efficiencies for equipment type, $g$, and $\varepsilon g$ is the fuel price elasticity for equipment type, $g$. We adopt this reduced form efficiency choice model for our baseline analyses using REEPS. For use in this modeling framework, we have re-estimated the fuel price elasticities of each equipment type, as shown in Table 6.1.

**Table 6.1: Estimated Fuel Price Elasticities for HVAC Equipment Efficiency Choice Model**

| **Heating (Screen HV-6c.1)** | **Fuel Price Elasticity** |
|---|---|
| Electric Furnace | na |
| Gas Furnace | 0.13 |
| LPG Furnace | 0.15 |
| Oil Furnace | 0.14 |
| Electric Heat Pump | 0.16 |
| Gas Hydronics | 0.13 |
| Oil Hydronics | 0.14 |
| Electric Room | na |
| Gas Room | 0.10 |
| Other Equipment | 0.10 |
| **Cooling (Screen HV-6c.2)** | |
| Central Air | 0.15 |
| Electric Heat Pump | 0.15 |
| Room Air | 0.10 |

(1) The fuel price elasticities are the elasticity of equipment efficiency with respect to fuel price, and are used in Equation 6.5.
(2) Elasticities are based on manufacturer shipment data.

For analyses requiring more detailed modeling of efficiency choice, such as impact analysis of Federal appliance standards, we have developed a specific efficiency choice model (implemented in a spreadsheet) to forecast the exogenous time series of equipment efficiencies described above (the *ExogEff* variable). The model contains two parameters of the form described in Section 6.1. To estimate the model parameters ($\beta_1$ and $\beta_2$), we use the data on equipment market share by efficiency, discussed in Section 4.3. The efficiency distribution data allow us to segment the shipments into several discrete efficiency levels (or bins). Each bin represents a grouped data set, which is in turn represented by an option $i$ having the average efficiency level of its respective bin. For each option $i$ we calculate its market share $M_i$, purchase price $PP_i$, and operating expenses $OC_i$. First, the size is determined from the sizing parameters and shell assignments given in Section 3.3. The purchase price of equipment is determined from the price formulae in Table 5.3 for each efficiency level *i* and for each technology. The operating expense for efficiency level *i* is simply a function of fuel price and unit energy consumption (which is in turn a function of the efficiency of option *i*), as shown in the following equation:

$$OC_i = UEC_i * P_{fuel}. \quad (6.6)$$

To estimate the model parameters, we used a least squares procedure developed by Berkson and described by Ben-Akiva and Lerman (1985). Berkson's procedure is based on the fact that a multinomial logit model with a linear-in-parameters utility function can be transformed into a form amenable to standard regression techniques. The MNL equation is transformed as follows:

$$\log\left(\frac{S_i}{S_j}\right) = \beta_1(PP_i - PP_j) + \beta_2(OC_i - OC_j) \quad (6.7)$$

where *j* is a chosen option used for normalization. The transformed data allow the logit model parameters $\beta_1$ and $\beta_2$ to be calculated using linear regression methods, albeit with the loss of one degree of freedom statistically due to the normalization. For each technology, we calculated the model parameters using 1990 fuel prices. The parameter estimates and associated implicit discount rates are shown in Table 6.2.

**Table 6.2: Estimated Coefficients of HVAC Equipment Efficiency Choice Model**

| Heating | Purchase Price | Operating Expense | r |
|---|---|---|---|
| Electric Furnace | n/a | n/a | |
| Gas Furnace | -0.0108 | -0.0467 | 23.1% |
| Oil Furnace | -0.0073 | -0.0845 | 8.7% |
| Electric Heat Pump | -0.0277 | -0.3015 | 9.2% |
| Gas Hydronics | -0.0318 | -0.0945 | 33.7% |
| Oil Hydronics | -0.0101 | -0.0879 | 11.5% |
| Electric Room | n/a | n/a | |
| Gas Room | -0.0079 | -0.0521 | 15.1% |
| Other Equipment | -0.0258 | -0.0934 | 27.6% |
| **Cooling** | | | |
| Central Air | -0.0048 | -0.0177 | 27.2% |
| Electric Heat Pump | -0.0172 | -0.2183 | 7.9% |
| Room Air | -0.0225 | -0.0863 | 26.1% |
| No Air | | | |

(1) The implicit discount rate, r, is calculated assuming infinite device lifetime, using Equation 6.2.
(2) Analysis is based on efficiency data from: (AHAM 1991, ARI 1991, GAMA 1992).

One should bear in mind a few important points about our methodology and the resulting parameter estimates. First, this methodology is quite different from some calculations of the implicit discount rate, such as those based on life-cycle cost minimization (Ruderman et al. 1987). This is because the qualitative choice model framework requires no assumptions about life-cycle cost. Even where the results of the two methods are in reasonable agreement, this does not mean that the *models themselves* are interchangeable.[7] Second, the implicit discount rates

[7] A simple explanation of the differences between the two approaches can be gleaned from the fact that life-cycle cost minimization methods focus on the average efficiency whereas the qualitative choice model requires a set of

we calculated *cannot* be used directly in other modeling frameworks. The estimated parameters $\beta_1$ and $\beta_2$ must be used directly in the same mathematical formulation specified if they are to retain any significance. The implicit discount rate is simply a derived quantity useful in interpreting the results, not a model result in and of itself.

### 6.3 New Home HVAC System Choice

The choice of HVAC system typically involves two decisions -- one for the type of heating equipment and the second for cooling equipment. Thus the multinomial logit model to represent these decisions requires two levels, otherwise known as a "nested" logit, which is the form expected in REEPS. The nested logit in turn requires specification of two utility functions. One is for the "upper level" cooling choice and the other is for the "lower level" heating choice. The complete model is estimated in a sequential or "two-level" manner, starting with the lower heating choice level. Currently, data limitations (described below) prevent estimation of the full HVAC nested logit. Due to insufficient data to estimate the cooling choice, we have adopted the default parameters for cooling choice from the REEPS HVAC module (Goett 1990), as shown in Table 6.3. The available data allow calculation of a national heating-choice model, which we discuss in this section, as well as a two-region heating-choice model, which we discuss in Appendix F. These new heating system parameter estimates are combined with the REEPS default cooling system parameters to run the REEPS HVAC model.

**Table 6.3: Cooling Equipment Choice Model for New Homes (REEPS Default)**

| Equipment Type | Utility Function |
|---|---|
| Central Air | $U_{h,CAC}$ = - 0.3 * ($CCapCost_{CAC}$ + $COpCost_{CAC}$ * N_CDD/CDD) / Discount / 1000 + 0.025*$Inc_h$ + 0.3 * Logsum + $C_{h,CAC}$ |
| No Central Air | $U_{h,NoCAC}$ = - 0.3 * ($CCapCost_{NoCAC}$ + $COpCost_{NoCAC}$ * N_CDD/CDD) / Discount / 1000 + 0.013 * $Inc_h$ + 0.3 * Logsum + $C_{h,NoCAC}$ |

Definitions: *h* is house type,
*CCapCost* is the installed cooling equipment price for equipment type *g*,
*COpCost* is an index of cooling equipment operating costs for equipment type *g*,
*N_CDD* is the normal (30-year average) cooling degree days, base 65˚F, for the region being modeled (US 30-year average CDD = 1438; North region = 1000; South region = 1662).
*CDD* is the actual annual cooling degree days, base 65˚F, for the region being modeled (1990 US average = 1592; North region = 1116; South region = 1860.).
*Discount* is the implicit discount rate used for HVAC equipment decisions (assumed to be 20% in the REEPS default input set)[8],
*Inc* is the average household income,
*Logsum* is the inclusive term from the heating-level logit model. This term implements the nested logit structure.
$C_{h,g}$ is the control-year calibration constant for equipment type *g*.

Notes: (1) Cooling degree day source: 1990 RECS (EIA 1992).
(2) The Logsum term is calculated as follows: $\ln(\sum_{sys} m_{h,sys} \times \exp(C_{h,sys} + U^t_{h,sys}))$.

where $m_{h,sys}$ is an availability multiplier for heating system, *sys*, in house type, *h*; $C_{h,sys}$ is the calibration constant for heating system, *sys*; in house type, *h*; and U is the heating system utility function from Table 6.4.

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observations, or in our case, a distribution. In cases where the average efficiency does not describe this distribution well (i.e., it is highly asymmetric), then the results of the two methods may differ considerably due to the non-linear nature of the model.

8 Note that this discount rate is for the HVAC ownership model and is distinct from the "market discount rate" used to characterize the efficiency choices. In practice, the REEPS default equipment choice models are relatively

To estimate logit parameters, one typically uses random samples of individual purchases, and indeed, the logit model was designed for use with data in this form. In our case, however, only aggregate (and averaged) data were available. We developed 10 data sets in order to create the national version of the HVAC market share decision model, with each data set corresponding to equipment choices in one of the ten federal regions. In this section, we review the data and procedures for the four basic aspects of model development: market shares of HVAC systems, thermal shells, equipment characteristics and cost estimates.

*Market Shares of HVAC Systems*

We used survey data from the National Association of Home Builders (NAHB 1989) for the market data in the analysis. The data were for single-family detached homes by state and by HVAC system category. Eight types of HVAC systems (combined heating and cooling equipment) were represented, composed of seven types of heating and two types of cooling equipment. The heating technologies included electric furnace, gas furnace, oil furnace, gas hydronic, oil hydronic, electric room, and electric (air source) heat pump. Gas furnaces were further segmented into homes with Central Air Conditioning (CAC) or Room Air Conditioning (RAC), to yield eight HVAC systems. We aggregated the data based on the ten Federal regions and the eight HVAC system types, resulting in a total of 80 grouped data points.

*Thermal Shells*

For each Federal region, we chose the city with the climate closest to that of the population-weighted average from the GLOM program (Andersson et al. 1986). We developed a set of heating and cooling loads for each city by using component loads (Hanford et al. 1994). We determined the component levels (insulation levels, windows, etc.) based on the averages for each grouped data point from the NAHB data set. We calculated the annual heating and cooling loads for the 80 data points based on the component loads, component levels, and the floor areas available in the NAHB data. These calculations are identical in form to those described in Section 3.2 and Appendix A.

*HVAC Equipment Characteristics*

Equipment characteristics used to estimate the decision model include the efficiency, size (capacity), and Unit Energy Consumption (UEC). No regional data were available for equipment efficiency, so we used the average efficiencies for 1987 shipments for each type of equipment. The equipment size was based on the calculated peak load and the sizing parameters for each equipment type. The sizing methodology is identical to that used for the two region model, as described in Section 5.1. The Unit Energy Consumption is calculated using Equation 5.3, with the fuel price elasticity set to 0. For the distribution system efficiency, we used estimates for new 1990 homes (Hanford et al. 1994) as none were available for 1987.

*Price and Operating Expense Estimates*

The price and operating expense data needed for model estimation include the purchase price of heating equipment, purchase price of the distribution system and the annual heating equipment operating expense. Equipment purchase price depends on equipment size and efficiency according to Equation 5.4, using the parameters provided in Table 5.3. We also added a regional price multiplier to this equation to account for differences in price levels between regions (Boghosian 1991). Distribution system price is based on square feet of floor area and system type, as given in Equations 5.5 and 5.6. Annual operating expense is simply the Unit Energy Consumption multiplied by the fuel price. We developed regional fuel price data from fuel prices reported by state for the residential sector (US DOE 1989a). The Federal Region-level

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insensitive to the discount rate, so the 20% discount rate has been selected to be generally representative of the market discount rates observed in the HVAC end-uses.

fuel prices are averages of the state-level fuel prices weighted by the number of households in each state (US Bureau of the Census 1992).

*Model Estimation*

As described in Section 6.2, Berkson's procedure simplifies the estimation of logit parameters using grouped data, thus we employed this method to estimate the HVAC equipment choice parameters. First, the equipment prices were normalized to the annual loads. For example, a gas furnace with purchase price of $2000 in a region with a heating load of 100 MBtu/year would have a normalized purchase price of 2000/100 = $20/MBtu. Previous studies have found that such a normalization is necessary to obtain reasonable estimates (Dubin 1985, Goett 1990). The equipment price and market share data are then normalized to a chosen option, as shown in Equation 6.7. The resulting parameters are shown in Table 6.4. Previous estimates of the implicit discount rates associated with heating choice have varied widely, from less than 4% to over 50% depending on the data as well as the model specification (EPRI 1988). Our model estimate is consistent with this established range.

**Table 6.4: Heating Equipment Choice Parameters**

| Parameter | Parameter Estimate |
|---|---|
| **Purchase Price ($\beta_1$)** | -0.0024 |
| **Operating Expense ($\beta_2$)** | -0.0051 |
| **Implicit Discount Rate (r)** | 47.3% |

(1) The implicit discount rate, r, is calculated assuming infinite device lifetime, using Equation 6.2.
(2) Analysis is based on 1987 NAHB equipment market shares and shell characteristics (NAHB 1989), and equipment price and sizing models described in Section 5.

These parameters only apply to heating equipment choice and not to the choice of cooling equipment. The data were not sufficiently varied nor detailed enough for the cooling estimation, with the result that the cooling parameters did not converge to negative values, which is a necessary condition for consistency in the model. Thus, we rely on the default cooling choice model, as described above.

We also estimated separate single-family heating equipment choice models for both the north and south regions, which are documented in Appendix F. The national equipment choice model presented above provides more robust results for national-level forecasts, due to more extensive data and a more accurate estimation technique. However, the regional equipment choice models may be preferred for cases where regional differences in equipment choice are important.

One should bear in mind that the equipment choice models documented in this report are based on data for equipment purchases in new single-family dwellings. Their application to other housing types and replacement purchase decisions may not produce reliable results. However, data limitations (specifically, a number of zero market shares for certain equipment types in the 1990 RECS dataset) do not allow estimation of heating equipment choice models for the other dwelling types (multifamily and mobile home). The estimation of replacement equipment choice models is similarly hampered by a lack of purchase data. Until better data are available, we believe that the best approach is to use the single-family equipment choice model for all housing types.

Finally, we have found that the allocation of system distribution prices in the central air options has a significant impact on the estimates. In our judgment, these prices are most sensibly assigned to the "upper," cooling-choice level in the nested logit model. However, removing them from the central air-contingent heating system data results in implicit discount rates of several hundred percent. Moreover, REEPS is structured with these distribution prices assigned to the heating level. Accordingly, our parameter estimates for single-family dwellings have been estimated with these distribution system prices included in the heating system price variables. For this reason, when these parameters are used in REEPS, the logit equation should include the combined heating and distribution system price variables (HCAPCOST + DISTCOST) and exclude the cooling and shell price variables (CCAPCOST and SHELCOST).

### 6.4. New Home Thermal Shell Choice

We adopted the REEPS default thermal shell choice model (McMenamin et al. 1992) at the present time because the thermal shell data to which we had access were not sufficiently disaggregated to allow the estimation of logit models for thermal shell choice. This default model simply applies a 20% discount rate to the Life-Cycle Cost (LCC) decision among the available thermal shell packages. There is no differentiation among different shell groups or housing types in this model. The simplicity of this model should not lead to inaccurate results, however, because during the REEPS calibration process the thermal shell decision model will automatically be calibrated to the control values for new home thermal shell market share, which were given in Tables 3.5-N and 3.5-S.

## 7. FUTURE WORK

Due to data, software and/or resource limitations, we were unable to incorporate some features into the model. We discuss these future work areas in this section.

### 7.1 Room Air Conditioners

We currently treat room air conditioners as a subset of homes without central air conditioning. We did not include a room air conditioner system type in the primary cooling options in order to limit the number of combined heating and cooling systems. For this reason, the upper level of the HVAC equipment logit model chooses between central air or no central air, and room air conditioner ownership is forecast by a simple saturation model in the secondary cooling equipment module. This treatment of room air conditioners as a secondary cooling system imposes several limitations on forecasting changes in the room air conditioner end-use. As mentioned, the ownership model is not a discrete choice model. Most importantly, REEPS does not endogenously forecast changes in secondary equipment efficiency or capacity. Thus, both the saturation and UEC of room air conditioners is fairly constant over time. One possible solution is to treat room air conditioners as an appliance in the REEPS appliance module. This is an intuitively appealing method because room air conditioners tend to be purchased and operated more like appliances rather than HVAC equipment. This formulation would require changes in the REEPS code to access variables from the HVAC module.

### 7.2. Common heating systems

Multifamily buildings are often more difficult than single-family buildings to analyze in an end-use forecasting framework because they include many different types of buildings, some of which have common heating and cooling systems for a building or part of a building. It becomes more difficult to interpret the energy characteristics and the economic tradeoffs in such cases both because of physical differences in the equipment and the fact that these consumers have no control over the choice of heating and cooling systems except in limited cases where a building is co-owned by its occupants. We would like to better characterize buildings that have common heating and cooling systems in the REEPS HVAC model. We plan to investigate the detail and availability of data and consider two possibilities for improving the representation. One method is to create a separate housing type for buildings with common systems and adjust the structure accordingly. Another possibility is to create separate equipment types for common heating systems and assign them to the share of multifamily buildings which have common heating systems, which could be estimated from the 1990 RECS.

### 7.3. Thermal Shell Retrofits

The REEPS thermal shell retrofit module has three significant limitations: 1) the default retrofit decision model is a simple life-cycle cost model, 2) new construction shell costs are used to model shell retrofits, and 3) thermal shell costs do not vary by housing type. We have not been able to obtain data on retrofit activity with which to specify the thermal shell retrofit decision model in REEPS. At a minimum, we would need household or grouped data which gave some indication of the thermal shell components before and after the retrofit. One possible method of obtaining these data would be to determine a subset of households common to both the 1987 and 1990 RECS in which retrofits were undertaken. The rates of retrofit activity could then be used in concert with our data on retrofit costs in order to develop some rough parameters for a conversion decision model. To solve the second and third limitations of the retrofit model will require changes to the REEPS computer code.

### 7.4. The Rebound Effect

When consumers purchase more efficient equipment, they sometimes change their behavior because their marginal cost of additional energy services has decreased. We would like to determine the size of this effect for the purpose of incorporating these behavioral changes into the models of energy usage in the HVAC model of REEPS. A simple elasticity parameter could be used in the usage Equation 5.3 to represent the percentage increase in consumption resulting from a percentage increase in efficiency. This would require metered household energy use data both before and after the change in equipment. The household data would have to include equipment nameplate data or give the capacity and efficiency of equipment in each case. Ideally, we would look at only those cases where the same type and size of equipment was chosen, with the only difference being the efficiency of the equipment.

### 7.5. Efficiency Choice

We depicted efficiency choice for the average loads based on thermal shells for three types of heating: electric resistance, heat pump, and fuels. This means that the operating expense was based on the average UEC determined from the average load. As with many aspects of this type of modeling, average data can cause erroneous and misleading results. In this case, the discrepancy stems from three simple facts: (1) the decision model for efficiency choice depends directly on the load, via the UEC, (2) the decision model is reduced-form for HVAC equipment, and (3) the decision model is nonlinear. This means that as the load diverges from this average due to changes in thermal shell market shares, the decision model becomes less and less appropriate. We need a means of estimating this divergence for all the relevant factors, which include other variables such as the exogenous cost multiplier and the sizing assumptions. There are two ways in which we could correct for this error. One is to seek a change in the REEPS software which will allow specific options and a multinomial logit model for HVAC equipment. The second way is to develop correction factors by iterating over many combinations of attributes, calculating the efficiencies, and estimating the gap between the reduced-form result and the iteratively predicted result for efficiency choice.

### 7.6. Passive Solar Features

We have not considered passive solar features in configuring our thermal shells for the model and would like to develop a structure for doing so. The current framework in REEPS makes it possible to develop such features by treating them as distinct thermal shell components. In order to implement the features, we would need to gather price data, do thermal simulations, and incorporate a separate shell type for systems which have the features. We could then develop a decision model for choices which include the passive solar features.

### 7.7. New Technologies

With the exception of our configuration of windows in the thermal shell section, we have only included mature technologies in our model. We would like to consider emerging technologies which could play an important role in reducing space conditioning energy consumption in the coming decades. Some of these technologies would be: natural gas heat pumps, ground source heat pumps, evaporative cooling, ductless air conditioning and heat pumps, and integrated space heating/water heating systems. In order to incorporate these designs into the model, we will need price data for different designs, performance and operating characteristics and data on the capacity and efficiency of the models currently being sold or designed. Since REEPS is quite flexible in configuring technologies, incorporating most technologies into our model is limited only by the availability of the price and design data. Some technologies, such as integrated space/water heating systems, will require changes to the REEPS code to allow feedbacks between the HVAC and appliance modules.

### 7.8 Thermal Distribution Systems

REEPS currently does not explicitly treat the efficiency of thermal distribution systems (ducts and hydronic piping). This is an important element in the HVAC module, however, because research has shown that typical thermal distribution systems may be only 60-70% efficient (Andrews and Modera 1991). REEPS implicitly accounts for this effect during the base year UEC calibration process, but we would like to directly incorporate thermal distribution efficiency into the UEC equation, in order to model policies aimed at improving duct efficiency. This would require a thermal distribution system efficiency choice model, and feedback of the resulting efficiencies into the UEC equation.

## 8. CONCLUSIONS

The report illustrates the diverse set of techniques and data sources required to configure an end-use forecasting model. We defined the thermal shells, configured heating and cooling equipment, developed equipment size, usage and price equations, and estimated decision model parameters to forecast consumer choices. The report also demonstrates the complexity and interdependence of the space conditioning end-uses and the fact that differences in methodology can have significant impacts on the results. The proliferation of models and model parameters and the lack of detailed documentation in this area have been sources of considerable confusion for practitioners and policy-makers alike. By making explicit the data and assumptions behind the analysis, we seek to clear up some of this confusion and move the debate beyond simply the numerical results of the models. This should permit researchers and policy makers to focus on important methodological and data issues which provide the proper context in which to consider the numerical results. While this report will be of most interest to practitioners in the area of residential end-use forecasting, it also provides important background for policy makers interested in addressing detailed programs and issues.

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## APPENDIX A: THERMAL SHELL COMPONENT LOADS

Table A.1 gives the single-family component loads for each component and level and for the North and South regions. We use the single-family component loads to describe all three housing types, with the exception of the residual component loads, which are specified separately for multi-family (residual loads are the remainder of total annual load that cannot be attributed to any of the shell components). By defining a thermal shell package based on a chosen level for each component and a set of building dimensions, the component loads allow simple computation of the total annual heating and cooling requirements. The total annual loads are simply the weighted linear sum of the component loads. We provide an example of the heating load calculation here for a single-family 2-story house in the north region with heated floor area of 2000 square feet and an unheated basement, as shown in Table A.1 below.

**Table A.1: Example Heating Load Calculation**

| **Component** | **Level** | **Area** *Weight* | **Heating** *Component Load (kBtu/sq.ft.)* | **Heating** *Building Load (MMBtu)* | **Cooling** *Component Load (kBtu/sq.ft.)* | **Cooling** *Building Load (MMBtu)* |
|---|---|---|---|---|---|---|
| Ceiling (Insulation) | R-19 | 1000 | 7.47 | 7.47 | 1.18 | 1.18 |
| Walls (Insulation) | R-11 | 1800 | 13.62 | 27.24 | 1.14 | 2.05 |
| Unheated Basement (Floor Insulation) | R-11 | 1000 | 3.25 | 3.25 | 1.59 | 1.59 |
| Infiltration (Air Changes per Hour) | 0.55 | 2000 | 13.18 | 26.36 | 0.58 | 1.16 |
| Windows (Glazing or Window type) | 2-G | 220 | 23.23 | 5.11 | 20.88 | 4.59 |
| Residual Load (MMBtu) (Single-family) | none | 1000 | 2.79 | 2.79 | -1.96 | -1.96 |
| TOTAL (MMBtu) | | | | 72.22 | | 8.61 |

The area is the relevant area or weight for each component. For walls, ceilings and windows, this weight is simply their total area. For infiltration, the relevant area is the total heated floor area of 2000 square feet. The residual load is weighted by 1000 to convert to kBtu. The heating and cooling component loads are taken from Table A.2. We divide the calculated building loads by 1000 to convert to MMBtu. Thus the total annual heating load for these building dimensions and this thermal shell package is 72.22 MMBtu and the total annual cooling load is 8.61 MMBtu.

**Table A.2: Normalized Single-Family Component Loads (Screen HV-2e.3)**
**(kBtu/sq. ft of component except as noted)**

| **Component Descriptions** | **Component** | **North (Chicago)** | | **South (Charleston)** | |
|---|---|---|---|---|---|
| | | *Heating* | *Cooling* | *Heating* | *Cooling* |
| **Ceiling** | R-0 | 34.40 | 5.42 | 14.45 | 8.49 |
| (kBtu/sqft of ceiling) | R-7 | 13.73 | 2.17 | 5.69 | 3.05 |
| *ceiling insulation* | R-11 | 10.43 | 1.65 | 4.29 | 2.18 |
| *R-value* | R-19 | 7.47 | 1.18 | 3.04 | 1.40 |
| | R-22 | 6.33 | 1.01 | 2.56 | 1.17 |
| | R-30 | 4.80 | 0.77 | 1.92 | 0.86 |
| | R-38 | 3.87 | 0.63 | 1.54 | 0.67 |
| | R-49 | 3.05 | 0.49 | 1.23 | 0.55 |
| | R-60 | 2.52 | 0.39 | 1.04 | 0.47 |
| **Wall** | R-0 | 32.85 | 2.61 | 12.25 | 3.90 |
| (kBtu/sqft of wall) | R-7 | 16.01 | 1.32 | 5.71 | 1.49 |
| *wall insulation* | R-11 | 13.62 | 1.14 | 4.78 | 1.14 |
| *R-value* | R-13 | 10.72 | 0.88 | 3.64 | 0.78 |
| | R-19 | 9.28 | 0.75 | 3.08 | 0.60 |
| | R-27 | 6.68 | 0.56 | 2.26 | 0.46 |
| | R-34 | 5.08 | 0.43 | 1.75 | 0.37 |
| **Slab** | R-0 | 65.02 | -7.72 | 34.26 | -42.54 |
| (kBtu/lin. ft of slab) | R-5 2ft | 31.58 | -6.46 | 22.16 | -42.18 |
| *perimeter R-value* | R-5 4ft | 22.01 | -5.49 | 19.32 | -41.51 |
| *and depth* | R-10 2ft | 25.38 | -6.10 | 20.17 | -42.06 |
| | R-10 4ft | 12.07 | -4.89 | 16.61 | -41.21 |
| **Heated Bsmt** | R-0 | 116.95 | 2.46 | 52.82 | -21.69 |
| (kBtu/lin. ft of bsmt) | R-5 4ft | 76.71 | 0.77 | 35.23 | -22.84 |
| *perimeter R-value* | R-5 8ft | 63.63 | 0.83 | 30.35 | -22.60 |
| *and depth* | R-10 4ft | 66.10 | 0.23 | 31.01 | -23.14 |
| | R-10 8ft | 45.92 | 0.29 | 24.81 | -22.90 |
| **Unheated Bsmt** | R-0 | 12.61 | 0.26 | 5.69 | -2.34 |
| (kBtu/sqft of fndn) | R-11 flr | 3.25 | 1.59 | 2.58 | -1.09 |
| *underfloor R-value* | R-19 flr | 0.60 | 1.94 | 1.80 | -0.80 |
| | R-30 flr | -1.10 | 2.16 | 1.30 | -0.61 |
| **Crawl Space** | R-0 | 23.22 | 2.14 | 10.29 | -0.59 |
| (kBtu/sqft of fndn) | R-11 flr | 3.93 | 2.71 | 3.10 | 0.01 |
| *underfloor R-value* | R-19 flr | 0.63 | 2.75 | 2.00 | 0.01 |
| | R-30 flr | -1.46 | 2.80 | 1.43 | 0.03 |
| | R-38 flr | -1.93 | 2.82 | 1.30 | 0.03 |
| | R-49 flr | -3.31 | 2.85 | 0.93 | 0.04 |
| **Infiltration** | 0.80 | 19.50 | 0.87 | 5.42 | 3.17 |
| (kBtu/sqft of floor) | 0.70 | 16.96 | 0.75 | 4.06 | 2.68 |
| *Air Changes per Hour (ACH)* | 0.55 | 13.18 | 0.58 | 2.40 | 1.97 |
| | 0.40 | 9.45 | 0.41 | 1.29 | 1.38 |
| **Windows** | 1.0-gla | 93.68 | 30.13 | 16.72 | 51.04 |
| (kBtu/sqft of window) | 2.0-gla | 23.23 | 20.88 | -7.17 | 36.46 |
| *no. of panes/design* | 3.0-gla | 0.17 | 18.89 | -12.36 | 35.04 |
| | 2-gla loE | 10.44 | 18.39 | -9.65 | 33.07 |
| | 2-gla loEAr | 1.55 | 18.26 | -11.76 | 33.75 |
| | Spectral. Sel. | 21.00 | 13.71 | -4.95 | 23.36 |
| | Superwindow | -7.86 | 15.52 | -12.58 | 29.88 |
| | Heat Mirror | 14.23 | 12.03 | -5.75 | 20.92 |
| **Residual Load** (Single-family) | | 2.79 | -1.96 | -0.18 | 9.38 |
| **Residual Load** (Multifamily) | | 1.25 | 2.56 | 3.22 | 10.78 |

Source: Hanford et al. (1994), Huang et al. (1987b).

(1) Window loads include conduction losses/gains and solar load for equally-distributed windows.

## APPENDIX B: HVAC EQUIPMENT VINTAGE BLOCKS

Tables B.1 through B.12 provide vintage block data for each type of heating and cooling equipment configured in our model. The vintage blocks describe the efficiency profile over time of existing equipment installed in homes. As equipment is retired according to the linear retirement/replacement function in REEPS, the vintage blocks allow for the appropriate efficiencies to be retired and the equipment stock to be adjusted accordingly.

**Table B.1 Central Gas Furnace Stock Data**

| Vintage Block Range | Average Efficiency [a] AFUE | North Region Share of 1990 Stock[b] (percent) | South Region Share of 1990 Stock[b] (percent) |
|---|---|---|---|
| pre-1971 | 65.9 | 27.2 | 24.2 |
| 1971, 1980 | 71.3 | 28.6 | 35.0 |
| 1981, 1985 | 74.2 | 18.0 | 22.9 |
| 1986, 1988 | 75.1 | 17.4 | 10.6 |
| 1989, 1990 | 76.4 | 8.7 | 7.3 |

Source: a. Average Shipment-Weighted Energy Factors (SWEFs), (GAMA 1991)
b. 1990 RECS (EIA 1993).

**Table B.2 Central Oil Furnace Stock Data**

| Vintage Block Range | Average Efficiency [a] AFUE | North Region Share of 1990 Stock[b] (percent) | South Region Share of 1990 Stock[b] (percent) |
|---|---|---|---|
| pre-1971 | 66.4 | 33.5 | 37.5 |
| 1971, 1980 | 73.8 | 23.0 | 23.8 |
| 1981, 1985 | 76.3 | 15.9 | 18.7 |
| 1986, 1988 | 77.2 | 18.0 | 14.9 |
| 1989, 1990 | 78.6 | 9.7 | 5.1 |

Source: a. Average Shipment-Weighted Energy Factors (SWEFs), (GAMA 1991)
b. 1990 RECS (EIA 1993).

**Table B.3 LPG Furnace Stock Data**

| Vintage Block Range | Average Efficiency [a] AFUE | North Region Share of 1990 Stock[b] (percent) | South Region Share of 1990 Stock[b] (percent) |
|---|---|---|---|
| pre-1971 | 65.9 | 15.7 | 9.0 |
| 1971, 1980 | 71.3 | 24.3 | 29.8 |
| 1981, 1985 | 74.2 | 17.6 | 27.5 |
| 1986, 1988 | 75.1 | 21.5 | 16.2 |
| 1989, 1990 | 76.4 | 21.0 | 17.5 |

Source: a. Average Shipment-Weighted Energy Factors (SWEFs), (GAMA 1991)
b. 1990 RECS (EIA 1993).

| **Table B.4 Gas Boilers Stock Data** | | | |
|---|---|---|---|
| **Vintage Block Range** | **Average Efficiency [a]** AFUE | **North Region Share of 1990 Stock[b]** (percent) | **South Region Share of 1990 Stock[b]** (percent) |
| pre-1971 | 70.1 | 40.9 | 41.8 |
| 1971, 1980 | 72.3 | 26.6 | 22.5 |
| 1981, 1985 | 77.4 | 13.2 | 8.9 |
| 1986, 1988 | 78.2 | 8.5 | 16.7 |
| 1989, 1990 | 79.7 | 10.9 | 10.1 |

Source: a. Engineering estimates based on available models, (Hydronics Institute 1992).
b. 1990 RECS (EIA 1993).

| **Table B.5 Oil Boilers Stock Data** | | | |
|---|---|---|---|
| **Vintage Block Range** | **Average Efficiency [a]** AFUE | **North Region Share of 1990 Stock[b]** (percent) | **South Region Share of 1990 Stock[b]** (percent) |
| pre-1971 | 71.2 | 41.8 | 69.2 |
| 1971, 1980 | 75.2 | 20.7 | 30.8 |
| 1981, 1985 | 77.4 | 15.2 | 0.0 |
| 1986, 1988 | 81.6 | 13.0 | 0.0 |
| 1989, 1990 | 83.1 | 9.3 | 0.0 |

Source: a. Engineering estimates based on available models, (Hydronics Institute 1992).
b. 1990 RECS (EIA 1993).

| **Table B.6 Gas Room Stock Data** | | | |
|---|---|---|---|
| **Vintage Block Range** | **Average Efficiency [a]** AFUE | **North Region Share of 1990 Stock[b]** (percent) | **South Region Share of 1990 Stock[b]** (percent) |
| pre-1971 | 56.4 | 36.4 | 48.3 |
| 1971, 1980 | 59.5 | 35.9 | 22.6 |
| 1981, 1985 | 63.1 | 11.5 | 15.6 |
| 1986, 1988 | 64.2 | 7.1 | 8.3 |
| 1989, 1990 | 65.6 | 9.2 | 5.2 |

Source: a. Engineering estimates based on available models, (GAMA 1991)
b. 1990 RECS (EIA 1993).

**Table B.7 Electric Central Furnace Stock Data**

| Vintage Block Range | Average Efficiency<br><br>N/A | North Region Share of 1990 Stock[a]<br><br>(percent) | South Region Share of 1990 Stock[a]<br><br>(percent) |
|---|---|---|---|
| pre-1971 | | 5.9 | 9.9 |
| 1971, 1980 | | 65.4 | 48.3 |
| 1981, 1985 | | 18.3 | 26.0 |
| 1986, 1988 | | 9.7 | 10.3 |
| 1989, 1990 | | 0.6 | 5.4 |

Source: a. 1990 RECS (EIA 1993).

**Table B.8 Electric Room Stock Data**

| Vintage Block Range | Average Efficiency<br><br>N/A | North Region Share of 1990 Stock[a]<br><br>(percent) | South Region Share of 1990 Stock[a]<br><br>(percent) |
|---|---|---|---|
| pre-1971 | | 30.2 | 25.8 |
| 1971, 1980 | | 39.1 | 23.6 |
| 1981, 1985 | | 18.3 | 19.9 |
| 1986, 1988 | | 5.4 | 20.8 |
| 1989, 1990 | | 7.0 | 9.9 |

Source: a. 1990 RECS (EIA 1993).

**Table B.9 Other Heating Equipment Stock Data**

| Vintage Block Range | Average Efficiency [a]<br><br>AFUE | North Region Share of 1990 Stock[b]<br><br>(percent) | South Region Share of 1990 Stock[b]<br><br>(percent) |
|---|---|---|---|
| pre-1971 | 70.0 | 10.9 | 7.6 |
| 1971, 1980 | 70.0 | 28.0 | 26.0 |
| 1981, 1985 | 70.0 | 32.3 | 27.3 |
| 1986, 1988 | 70.0 | 21.7 | 29.5 |
| 1989, 1990 | 70.0 | 7.1 | 9.6 |

Source: a. Fixed value, no source; includes equipment such as wood stoves and kerosene heaters.
b. 1990 RECS (EIA 1993).

**Table B.10 Central Air Conditioner Stock Data**

| Vintage Block Range | Average Efficiency [a] SEER | North Region Share of 1990 Stock[b] (percent) | South Region Share of 1990 Stock[b] (percent) |
|---|---|---|---|
| pre-1971 | 6.74 | 10.4 | 10.0 |
| 1971, 1980 | 7.33 | 35.2 | 33.2 |
| 1981, 1985 | 8.42 | 18.9 | 28.5 |
| 1986, 1988 | 9.04 | 22.5 | 16.4 |
| 1989, 1990 | 9.21 | 13.0 | 11.9 |

Source: a. Average Shipment-Weighted Energy Factors (SWEFs), (ARI 1991).
b. 1990 RECS (EIA 1993).

**Table B.11 Room Air Conditioner Stock Data**

| Vintage Block Range | Average Efficiency [a] EER | North Region Share of 1990 Stock[b] (percent) | South Region Share of 1990 Stock[b] (percent) |
|---|---|---|---|
| pre-1971 | 5.82 | 7.0 | 6.7 |
| 1971, 1980 | 6.51 | 26.6 | 27.1 |
| 1981, 1985 | 7.43 | 28.0 | 34.3 |
| 1986, 1988 | 8.52 | 25.0 | 20.7 |
| 1989, 1990 | 8.64 | 13.3 | 11.2 |

Source: a. Average Shipment-Weighted Energy Factors (SWEFs), (AHAM 1991).
b. 1990 RECS (EIA 1993)., based on the "most used" room air conditioner in the household.

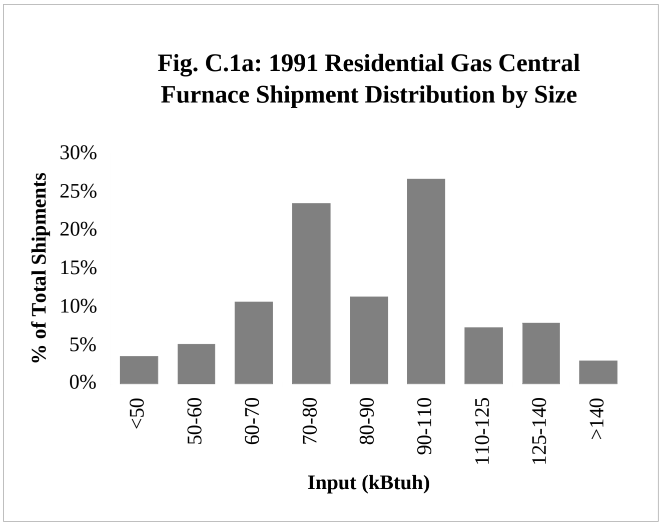
**Table B.12 Heat Pump Stock Data**

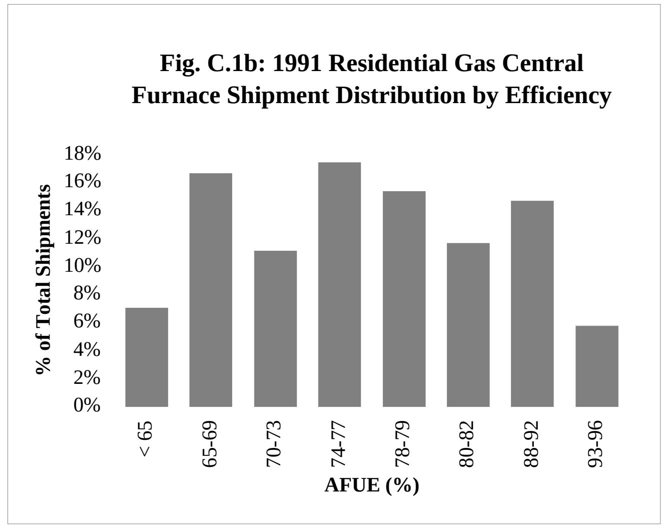
| Vintage Block Range | Average Efficiency [a] SEER | North Region Share of 1990 Stock[b] (percent) | South Region Share of 1990 Stock[b] (percent) |
|---|---|---|---|
| pre-1971 | 7.11 | 0.0 | 2.9 |
| 1971, 1980 | 7.96 | 32.5 | 20.3 |
| 1981, 1985 | 8.85 | 36.8 | 40.0 |
| 1986, 1988 | 9.12 | 21.4 | 26.8 |
| 1989, 1990 | 9.37 | 9.2 | 9.9 |

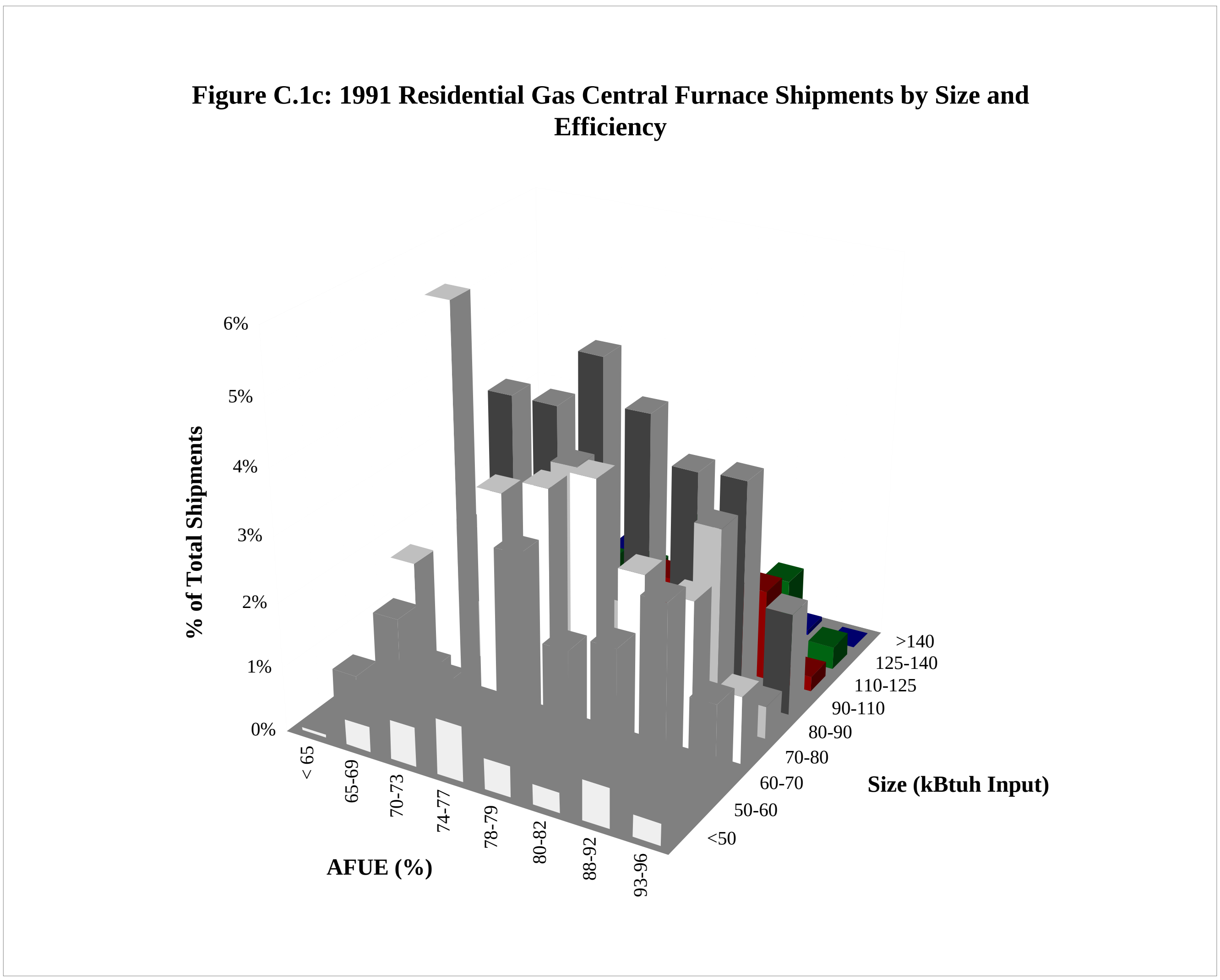
Source: a. Average Shipment-Weighted Energy Factors (SWEFs), (ARI 1991).
b. 1990 RECS (EIA 1993).

## APPENDIX C: SIZE AND EFFICIENCY DISTRIBUTIONS

Figures C.1 a-c through C.4 a-c show the distribution by size (capacity) and efficiency for the most recent year available for four types of heating and cooling equipment. These data represent the minimum level of disaggregation necessary to develop decision models and parameters. The data represent shipments reported by the relevant trade organizations for the various products (ARI 1991, GAMA 1992). Some trade organizations provide the data to a sufficient level of detail for our analysis (ARI 1991). In those cases where the trade organizations provide only a few efficiency categories, we have broken these out into additional categories by tabulating the number of *models* within a given size category as listed in the model directories (GAMA 1990). Note that this approximation may not exactly characterize the distribution of equipment *sales*, since the number of models is only loosely correlated with sales.




(1) Sources: GAMA (1991a), GAMA (1992).
(2) Some size categories have been combined at the two ends of the distribution.
(3) Efficiency categories are based on three categories in the shipment data (GAMA 1992) and then broken out into eight categories based on the number of models within each of the three categories as given in the model directory (GAMA 1991a).

**Fig. C.2a: 1991 Residential Oil Central Furnace Shipment Distribution by Size**

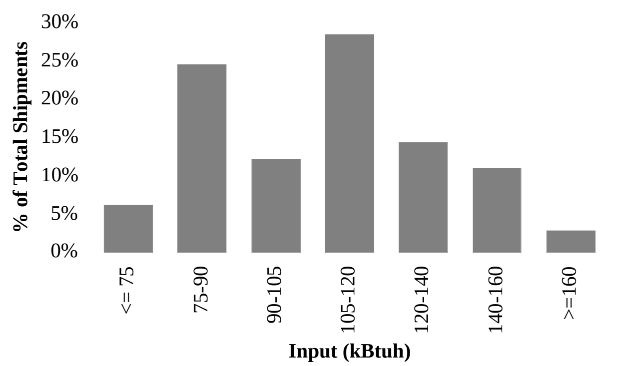



**Fig. C.2b: 1991 Residential Oil Central Furnace Shipment Distribution by Effic.**

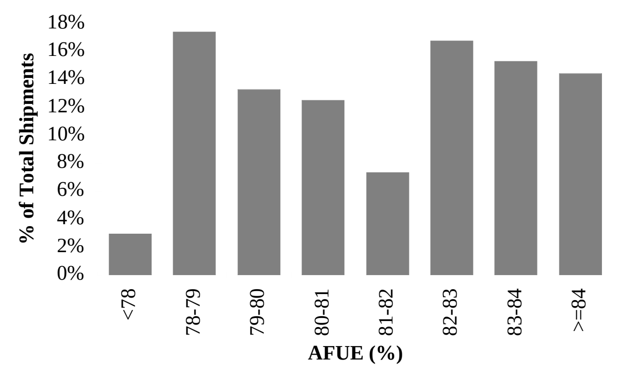
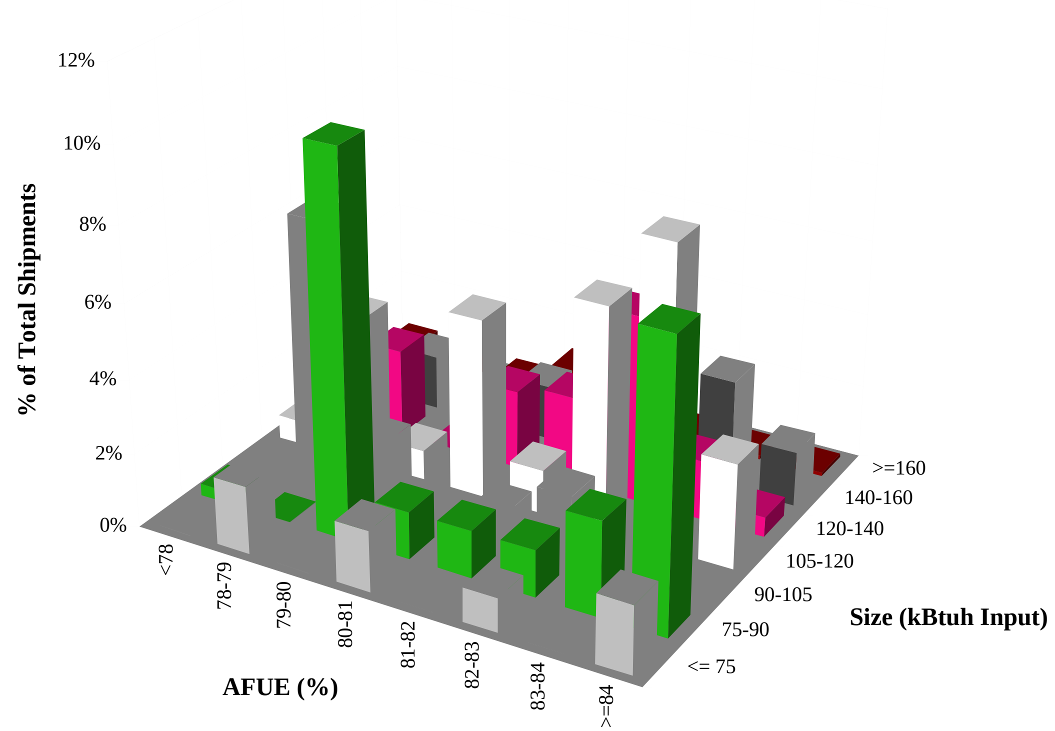



**Fig. C.2c: 1991 Residential Oil Central Furnace Shipments by Size and Effic.**




(1) Sources: GAMA (1991a), GAMA (1992)
(2) Some size categories have been combined at the two ends of the distribution.
(3) Efficiency categories are based on three categories in the shipment data (GAMA 1992) and then broken out into eight categories based on the number of models within each of the three categories as given in the model directory (GAMA 1991a).

**Fig. C.3a: 1990 Residential Central Air Cond. Shipment Dist'n. by Output Capacity**

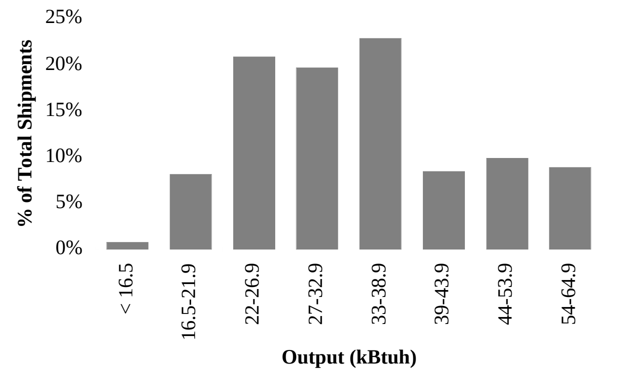



**Fig. C.3b: 1990 Residential Central Air Conditioner Shipment Distribution by Effic.**

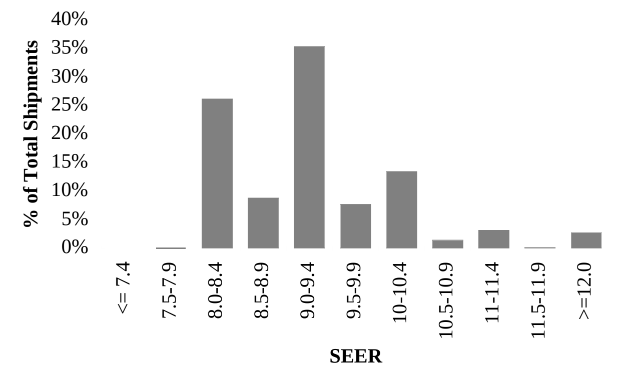
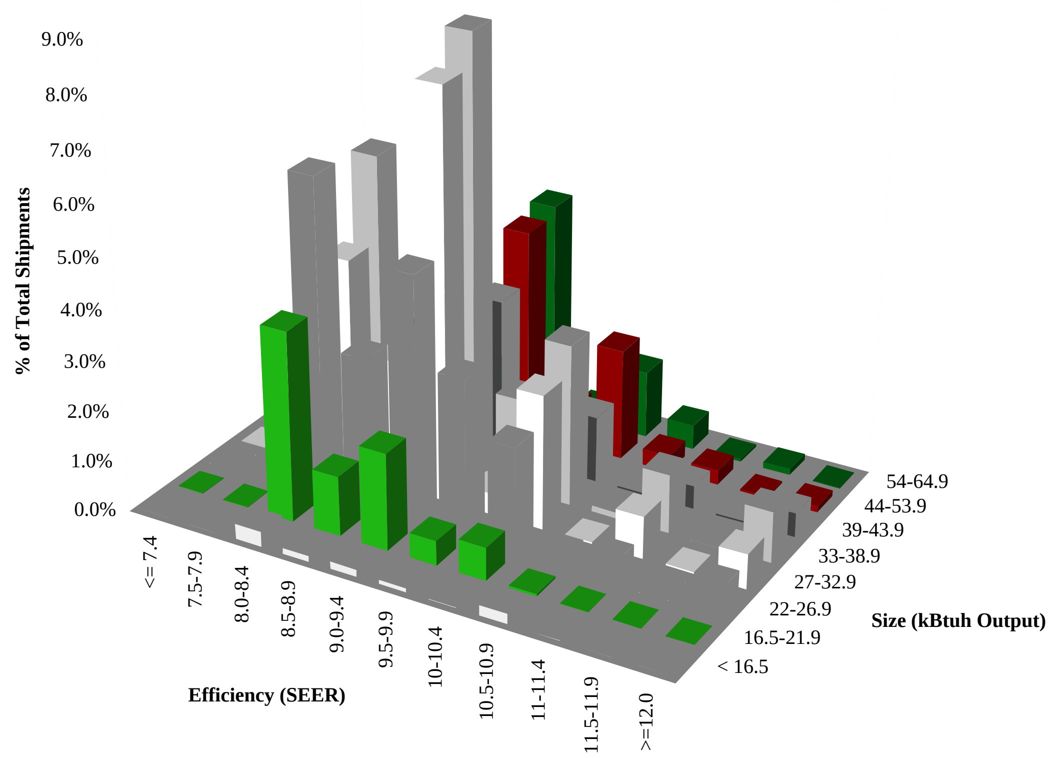



**Fig. C.3c: 1990 Residential Central Air Cond. Shipment Dist'n. by Size and Effic.**




(1) Source: ARI (1991).
(2) Residential Central Air Conditioners are defined as those < 65 kBtuh Output.
(3) The distributions shown include only split-systems.

**Fig. C.4a: 1990 Residential Heat Pump Shipment Distribution by Output Capacity**

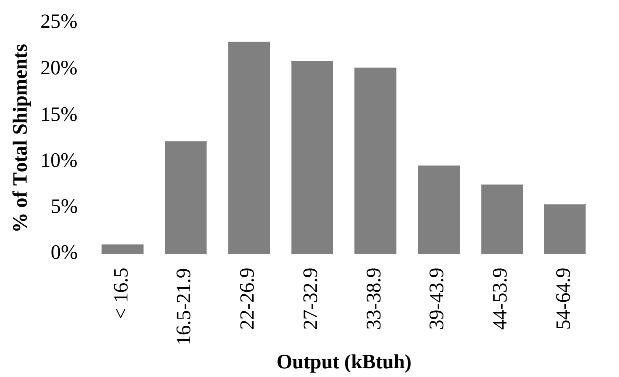



**Fig. C.4b: 1990 Residential Heat Pump Shipment Distribution by Efficiency**

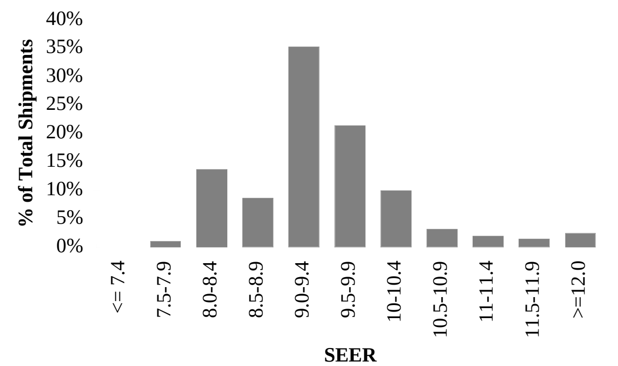
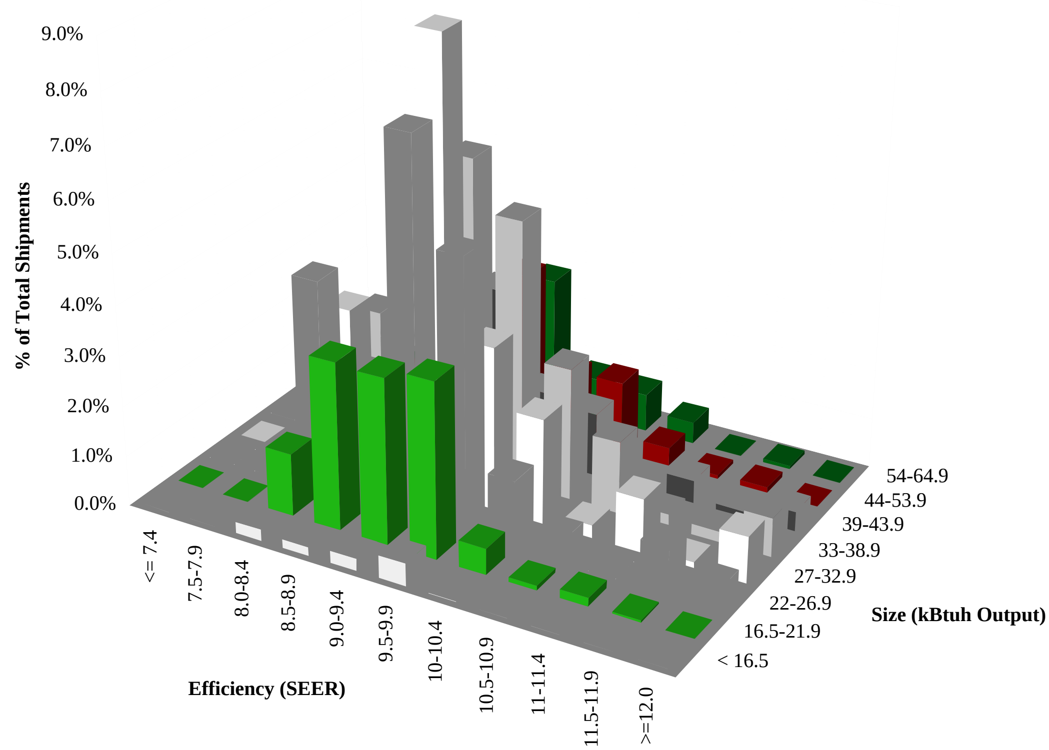



**Fig. C.4c: 1990 Residential Heat Pump Shipment Distribution by Size and Effic.**




(1) Source: ARI (1991).
(2) Residential Heat Pumps are defined as those < 65 kBtuh Output.
(3) The distributions shown include only split-systems.

## APPENDIX D: PEAK LOAD CALCULATIONS

Tables D.1 through D.4 show the data and regression lines for the calculation of peak loads based on annual loads. This calculation is necessary because the annual loads are available within the REEPS forecast as endogenous variables whereas the peak loads are not. We assumed that the peak heating and cooling loads could be expressed as a linear function of the respective annual loads in each region. There are separate functions for single-family homes and multifamily homes, as shown in the eight graphs. The resulting regression relations are used to estimate installed equipment capacity as a function of peak load for each heating/cooling system. The regression parameters are presented in Table 5.1 in the main text.

**Table D.1-N: SF North Heating Peak vs. Annual Load**

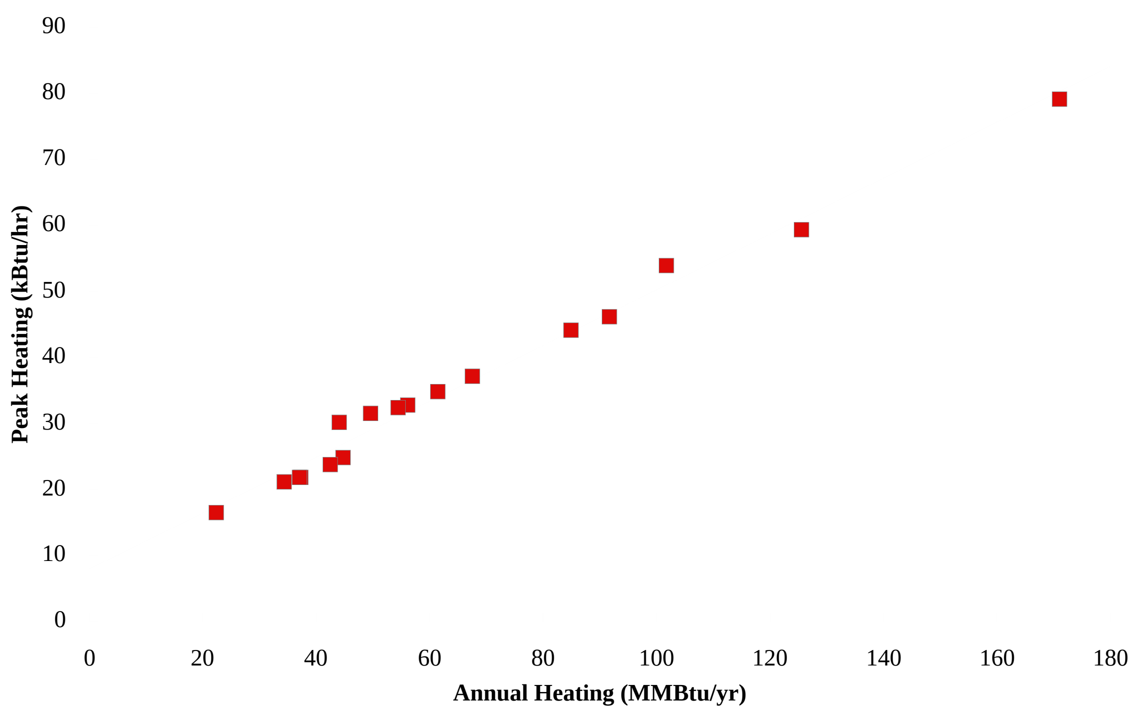
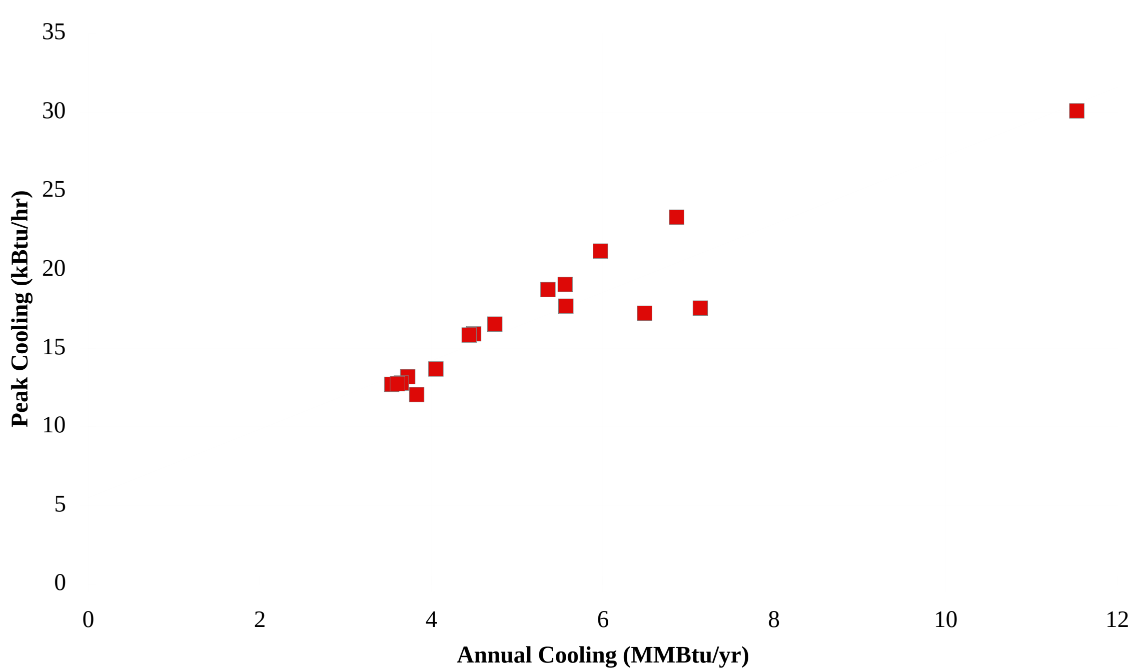
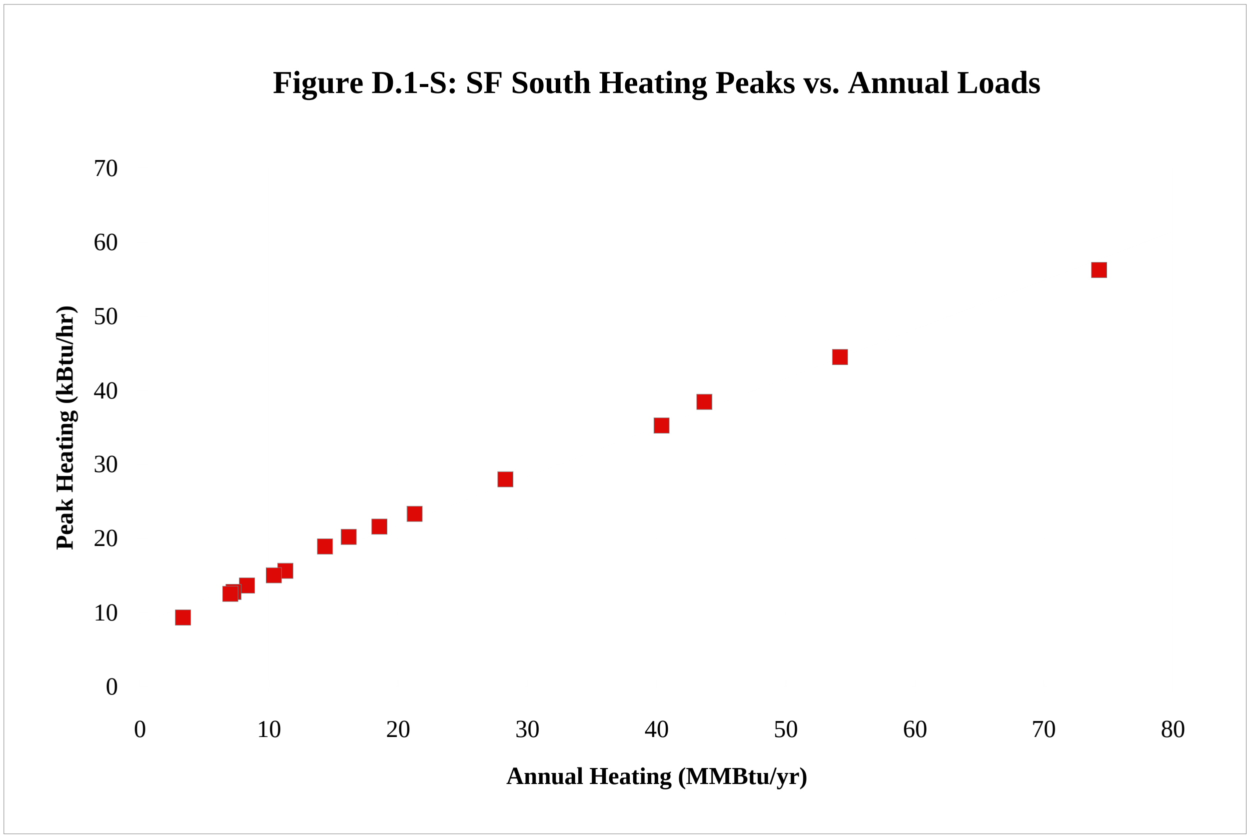
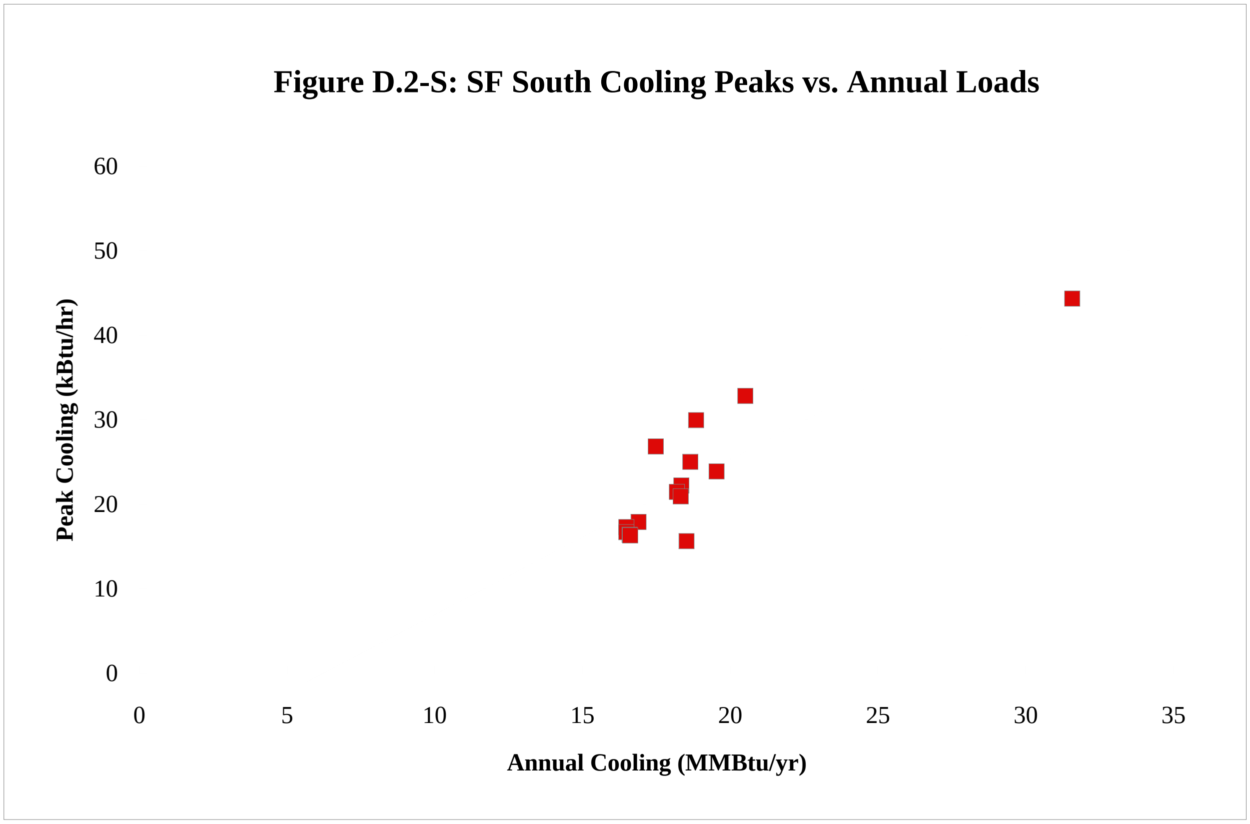



**Figure D.2-N: SF North Cooling Peak vs Annual Load**




(1) Source: Based on DOE-2 simulation runs for single-family prototypes of differing thermal integrity.




(1) Source: Based on DOE-2 simulation runs for prototypes of differing thermal integrity.

**Figure D.3-N: MF North Heating Peak vs. Annual Load**

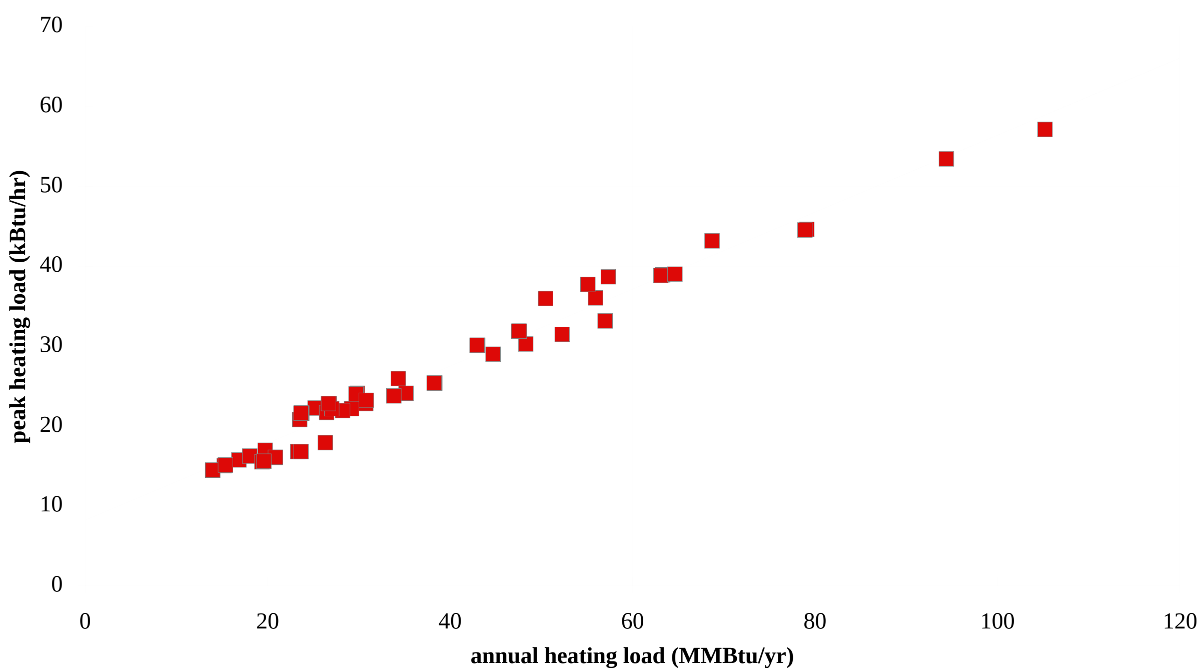
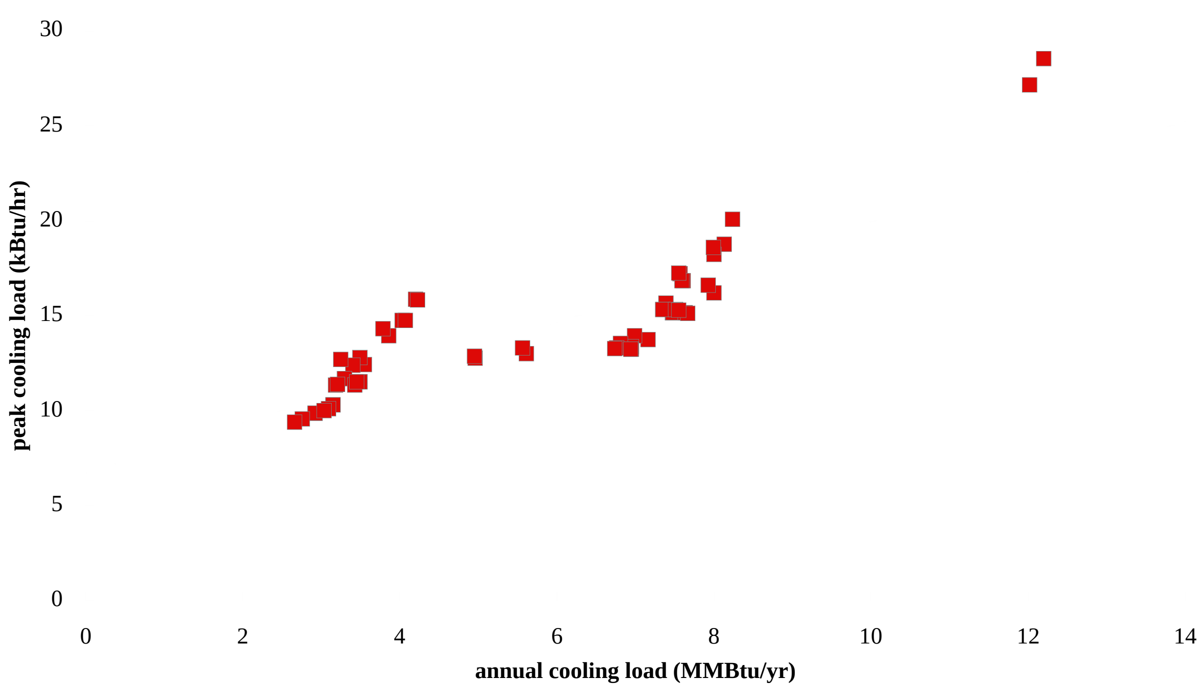
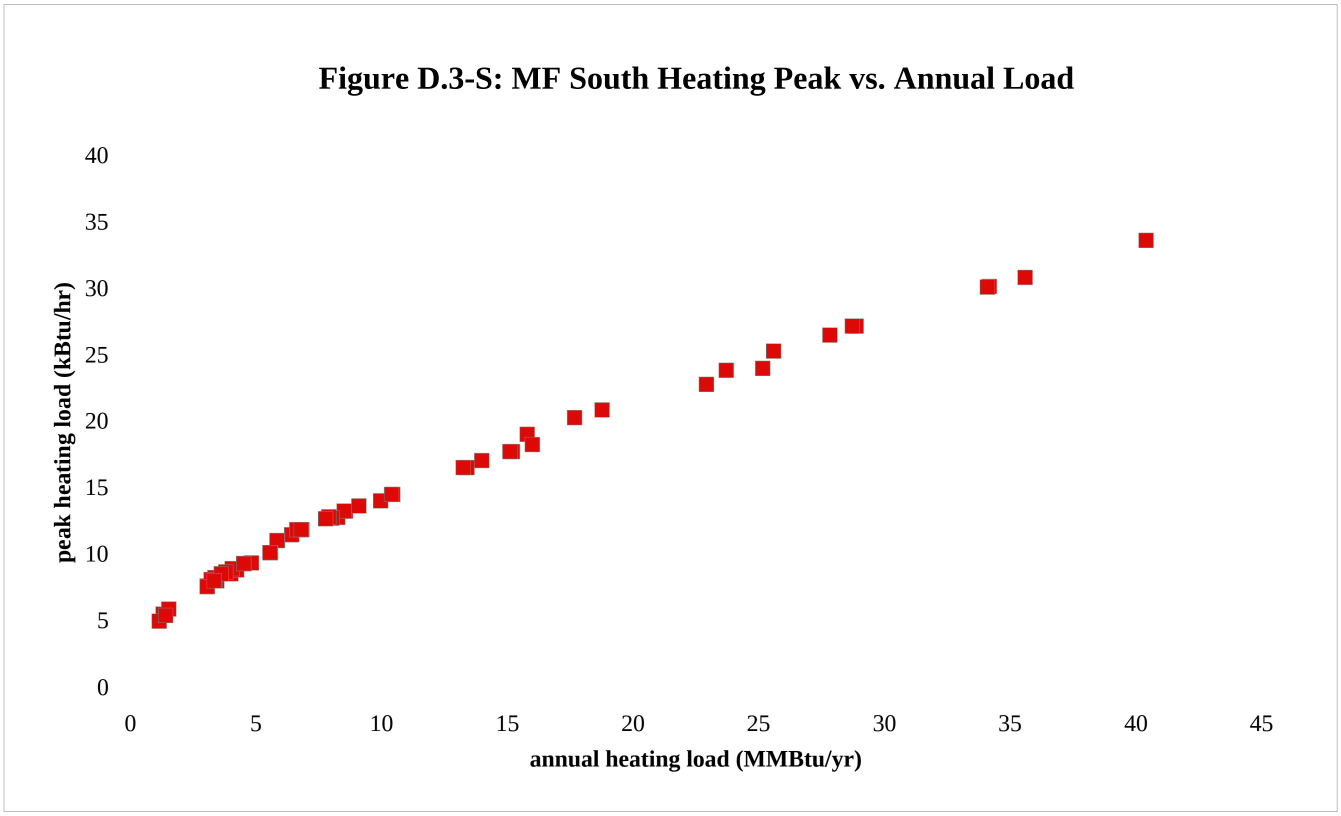
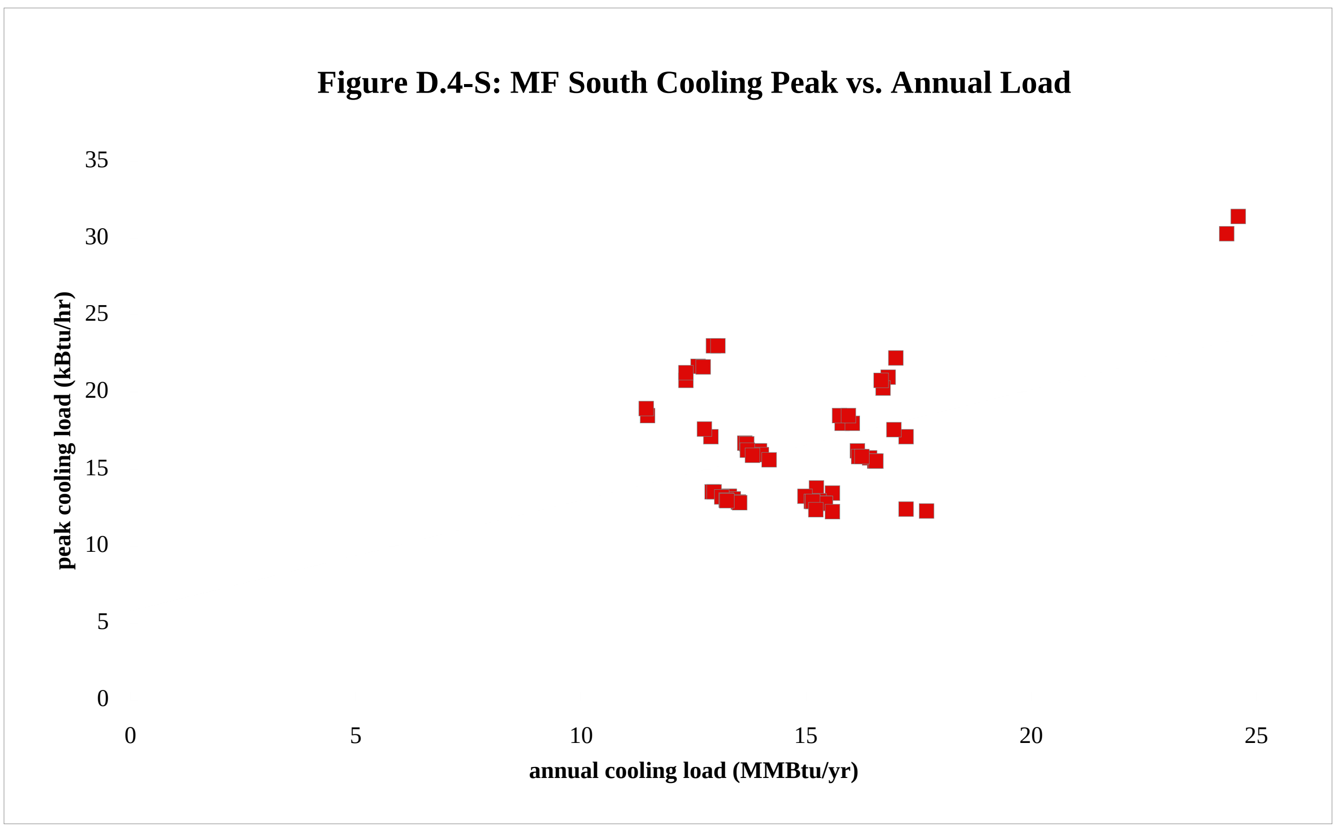



**Figure D.4-N: MF North Cooling Peak vs. Annual Load**




(1) Source: Based on DOE-2 simulation runs for multifamily prototypes of differing thermal integrity.



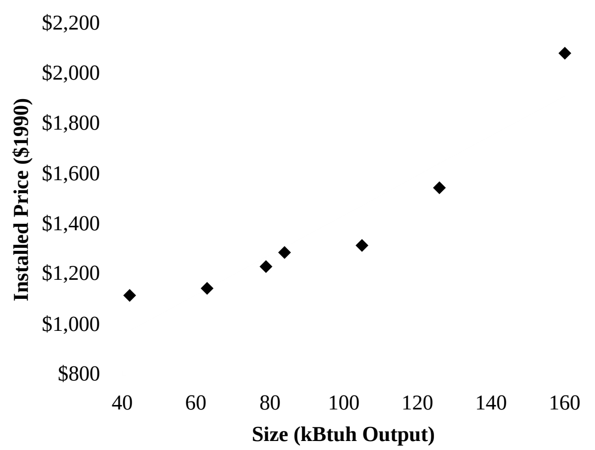

(1) Source: Based on DOE-2 simulation runs for multi-family prototypes of differing thermal integrity.

## APPENDIX E: EQUIPMENT PRICE DATA AND PARAMETER ESTIMATION

There were a number of different steps in the estimation of the heating and cooling equipment price models. As discussed in Section 5.3, REEPS estimates the purchase price of equipment as a function of size and efficiency. The purchase price includes both the price of the materials and the installation price. We calculated separately the installation price and material price to an HVAC subcontractor for various sizes of equipment (R.S. MEANS Co. 1991b) and deflated these prices from 1992 to 1990 dollars using a Purchaser Price Index for Appliances (US Bureau of Labor Statistics 1992). We added sales tax to the material price of the equipment, using the average value for the U.S. (R.S. MEANS Co. 1991c) of 4.6%. We added a subcontractor markup of 15-25% to the material and installation prices and then added a contractor markup of 10-15% to the total installed price.

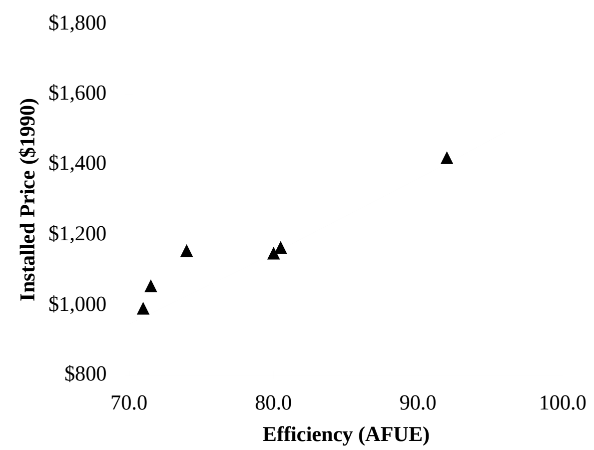
Next we assessed the relationship between price and efficiency for each equipment type. We determined the manufacturer price for models of a given size, but of varying efficiency (ADM 1987) and inflated these values to 1990 dollars again using the PPI for Appliances. We calibrated the values based on size to the values based on efficiency by assuming that the MEANS data is based on the average efficiency of equipment. This allowed us to develop an estimate of the "implicit" manufacturer markup in order to have a single function for each equipment type. This function was obtained by fitting a linear regression line to the price-size data and fitting a non-linear regression to the manufacturer price data with the implicit manufacturer markup. This process yielded parameters b, m, and $\varepsilon$ in Equation 5.4. The data points and regression line for the linear regressions are shown in Figures E.1a to E.7a while the data points and regression lines for the non-linear regressions are presented in Figures E.1b to E.7b. Figures E.1c to E.7c show a family of cost curves based on the estimated price-size and price-efficiency parameters for each technology.

**Figure E.1a: Gas Central Furnace Installed Price by Size**



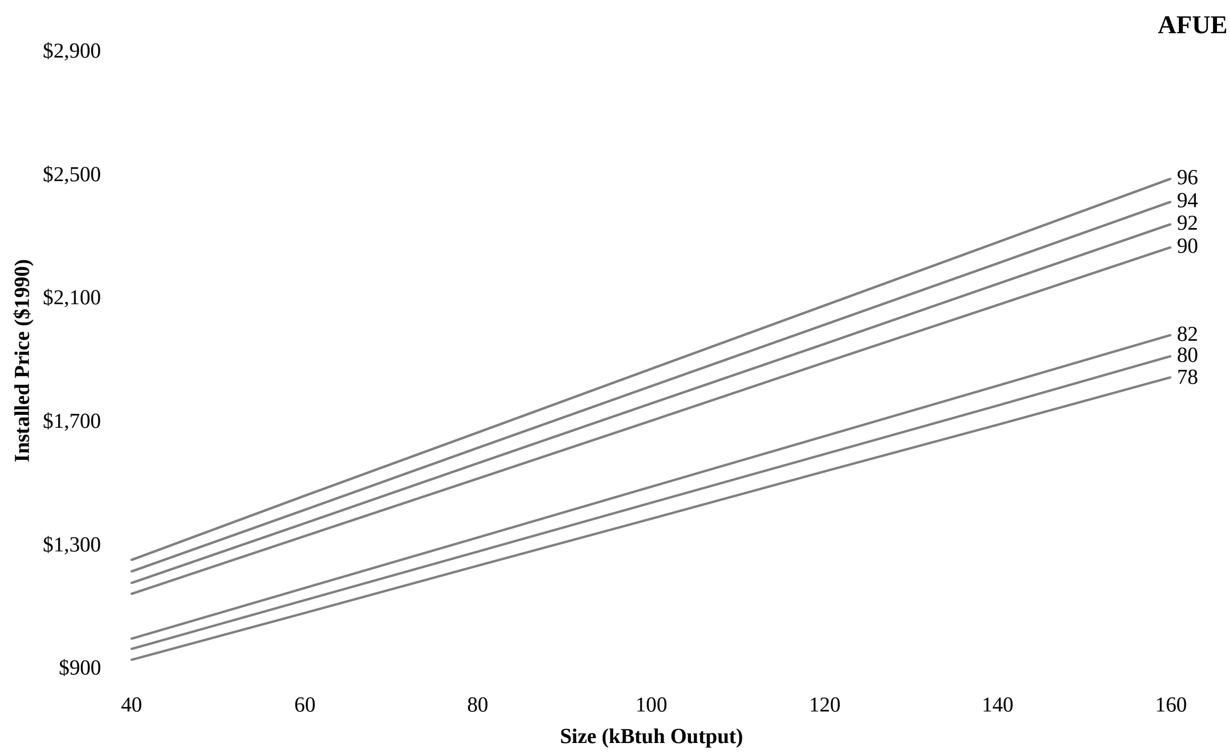

(1) Source: R.S. MEANS (1991c)
(2) Size refers to furnace output capacity in kBtuh.
(3) Prices based on models available in 1991.
(4) Linear regression curve based on the points shown.

**Figure E.1b: Gas Central Furnace Installed Price by Efficiency**



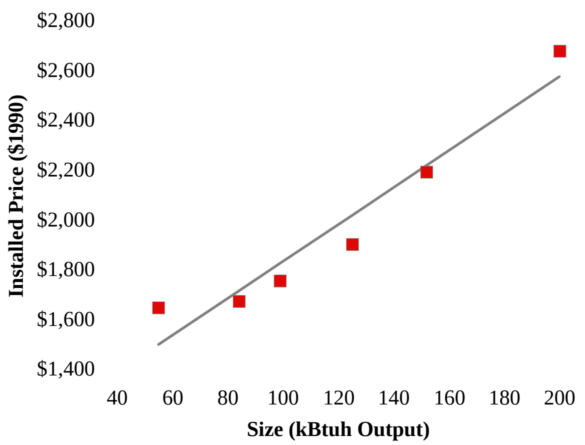

(1) Sources: ADM (1987); R.S. MEANS (1991c).
(2) AFUE is Annual Fuel Utilization Efficiency by DOE test procedures.
(3) Prices based on gas furnace with 80 kBtuh Input, 64 kBtuh Output.
(4) Non-linear regression curve based on the points shown.

**Figure E.1c: Gas Central Furnace Installed Price by Size and Efficiency**



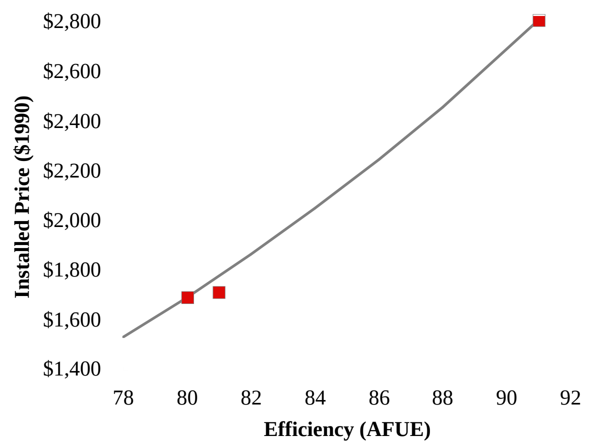

(1) Source: equipment price parameters in Table 5.3 as derived from the data shown above in Figures E.1a and E.1b.
(2) Installed price represents the purchase price of equipment to the final consumer (household), including both materials and labor.
(3) Prices associated with the distribution system, such as ducting, are not included here.
(4) Gas furnaces are often not available in the 82-90 AFUE range since condensing furnaces are generally > 90% AFUE.
(5) As of Jan. 1, 1992, appliance standards mandate a minimum 78% AFUE for residential (<225 kBtuh input) central gas furnaces.

**Figure E.2a: Oil Central Furnace Installed Price by Size**



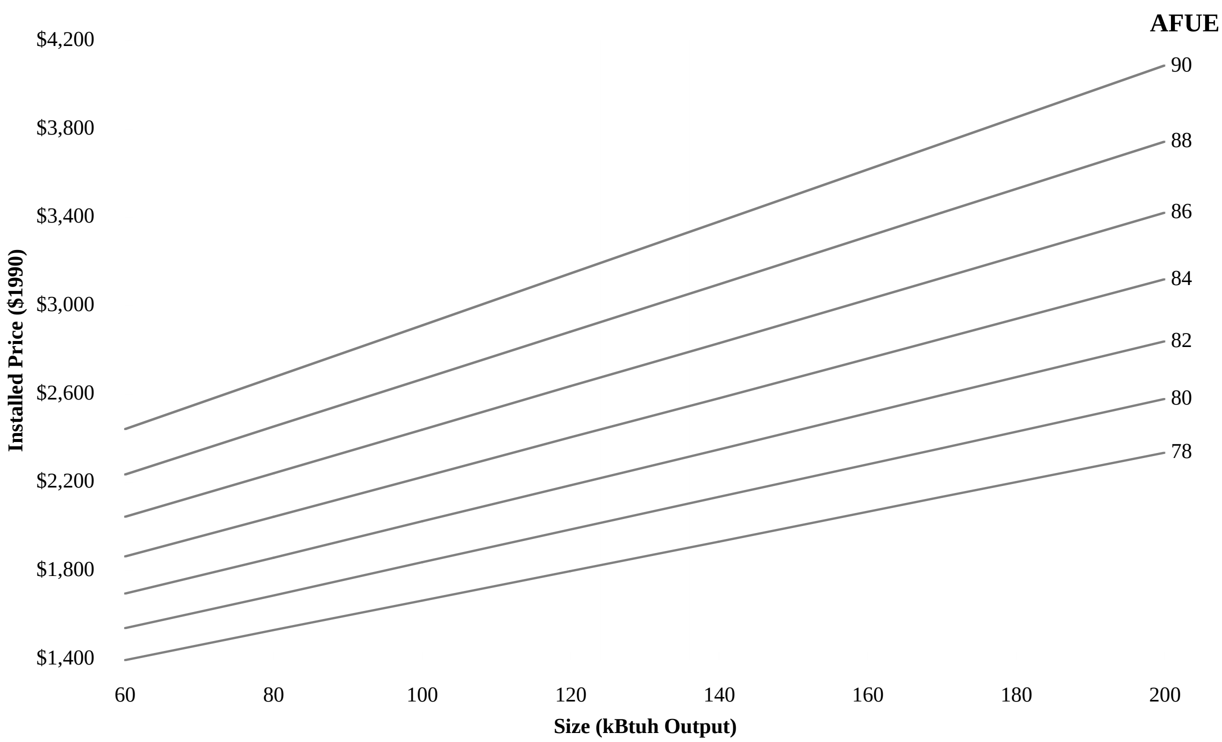

(1) Source: R.S. MEANS (1991c)
(2) Size refers to furnace output capacity in kBtuh.
(3) Prices based on models available in 1991.
(4) Linear regression curve based on the points shown.

**Figure E.2b: Oil Central Furnace Installed Price by Efficiency**



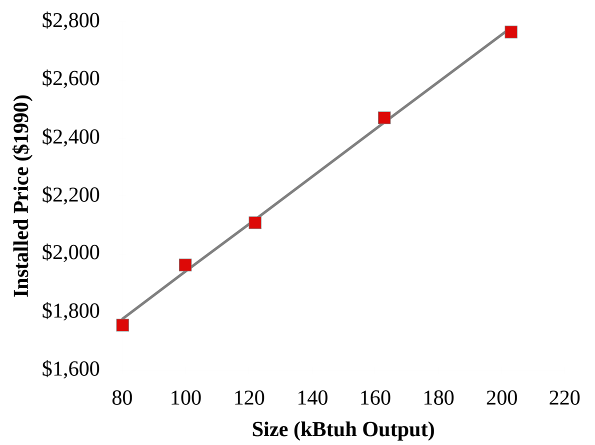

(1) Sources: ADM (1987); R.S. MEANS (1991c).
(2) AFUE is Annual Fuel Utilization Efficiency by DOE test procedures.
(3) Prices based on oil furnace with 105 kBtuh Input, 87 kBtuh Output.
(4) Non-linear regression curve based on the points shown.

**Figure E.2c: Oil Central Furnace Installed Price by Size and Efficiency**



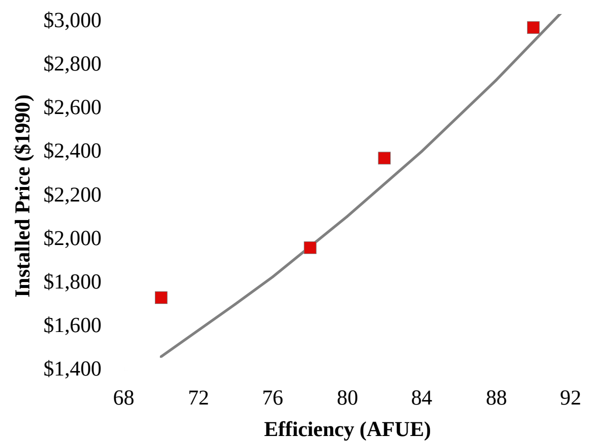

(1) Source: equipment cost parameters in Table 5.3 as derived from the data shown above in Figures E.2a and E.2b.
(2) Installed price represents the purchase price of equipment to the final consumer (household), including both materials and labor.
(3) Prices associated with the distribution system, such as ducting, are not included here.
(4) There are currently no listed oil furnace models available that are > 90% AFUE (GAMA 1991a).
(5) As of Jan. 1, 1992, appliance standards mandate a minimum 78% AFUE for residential (<225 kBtuh input) central oil furnaces.

**Figure E.3a: Gas Boiler Installed Price by Size**



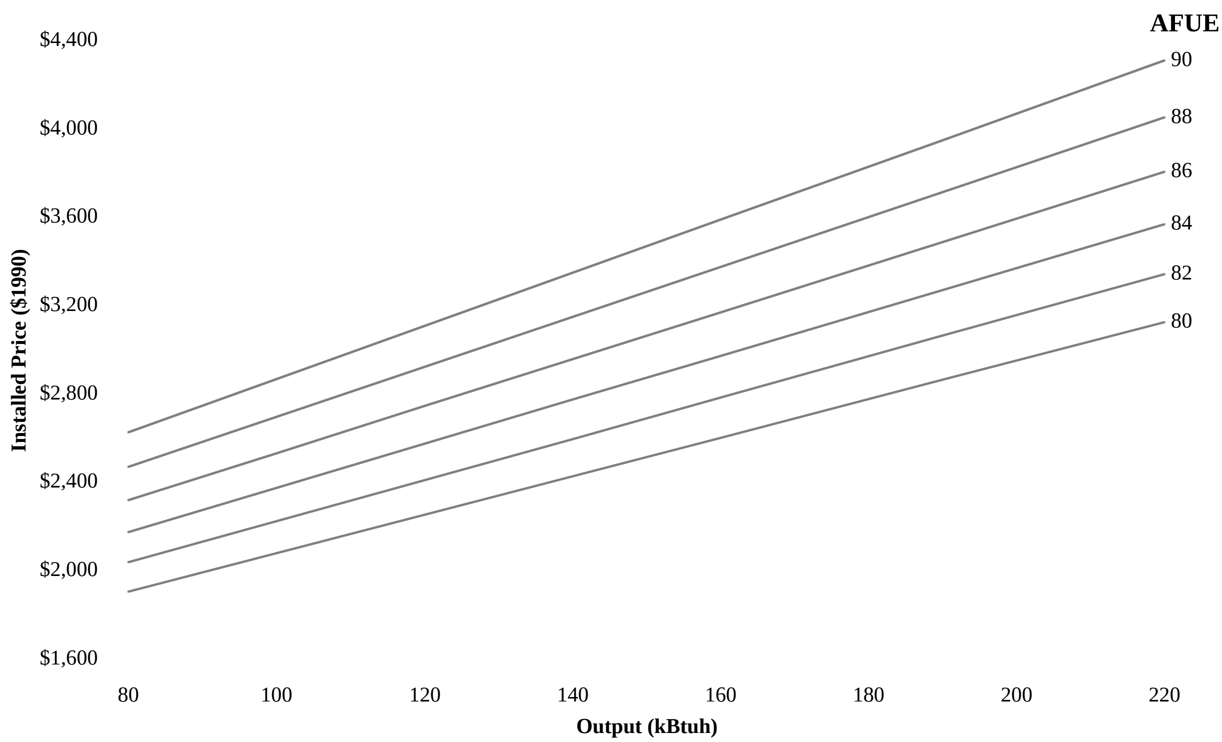

(1) Source: R.S. MEANS (1991b)
(2) Size refers to boiler output capacity in kBtuh.
(3) Prices are for cast-iron hot-water gas boiler models available in 1991.
(4) Linear regression curve based on the points shown.

**Figure E.3b: Gas Boiler Installed Price by Efficiency**

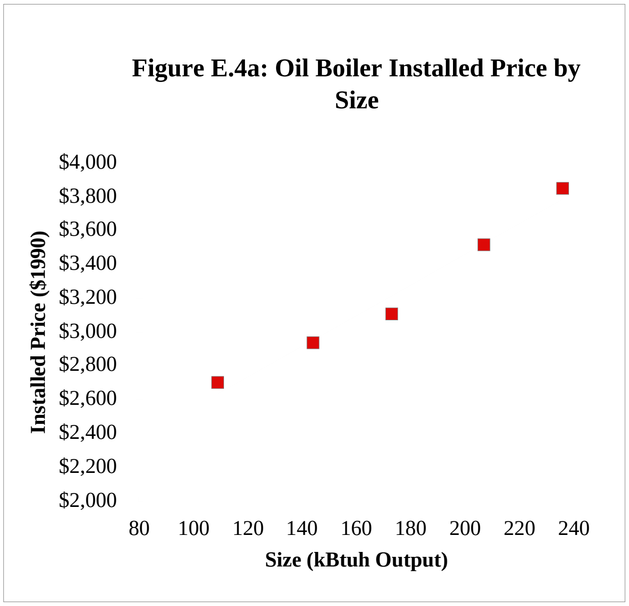



(1) Sources: ADM (1987); R.S. MEANS (1991b).
(2) AFUE is Annual Fuel Utilization Efficiency by DOE test procedures.
(3) Prices for gas hot-water boiler, 125 kBtuh Input, 100 kBtuh Output.
(4) Non-linear regression curve based on the points shown.

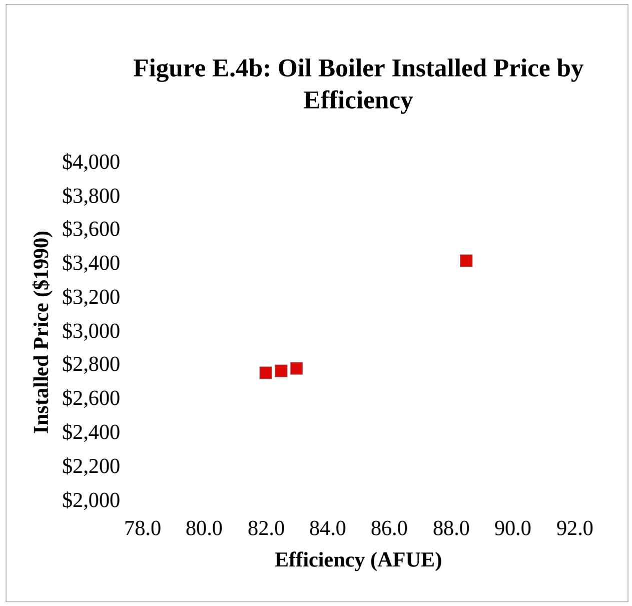
**Figure E.3c: Gas Boilers Installed Price by Size and Efficiency**



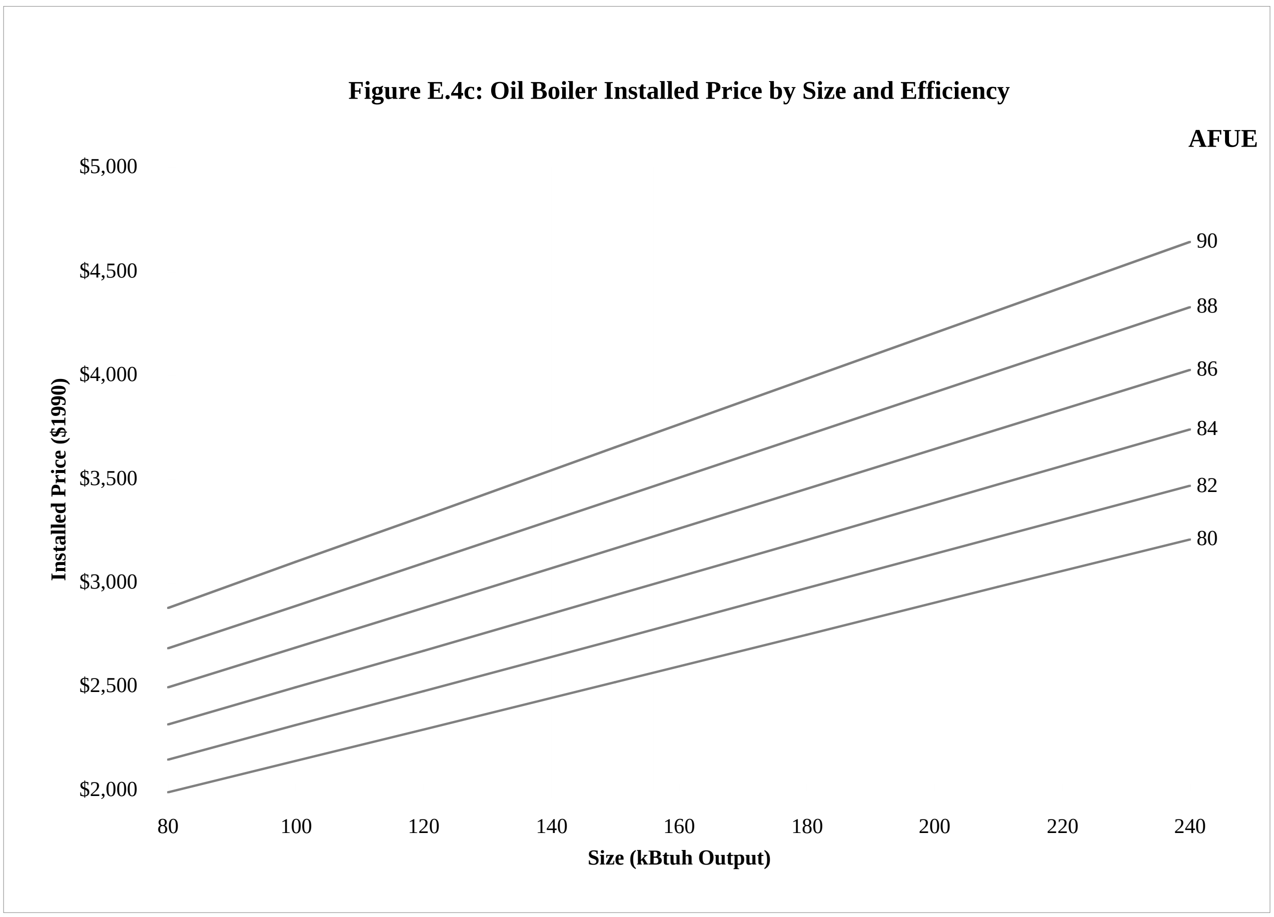

(1) Source: equipment cost parameters in Table 5.3 as derived from the data shown above in Figures E.3a and E.3b.
(2) Installed price represents the purchase price of equipment to the final consumer (household), including both materials and labor.
(3) Prices associated with the distribution system, such as radiators or piping, are not included here.
(4) There were no hot-water cast-iron boiler models > 90% AFUE in the model directory (Hydronics Institute 1992)
(5) As of Jan. 1, 1992, appliance standards mandate a minimum 80% AFUE for residential (<300 kBtuh input) hot-water boilers.




(1) Source: R.S. MEANS (1991b)
(2) Size refers to boiler output capacity in kBtuh.
(3) Prices are for cast-iron hot-water oil boiler models available in 1991.
(4) Linear regression curve based on the points shown.

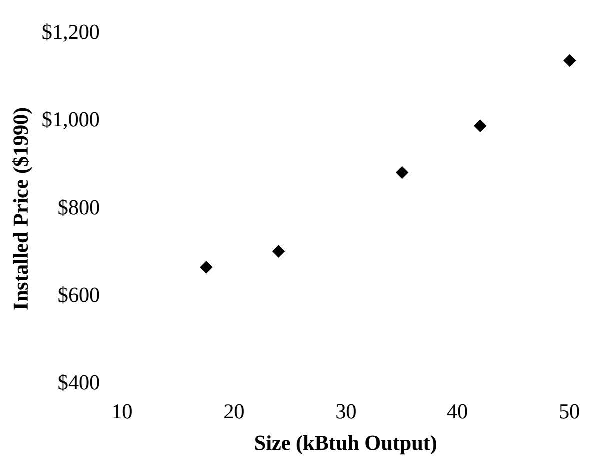



(1) Sources: ADM (1987); R.S. MEANS (1991b).
(2) AFUE is Annual Fuel Utilization Efficiency by DOE test procedure.
(3) Prices for oil hot-water boiler, 125 kBtuh Input, 100 kBtuh Output.
(4) Non-linear regression curve based on the points shown.



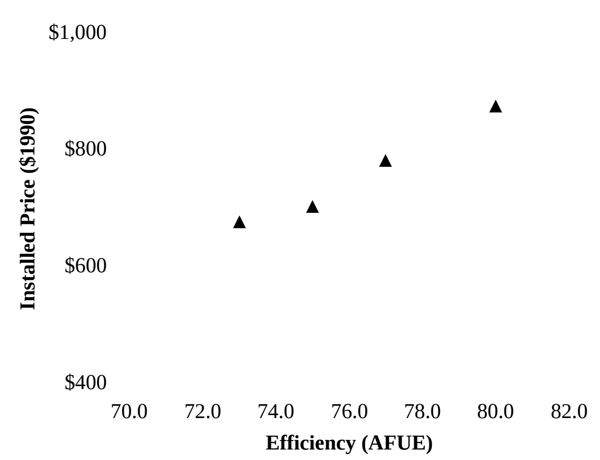

(1) Source: equipment cost parameters in Table 5.3 as derived from the data shown above in Figures E.4a and E.4b.
(2) Installed price represents the purchase price of equipment to the final consumer (household), including both materials and labor.
(3) Prices associated with the distribution system, such as radiators or piping, are not included here.
(4) There were no hot-water cast-iron boiler models >90% AFUE in the model directory (Hydronics Institute 1992).
(5) As of Jan. 1, 1992, appliance standards mandate a minimum 80% AFUE for residential (<300 kBtuh input) hot-water boilers.

**Figure E.5a: Gas Wall Furnace Installed Price by Size**



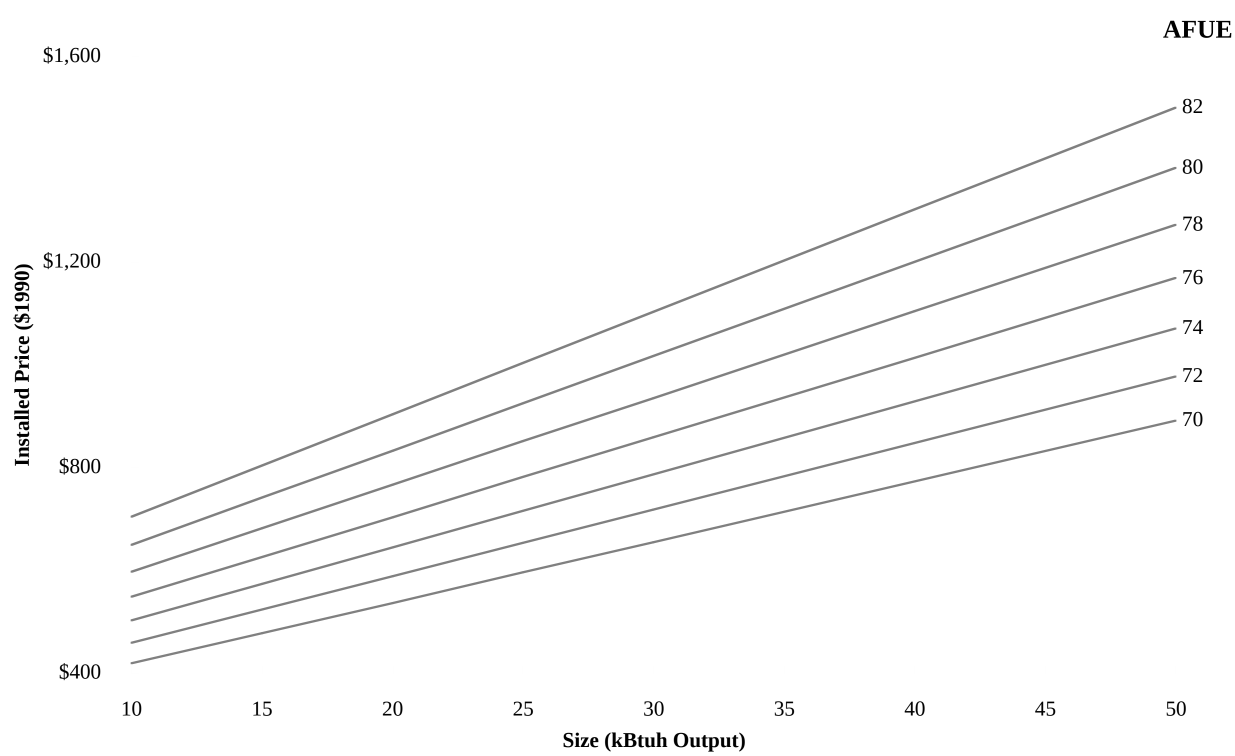

(1) Source: R.S. MEANS (1991c)
(2) Size refers to furnace output capacity in kBtuh.
(3) Prices based on models available in 1991.
(4) Linear regression curve based on the points shown.

**Figure E.5b: Gas Wall Furnace Installed Price by Efficiency**

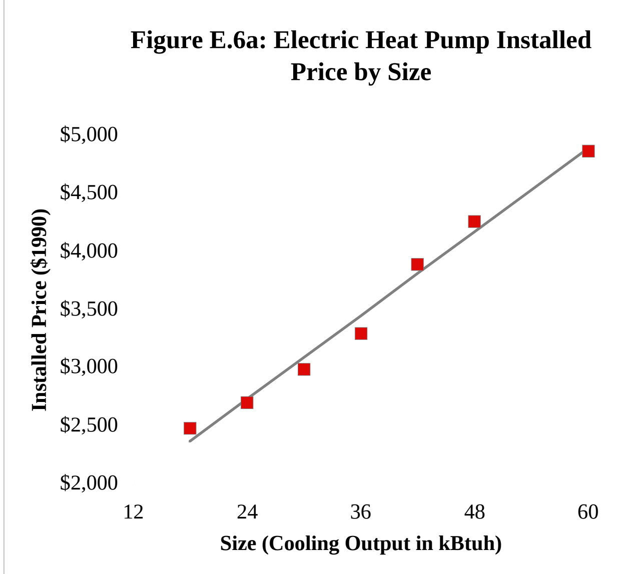



(1) Sources: ADM (1987); R.S. MEANS (1991c).
(2) AFUE is Annual Fuel Utilization Efficiency by DOE test procedure.
(3) Prices for forced-air wall furnace, 30 kBtuh Input, 24 kBtuh Output.
(4) Non-linear regression curve based on the points shown.

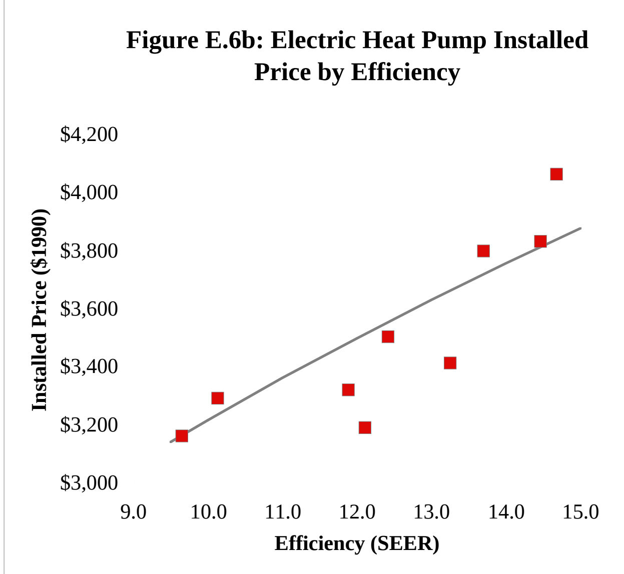
**Figure E.5c: Gas Wall Furnace Installed Price by Size and Efficiency**



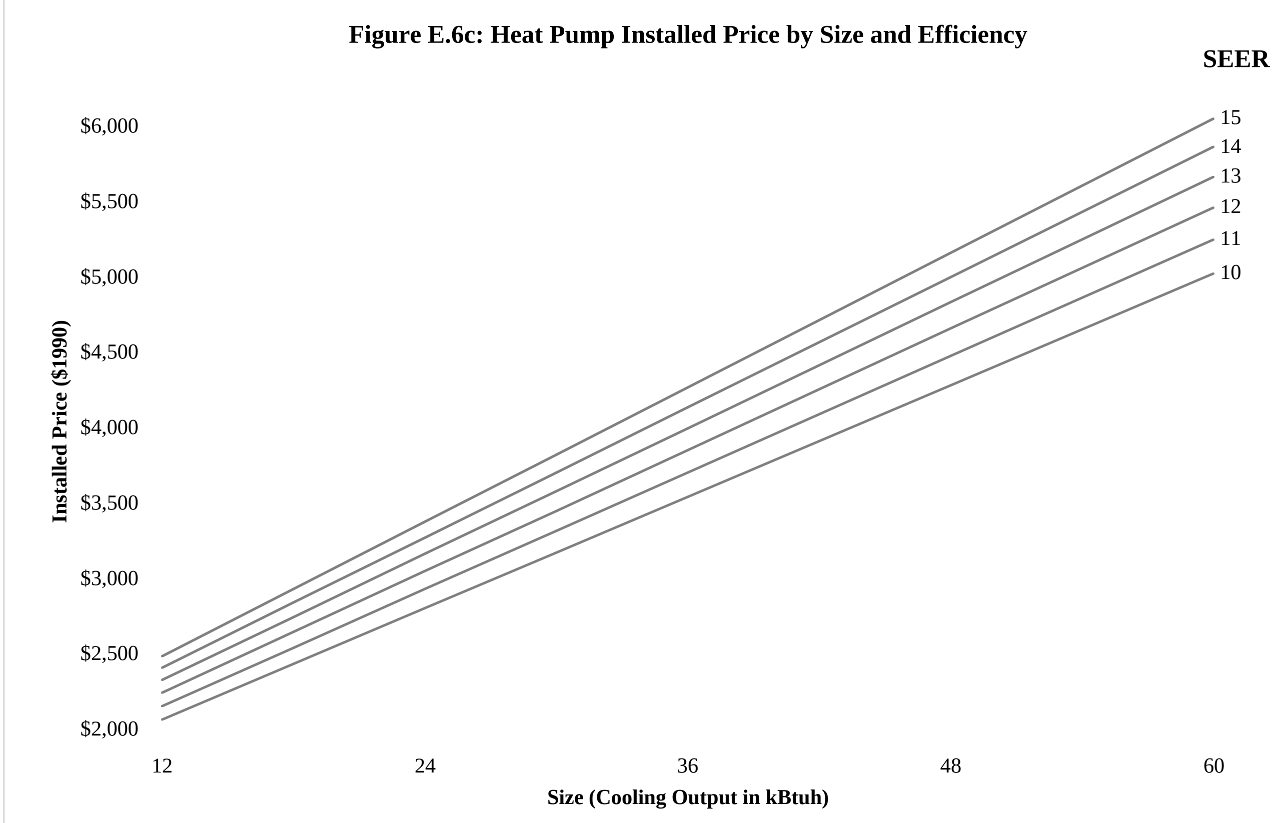

(1) Source: equipment cost parameters in Table 5.3 as derived from the data shown above in Figures E.5a and E.5b.
(2) Installed price represents the purchase price of equipment to the final consumer (household), including both materials and labor.
(3) Gravity wall furnaces cost approximately 40% less than Forced-Air Wall Furnaces and have 10% lower AFUE for a given size (EPRI 1987).
(4) Gas Wall Furnaces represent approximately 65% of the total market for non-central residential home heating equipment (GAMA 1992).
(5) As of Jan. 1, 1990, NAECA mandated a minimum 56-74% AFUE for residential home heating equipment, depending on product class and size.




(1) Source: R.S. MEANS (1991c)
(2) Size refers to heat pump cooling output capacity in kBtuh.
(3) Prices based on models available in 1991.
(4) Linear regression curve based on the points shown.

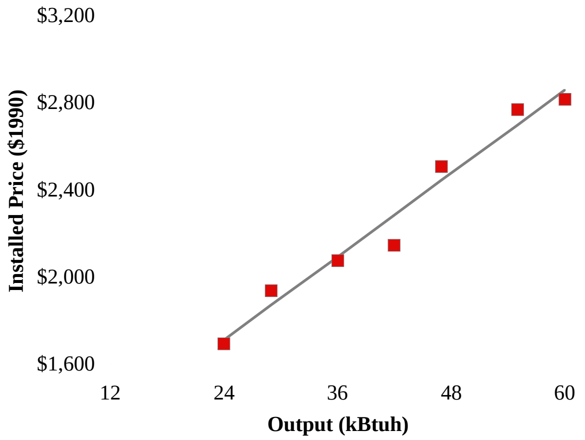



(1) Sources: ADM (1987); R.S. MEANS (1991c).
(2) SEER is Seasonal Energy-Efficiency Ratio by DOE test procedures.
(3) Prices are for split-system heat pump with 36 kBtuh cooling output.
(4) Non-linear regression curve based on the points shown.



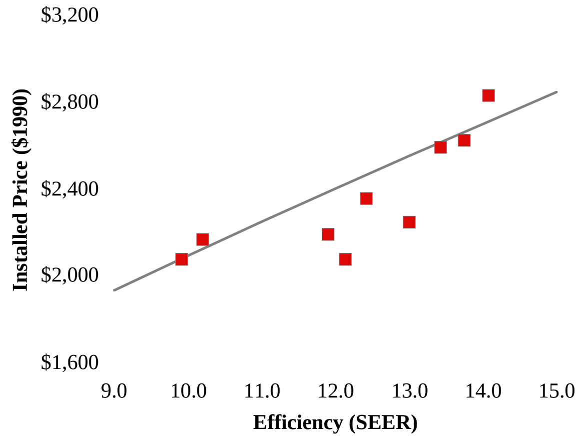

(1) Source: equipment cost parameters in Table 5.3 as derived from the data shown in Figures E.6a and E.6b.
(2) Installed price represents the purchase price of equipment to the final consumer (household), including both materials and labor.
(3) Prices associated with the distribution system, such as ducting, are not included here.
(4) Data are for split-system air-source electric heat pumps.
(5) As of Jan. 1,1992, appliance standards mandate a minimum SEER of 10.0 for residential (<65 kBtuh) split-system heat pumps.

**Figure E.7a: Central Air Conditioning Installed Price by Output Capacity**



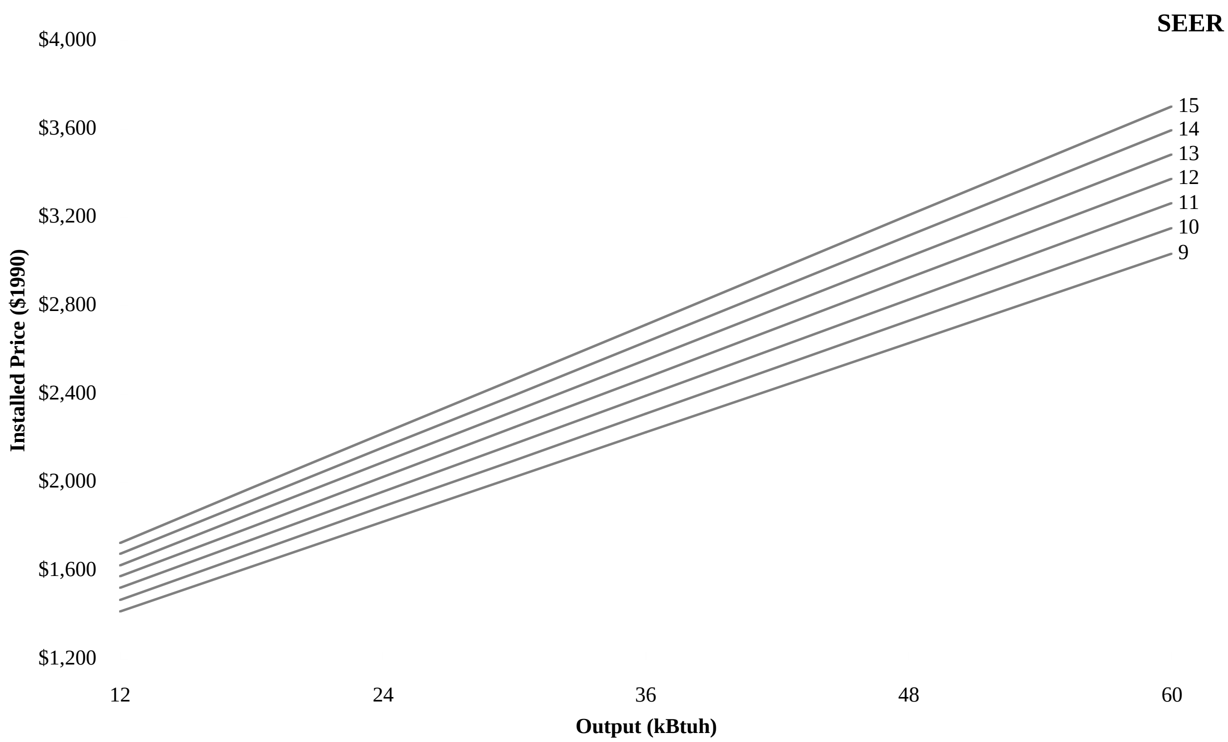

(1) Source: R.S. MEANS (1991c)
(2) Size refers to central air output capacity in kBtuh.
(3) Prices based on models available in 1991.
(4) Linear regression curve based on the points shown.

**Figure E.7b: Central Air Cond. Installed Price by Efficiency**




(1) Sources: ADM (1987); R.S. MEANS (1991c).
(2) SEER is Seasonal Energy-Efficiency Ratio by DOE test procedures.
(3) Prices based on split-system central air with 36 kBtuh output.
(4) Non-linear regression curve based on the points shown.

**Figure E.7c: Central Air Conditioning Installed Price by Size and Efficiency**




(1) Source: equipment cost parameters in Table 5.3 as derived from the data shown in Figures E.7a and E.7b.
(2) Installed price represents the purchase price of equipment to the final consumer (household), including both materials and labor.
(3) Prices associated with the distribution system, such as ducting, are not included here.
(4) Data are for split-system air-source central air conditioners.
(5) As of Jan. 1,1992, appliance standards mandate a minimum SEER of 10.0 for residential (<65 kBtuh) split-system central air conditioners.

## APPENDIX F: REGIONAL HVAC SYSTEM CHOICE MODELS

In addition to the National HVAC system choice model documented in Section 6.3, we have also estimated separate logit parameters for North and South HVAC models. The procedures we used to estimate the regional parameters are very similar to the procedures used in the National version, as described in Section 6.3. In fact, the steps required to prepare the data for the logit estimation are nearly identical. The main difference lies in the econometric estimation method itself. A maximum likelihood estimation technique using the SST statistical program (Dubin and Rivers 1988) was used rather than Berkson's method. We believe that Berkson's method is more appropriate for grouped data, but we were not aware of this specialized technique at the time these regional estimations were performed.

As is the case with the National HVAC equipment choice model, only aggregate (and averaged) data were available to estimate the regional models. Consequently, we developed a grouped data set based on the market share of heating equipment in new homes (1980s) in the 1990 RECS, and applied a multinomial logit algorithm to this data set to estimate the decision model parameters. The average heating load for each system was calculated from the thermal shells and component loads specified in Section 3, to which we applied the peak heating load equation and sizing factors from Section 5.1 in order to determine installed equipment sizes. The purchase price for each system was based on this calculated size and the average efficiency for each equipment type, using Equation 5.4. The operating expense was determined from the UEC for each technology, using Equation 6.5. The resulting data sets are shown in Tables F.1 and F.3. These data were then used to estimate a suitable set of parameters according to the standard utility equation from Equation 6.1. Appendix G provides more detail on the supporting theory used in the model estimation.

We experimented extensively to obtain reasonable estimates, testing various specifications of alternative-specific constants as well as different definitions of the price variables. With our data, the constants serve in several cases to ensure that the signs of the price coefficients are negative (the most basic criteria for evaluating the estimates, as noted previously). In several cases, as the data in Tables F.1 and F.3 indicate, a system option that dominates one or more other options in both price elements (in other words, has a higher life-cycle cost at any positive discount rate) is observed to have a higher market share. This indicates the presence of significant unobserved factors in consumers' choices. In such cases, assigning a constant to either the dominated or dominating option may be necessary to obtain sensible results.

In order to estimate the parameters, the equipment prices were normalized to the average annual heating loads. For example, a gas furnace with purchase price of $2000 in a region with a heating load of 100 MMBtu would have a normalized purchase price of 2000/100 = $20/MMBtu. Previous studies have found that such a normalization is necessary to obtain reasonable estimates (Dubin 1985, Goett 1990). For single-family dwellings, the model parameters (including price coefficients and, as appropriate, alternative-specific constants) were computed for north and south regions of the U.S. and for two cooling choices (central air and no central air), yielding a total of four sets of parameters.. The resulting parameter estimates are presented in Tables F.2 and F.4. Data limitations (specifically, a number of zero market shares for certain choices) precluded the same level of estimation detail for the other dwelling types (multifamily and mobile home)

| **Table F.1: Data Used to Estimate Regional Single-Family Heating Choice Model, given Central Air Conditioning** | | | |
|---|---|---|---|
| | **Market Share (percent)** | **Purchase Price (1990$/MMBtu)** | **Operating Expense (1990$/MMBtu)** |
| **North** | | | |
| Electric Furnace | 5.1 | 78.27 | 18.51 |
| Gas Furnace | 68.5 | 58.93 | 5.00 |
| Oil Furnace | 2.7 | 62.94 | 6.22 |
| Gas Hydronics | 4.3 | 132.75 | 6.14 |
| Other | 0.4 | 78.35 | 8.14 |
| Electric Heat Pump | 19.0 | 86.88 | 10.66 |
| **South** | | | |
| Electric Furnace | 12.5 | 186.99 | 21.48 |
| Gas Furnace | 48.5 | 106.02 | 30.14 |
| Gas Hydronics | 0.3 | 237.03 | 47.82 |
| Other | 0.7 | 143.43 | 28.96 |
| Electric Heat Pump | 37.9 | 143.81 | 13.80 |

(1) Shares are of households with central air from 1990 RECS (EIA 1993).
(2) Prices and operating expenses are normalized to the average annual heating load (MMBtu) in order to yield reasonable logit parameter estimates.

| **Table F.2: Estimated Coefficients of Single-Family HVAC Equipment Choice Model, Given Central Air Conditioning** | | | |
|---|---|---|---|
| **Region** | **Purchase Price** | **Operating Expense** | **r** |
| North | -0.031 | -0.126 | 24.6% |
| South | -0.0321 | -0.7436 | 4.3% |

(1) The implicit discount rate, r, is calculated assuming infinite device lifetime, using Equation 6.2.
(2) Analysis is based on market share data from 1990 RECS (EIA 1993) and equipment price and operating expense estimation methods described in Section 6.3.

| **Table F.3: Data Used to Estimate Regional Single-Family Heating Choice Model, Given No Central Air Conditioning** | | | |
|---|---|---|---|
| | **Market Share (percent)** | **Purchase Price (1990$/MMBtu)** | **Operating Expense (1990$/MMBtu)** |
| **North** | | | |
| Gas Furnace | 61.4 | 58.93 | 5.00 |
| Gas Hydronics | 6.4 | 82.54 | 6.14 |
| Oil Hydronics | 8.6 | 82.99 | 8.06 |
| Electric Room | 14.2 | 26.36 | 18.51 |
| Gas Room | 0.6 | 14.38 | 4.86 |
| Other | 8.8 | 15.11 | 8.14 |
| **South** | | | |
| Gas Furnace | 72.4 | 106.02 | 30.14 |
| Oil Furnace | 5.2 | 114.33 | 34.78 |
| Electric Room | 15.1 | 53.73 | 21.48 |
| Other | 7.3 | 27.67 | 28.96 |
| (1) Shares are of households without central air from 1990 RECS (EIA 1993).<br>(2) Prices and operating expenses are normalized to the average annual heating load (MMBtu) in order to yield reasonable logit parameter estimates. | | | |

| **Table F.4: Estimated Coefficients of Single-Family HVAC Equipment Choice Model, Given No Central Air Conditioning** | | | | | |
|---|---|---|---|---|---|
| **Region** | **Purchase Price** | **Operating Expense** | **Constant (Gas Room)** | **Constant (Other)** | **r** |
| North | -0.0635 | -0.2587 | -7.7828 | -3.8923 | 24.6% |
| South | -0.0281 | -0.0380 | na | na | 73.9% |
| (1) The implicit discount rate, r, is calculated assuming infinite device lifetime, using Equation 6.2.<br>(2) Analysis is based on market share data from 1990 RECS (EIA 1993) and equipment price and operating expense estimation methods described in Section 6.3.<br>(3) The constants are additive, and only apply to the utility equation (Equation 6.1) of the specified equipment option. | | | | | |

## APPENDIX G: QUALITATIVE CHOICE ANALYSIS

Qualitative Choice Analysis (QCA) provides the theoretical framework for the HVAC decision models we adopted in this analysis. In this appendix, we provide a brief overview of several key ideas of QCA. The material herein is taken primarily from Train (1986) and from notes from a workshop sponsored by the Econometrics Laboratory on the U.C. Berkeley campus (McFadden et al. 1992).

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Two of the hallmarks of neo-classical economic analysis are a focus on aggregate – that is, market-level-phenomena and the assumption of continuity (and usually differentiability) of the variables under study. The latter assumption is reflected both in the basic theory of consumer choice, including the assumption of smooth indifference curves, and in the econometric estimation of market demand functions; at the market level, where individual differences are too fine to be captured, the modeling assumption of continuity is generally thought to be a good approximation to reality.

It is arguable, however, that 1) phenomena such as aggregate demand, being just the sum of many individual decisions, should ideally be studied with methods that explicitly capture individual-level behavior, and 2) at the level of the individual, many if not most real-life choices have a discrete rather than continuous quality to them. Thus, for example, a consumer buying a refrigerator will ultimately choose between, for example, manual defrost and auto defrost, rather than some combination of the two. In buying a car, a consumer must ultimately purchase a Toyota or a Honda or a Ford or a Chevrolet--not some combination of the four. Qualitative choice analysis was devised for the economic analysis of such situations. Train describes QCA as "[one of a variety of] methods for examining the behavior of individuals when continuous methods are inappropriate." "Methods" here refers to both a theoretical or conceptual approach to the choice problem and to the econometric techniques that have been developed for this type of analysis.

Before providing a more technical description of these methods, an informal discussion may be helpful. To begin, the individual ("consumer") is seen, as suggested above, as choosing one from among a number of discrete alternatives. The individual is conceived of as a decision-making "black box:" she evaluates the options in terms of their various features as well as her own preferences, and chooses what she considers the best alternative (in economic terms, the one that maximizes her utility). So for example, she may be choosing between a manual and an auto-defrost refrigerator; she will (in some manner that is left unspecified) evaluate, for example, the purchase prices, operating costs, convenience features, colors, styles, and possibly other features, and then choose one in a way that may also depend on such factors as her income or beliefs. Several things about this picture deserve emphasis. First, exactly "how" the decision is made--for example, the psychological process involved--is essentially ignored by saying that the decision is a matter of "maximizing utility." (This approach is, of course, characteristic of economic modeling.) Furthermore, in this way in thinking, the decision-maker is a *deterministic* black box; that is, the output (the decision) is a non-probabilistic function of the inputs (the features of the alternatives and her own characteristics).

As the reader may know, however, QCA models themselves are probabilistic in nature. The idea is that the observer cannot possibly see everything that went into the decision, such as "beliefs." So the observer can, in principle, predict only imperfectly what decision will be made even knowing such things as certain characteristics of the alternatives and the decision-maker. The probabilistic elements of QCA arise from this state of partial ignorance of the observer. In particular, the aim of QCA models is not to elicit or to study (directly, at least) the form of the function transforming inputs into decisions. Rather, *it is to derive numerical estimates of the probabilities that the decision-maker will make various choices, given certain assumptions about (among other things) the form of the decision-maker's utility function, and given observations of the decision-maker's actual choices and information about the decision-maker herself.* There are several interpretations of what concept of "probability" is at work here. One can think, for example, of a decision-maker repeatedly facing the same choice; then the probability that a particular alternative will be chosen can be interpreted as the limiting proportion of the number of times that alternative is in fact chosen as the number of repeats becomes "large." Or, one can think of a number of decision-makers with the same observable characteristics being observed, sequentially, facing the same choice situation; then the probability can again be interpreted as a limiting proportion. The point is, again, that the probabilistic nature of the models is interpreted in terms of the relationship between the observer and the decision-maker; QCA models are *not* models of "decision-making under uncertainty" as these are typically defined in economics or operations research.

To begin a more precise description, the technical specification of the decision-maker's situation is that the possible alternatives form a *finite partition* of her universe of choice, that is, the alternatives are a) finite in number, b) mutually exclusive, and c) exhaustive (that is, she must choose one and only one alternative). It is often possible to adjust the model so that these conditions are satisfied in situations in which they are not readily apparent.

Now suppose one wishes to analyze some such situation, for example, a choice among appliances or cars. Following is a description of the generic qualitative choice model (Train's notation will be used for the duration). A particular decision-maker will be indicated by the index $n$.. Denote the set of alternatives she faces by $J_n$, the observed (by the researcher) characteristics of alternative $i$ as faced by decision-maker $n$ as the vector $z_{in}$, and the observed characteristics of the decision-maker as the vector $S_n$. Then the probability that decision-maker $n$ chooses alternative $i$ is a parametric function of the form

$$P_{in} = f(z_{in}, z_{jn} \forall j \in J_n, j \neq i, s_n, \beta),$$

where the expression "$\forall j \in J_n$" means "for all $j$ in $J_n$," and $\beta$ is a vector of parameters. This equation describes, conceptually, the overall framework of QCA analysis. The details and the applications have to do primarily with first specifying the function $f$ and then estimating the vector of parameters.

The first step in implementing this abstract framework is to examine more carefully the relation between what the decision-maker is doing and what the observer is seeing, and to introduce notation that reflects this distinction between "observable" and "unobservable." We write the utility that decision-maker $n$ derives from selecting alternative i as a function of $x_{in}$, the relevant characteristics of the alternative, and $r_n$, the relevant characteristics of the decision-maker; thus,

$$U_{in} = U(x_{in}, r_n)$$

for all $i$ in $J_n$. Here, $U$ is a function whose form we have yet to describe. We partition $x_{in}$ into those characteristics of the alternative that are observed by the researcher, labeled $z_{in}$ as before, and those that are not (and are left unlabeled), and we partition $r_n$ into characteristics of the decision-maker that are observed by the researcher, labeled $s_n$ as before, and those that are not (and again are left unlabeled). Finally, we break up $U(x_{in}, r_n)$ into an observed component that is known up to a vector $\beta$ of parameters to be estimated and that we label $V(z_{in}, s_n, \beta)$, and an unknown component which we label $e_{in}$. Then we can write the utility derived by the decision-maker from alternative i as

$$U_{in} = V(z_{in}, s_n, \beta) + e_{in}.$$

At this point, a more concrete specification can be provided. To apply the general scheme, one needs to first view $e_{in}$ as a random variable, and specify a particular form for it, and second to specify a particular form for the observable (or "representative") utility $V(z_{in}, s_n, \beta)$. Different qualitative choice models, such as logit or probit, arise from particular specifications of the random variable. For our purposes, the model of interest is the logit. *The logit model is obtained by assuming that the error terms* $e_{in}$*, where the index i ranges over all alternatives in* $J_n$*, are independently and identically distributed according to the extreme value (also called "Weibull") distribution.* (The adjective "multinomial" in this context simply means that more than two alternatives are available.) In addition, in our applications (and in many others) it is assumed that the observable utility function is linear, that is, we assume that this function is of the form

$$V_{in} = \beta w(z_{in}, s_n),$$

where $w$ is a vector function of the observable data and $\beta$ is, as before, a vector of parameters. (Note that the expression $\beta w(z_{in}, s_n)$ is a vector or inner product.) If we suppress the functional dependence of the function $w$ on the data and simply write is as $w_{in}$, then it can be shown that the probabilities take the form

$$P_{in} = \frac{e^{\beta w_{in}}}{\sum_{j \in J_n} e^{\beta w_{jn}}}.$$

(Note that two steps have been combined into one here; the logit probabilities always take this form of "exponential divided by sum of exponentials;" the exponents themselves are the representative utilities, which in the case just written--but not in general-- are linear.)

There are several things to note about this last expression. First, the probabilities defined in this way sum to one (as they should). Second, if one graphs $P_{in}$ as a function of $w_{in}$, the familiar "S-shaped" or logit curve is obtained. (This is also true more generally, that is, it doesn't depend on the linearity of representative utility.) Third (actually a corollary of the latter observation), probability is a (highly) non-linear function of the data; this is the source of the oft-mentioned caution against constructing a model of this form and then plugging averaged data into it.

Another point is worth noting here: the primary reason for the particular stochastic specification that gives rise to the logit (that is, independent and identically distributed Weibull) is "analytical tractability." The probit model is based on the more natural assumption that the error terms have a joint multivariate normal distribution with a general variance-covariance matrix. This model, however, gives rise to some very difficult integrals in the expressions for the choice probabilities, with attendant estimation problems. (Hausman used a probit model in his famous 1979 air conditioner choice paper, which is a good example of that type of approach (Hausman 1979))

We will now write down how the above formalism looks in an example. Suppose that a decision-maker--a household--is to choose between a gas and an electric oven, and that we decide that the decision will be made on the basis of (or, "utility depends upon") the purchase price and operating cost, which we can observe, and upon the household's view of other characteristics of the ovens, such as appearance, quality, and so forth, which we can't observe. If we also assume that observed utility is a linear function of these factors, then we can write the utility of the two choices, respectively, as

$$U_g = \beta_1 PP_g + \beta_2 OC_g + e_g \quad \text{and} \quad U_r = \beta_1 PP_r + \beta_2 OC_r + e_r,$$

where the subscripts indicate gas and electric, respectively, PP is purchase price and OC operating cost, and the beta's are scalar parameters. If the error terms are distributed Weibull, then the probability that the household chooses the gas oven is

$$P_g = \frac{e^{\beta_1 PP_g + \beta_2 OC_g}}{e^{\beta_1 PP_g + \beta_2 OC_g} + e^{\beta_1 PP_r + \beta_2 OC_r}},$$

and the probability it chooses electric is analogous.

The parameters in the logit models are estimated by maximum likelihood methods (given certain assumptions on the character of the sampled data). Briefly, these are statistical optimization methods in which the maximization of what is called a "(log) likelihood function" yields the values of the parameters that give the highest probability that the decision-makers made the choices that are actually observed. The log likelihood is also used to construct what is called the "likelihood ratio index," which is a measure of goodness-of-fit, and can be used in hypothesis testing. In addition, standard hypothesis tests can be performed on individual parameters using the t-test.

One important elaboration of the basic logit model that we should mention briefly is the adding of constant terms--so-called "alternative-specific constants"--to the linear observable utility functions. This has several important functions. First, it corrects the (probably false) assumption that the errors have zero mean (which is a feature of the standard Weibull distribution). In this sense, it is like adding intercept terms in a linear regression. Second, when the parameters are estimated, it results in observed proportions in the sample being reproduced exactly in the model. Third, it allows up to a certain point for the correction of a central potential flaw in the underlying model, which we now discuss.

One mathematical consequence of the logit model is a property called "the independence of irrelevant alternatives (IIA)," which means that according to the model the ratio of the probabilities associated with any two choices is independent of any other alternative. Conceptually, this property enables one to correctly estimate a model on only a subset of observed alternatives, and also, given an estimated model, to predict demand for new alternatives.

There are some situations in which IIA may hold for some pairs of alternatives but not for others, or, put another way, there are "nests" of alternatives for which IIA holds. Another qualitative choice model, the "GEV" (for "generalized extreme value") or "nested logit" is appropriate in these situations. The GEV model is derived from the assumption that the error terms as described above--the $e_{in}$--are distributed in accordance with a generalized extreme value (or GEV) distribution. Under this assumption, one can derive expressions for the choice probabilities that are analogous to those in the logit (and reduce to them in the case where the error terms are uncorrelated) but are more elaborate; we won't write down the general form here. GEV models can also be estimated globally by maximum likelihood techniques. More common, however, is to perform a "bottom-up" sequential estimation (imagine here the usual upside-down "tree" diagram with two levels) starting at the lower or "nest" level; this exploits the fact that GEV choice probabilities can be decomposed into conditional and marginal probabilities that are logit.

There are several ways of obtaining aggregate (i.e., population) estimates from QCA models. The most straightforward is sample enumeration. Each individual in the sample is given a weight $w_n$ (where the subscript $n$ corresponds to the individual) depending on the characteristics of the sample, assuming "exogenous" samples, i.e., random or stratified random samples in which the strata (if any) are exogenous to the choice being studied. If the sample is random and consists of $N$ observations, the weight is $1/N$ for each individual; if the sample is stratified, the weight varies over strata but is the same for all individuals within strata. In any case, the average probability for alternative $i$ is estimated as

$$\overline{P_i} = \sum_n w_n P_{in},$$

and the number of individuals in the population predicted to choose alternative $i$ is estimated as

$$N_i = N\overline{P_i}.$$

## APPENDIX H: NATIONAL HVAC MODEL

In addition to the two regional REEPS HVAC models described in this report, we have also developed a *national* HVAC model for use in quick reaction analyses. In general, identical methods and data sources were used to develop both models. The three main differences between the disaggregated (North and South) and national models are: 1) climate, 2) UECs for HVAC equipment, and 3) the number of housing types[1]. In executing the models in the REEPS environment, the main difference is the reduced time required to set-up the national model inputs and the elimination of the need to aggregate the results. Despite the potentially more accurate forecast results of the regional models, the national model offers distinct advantages in being quicker to develop and run. The last section of this appendix describes how to select the most appropriate version of the HVAC model for particular applications. We maintain both the regional and national versions of the model for use in a variety of modeling situations.

The following sections describe the ways in which development of the national model differed from the regional models, and present the inputs to the national model.

### H.1 Thermal Shell and HVAC Equipment Data

The space conditioning loads were derived from the same database of simulated shell component loads as the regional models. For the national model, we used the climate of Washington, D.C. to model the national average space conditioning loads. Building characteristics were based on data from the 1990 RECS, as shown in Table H.1. As the table indicates, the national model has three house-types. The space conditioning load attributed to each of these shell components (in a national average climate) is shown in Table H.2. The thermal shell components were combined to develop a set of thermal shell packages for the national model, as shown in Table H.3. The market shares of these shell packages are shown in Tables H.4 and H.5 for existing and new homes, respectively. The new construction cost of each thermal shell package is based on the component costs in Table H.6.

**Table H.1: REEPS National Model Building Characteristics**

| | Housing Type | | |
|---|---|---|---|
| | Single-Family | Multifamily | Manuf. Homes |
| Number of Stories | 2 | 1 | 1 |
| Foundation Type | Unheated Basement | | |
| *Component Dimensions (square feet)* | | | |
| Conditioned Floor Area | 1744 | 1074 | 1205 |
| Ceiling | 872 | 479 | 1205 |
| Walls | 1683 | 476 | 992 |
| Windows | 209 | 73 | 145 |
| Infiltration | 1744 | 1074 | 1205 |
| Foundation Area | 872 | 31 | 1205 |
| Foundation Perimeter (linear ft) | 118 | | 142 |
| 1990 Stock (millions) | 60.4 | 24.5 | 6.1 |

Sources: Single-family: 1990 RECS (EIA 1993); Multifamily: Ritschard and Huang (1989); Manufactured Homes: US Bureau of Census (1991) Housing Stock from 1990 Census (US Bureau of the Census 1992).
1) Multifamily foundation area is per apartment unit.
2) Wall area assumes 8 foot wall height and is net of windows.

[1]The national model has three house-types rather than the regional models' four house-types (the two sizes of single-family houses have been reduced to one). This allows the national HVAC and appliance models to be run simultaneously in the REEPS environment, because both have the same house-type segmentation.

| Table H.2: Normalized Component Loads (Screen HV-2e.3)<br>(kBtu/sq. ft of component except as noted) | | | |
|---|---|---|---|
| **Component Descriptions** | **Component** | **National (Washington, D.C.)** | |
| | | *Heating* | *Cooling* |
| **Ceiling** | R-0 | 25.63 | 7.04 |
| (kBtu/sqft of ceiling) | R-7 | 10.21 | 2.89 |
| *ceiling insulation* | R-11 | 7.75 | 2.23 |
| *R-value* | R-19 | 5.54 | 1.63 |
| | R-22 | 4.69 | 1.39 |
| | R-30 | 3.55 | 1.05 |
| | R-38 | 2.87 | 0.85 |
| | R-49 | 2.26 | 0.67 |
| | R-60 | 1.87 | 0.55 |
| **Wall** | R-0 | 23.61 | 3.53 |
| (kBtu/sqft of wall) | R-7 | 11.59 | 1.83 |
| *wall insulation* | R-11 | 9.87 | 1.59 |
| *R-value* | R-13 | 7.78 | 1.26 |
| | R-19 | 6.74 | 1.09 |
| | R-27 | 4.86 | 0.79 |
| | R-34 | 3.70 | 0.62 |
| **Slab** | R-0 | 42.63 | -7.51 |
| (kBtu/lin. ft of slab) | R-5 2ft | 18.89 | -7.39 |
| *perimeter R-value* | R-5 4ft | 12.15 | -6.90 |
| *and depth* | R-10 2ft | 14.50 | -7.33 |
| | R-10 4ft | 5.10 | -6.60 |
| **Heated Bsmt** | R-0 | 79.86 | 8.28 |
| (kBtu/lin. ft of bsmt) | R-5 4ft | 52.51 | 3.76 |
| *perimeter R-value* | R-5 8ft | 43.41 | 3.40 |
| *and depth* | R-10 4ft | 45.52 | 2.55 |
| | R-10 8ft | 31.36 | 1.89 |
| **Unheated Bsmt** | R-0 | 8.61 | 0.89 |
| (kBtu/sqft of fndn) | R-11 flr | 1.34 | 2.53 |
| *underfloor R-value* | R-19 flr | -0.65 | 2.97 |
| | R-30 flr | -1.93 | 3.25 |
| **Crawl Space** | R-0 | 15.10 | 3.04 |
| (kBtu/sqft of fndn) | R-11 flr | 1.34 | 3.73 |
| *underfloor R-value* | R-19 flr | -0.99 | 3.83 |
| | R-30 flr | -2.41 | 3.90 |
| | R-38 flr | -2.74 | 3.91 |
| | R-49 flr | -3.67 | 3.96 |
| **Infiltration** | 0.80 | 14.62 | 1.73 |
| (kBtu/sqft of floor) | 0.70 | 12.74 | 1.51 |
| *Air Changes per Hour (ACH)* | 0.55 | 10.02 | 1.20 |
| | 0.40 | 6.75 | 0.81 |
| **Windows** | 1.0-gla | 63.9 | 38.7 |
| (kBtu/sqft of window) | 2.0-gla | 15.4 | 27.4 |
| *no. of panes/design* | 3.0-gla | -1.1 | 24.9 |
| | 2-gla loE | 6.4 | 24.2 |
| | 2-gla loEAr | -0.0 | 24.1 |
| | Spectral. Sel. | 14.3 | 18.1 |
| | Superwindow | -6.7 | 20.6 |
| | Heat Mirror | 9.5 | 15.9 |
| **Residual Load** (Single-family) | | 1.98 | -2.06 |
| **Residual Load** (Multifamily) | | 1.28 | 4.18 |
| Source: Hanford et al. (1994), Huang et al. (1987b). | | | |

| **Table H.3: National Thermal Shell Packages** | | | | | |
|---|---|---|---|---|---|
| | **Component** | | | | |
| **Package** | **Ceiling** | **Walls** | **Windows** | **Infiltration (ACH)** | **Foundation (Unheated Basement)** |
| 1 | R-0 | R-0 | 1-G | 0.8 | R-0 |
| 2 | R-7 | R-0 | 1-G | 0.7 | R-0 |
| 3 | R-11 | R-7 | 1-G | 0.7 | R-0 |
| 4 | R-19 | R-7 | 2-G | 0.55 | R-11 |
| 5 | R-22 | R-11 | 2-G | 0.55 | R-11 |
| 6 | R-30 | R-13 | 2-G | 0.55 | R-11 |
| 7 | R-30 | R-13 | 2GLeA | 0.55 | R-11 |
| 8 | R-38 | R-19 | 2GLeA | 0.4 | R-11 |
| 9 | R-49 | R-19 | 2GLeA | 0.4 | R-19 |
| 10 | R-38 | R-19 | Superwindow | 0.4 | R-19 |
| 11 | R-49 | R-27 | Superwindow | 0.4 | R-19 |
| 12 | R-60 | R-34 | Superwindow | 0.4 | R-30 |

1) ACH = Air Changes per Hour
2) See Table 3.1 in the main body of this report for a more extensive description of component levels.

**Table H.4: National Thermal Shell Shares for Existing Homes (Screen HV-3f.1)**
**(% of Shell Group)**

| ***House Type:*** | **Single-Family** | | | | | **MF** | **MH** |
|---|---|---|---|---|---|---|---|
| ***Shell Group:*** | **HP** | **Elec** | **NG/CA** | **Fuels** | **Other** | **All** | **All** |
| Package | | | | | | | |
| 1 | 2.7% | 14.1% | 5.9% | 11.8% | 16.9% | 7.7% | 10.8% |
| 2 | 5.1% | 6.3% | 5.9% | 15.7% | 9.0% | 15.0% | 19.6% |
| 3 | 17.2% | 14.2% | 18.5% | 16.4% | 14.3% | 5.2% | 18.8% |
| 4 | 9.5% | 18.4% | 18.0% | 24.6% | 15.7% | 31.9% | 15.6% |
| 5 | 38.8% | 36.3% | 39.1% | 29.0% | 31.0% | 32.9% | 19.8% |
| 6 | 16.7% | 5.7% | 5.8% | 1.6% | 6.8% | 7.3% | 5.1% |
| 7 | 9.2% | 5.0% | 6.5% | 0.9% | 5.6% | | 10.3% |
| 8 | 0.9% | | 0.3% | | 0.8% | | |
| 9 | | | | | | | |
| 10 | | | | | | | |
| 11 | | | | | | | |
| 12 | | | | | | | |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| 1990 Stock (thousands) | 4,429 | 7,781 | 15,215 | 28,912 | 8,027 | 24,415 | 5,212 |

(1) MF = Multifamily, MH = Manufactured Home.
(2) HP = Heat Pump, Elec = Electric Heat, NG/CA = Natural Gas Furnace/Central Air, Fuels = Oil and Gas, Other = LPG and Misc.
(3) Sources: 1990 RECS (EIA 1993), Ritschard et al. (1992), Ritschard and Huang (1989).

**Table H.5: National Thermal Shell Shares for New Homes (Screen HV-4e) (% of Shell Group)**

| ***House Type:*** | **Single-Family** | | | | | **MF** | **MH** |
|---|---|---|---|---|---|---|---|
| ***Shell Group:*** | **HP** | **Elec** | **NG/CA** | **Fuels** | **Other** | **All** | **All** |
| Package | | | | | | | |
| 1 | | | | | | | |
| 2 | | | | | | | |
| 3 | 19.7% | 42.2% | 12.8% | 7.0% | 15.8% | 65.4% | 28.2% |
| 4 | 2.1% | 0.0% | 0.9% | 0.0% | 0.0% | 1.5% | 23.3% |
| 5 | 46.9% | 10.1% | 11.4% | 9.5% | 9.9% | 8.9% | 14.4% |
| 6 | 28.6% | 35.5% | 58.4% | 59.5% | 50.9% | 24.3% | 31.2% |
| 7 | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | | 0.0% |
| 8 | 2.6% | 12.2% | 16.5% | 24.1% | 23.3% | | 2.8% |
| 9 | | | | | | | |
| 10 | | | | | | | |
| 11 | | | | | | | |
| 12 | | | | | | | |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

(1) MF = Multifamily, MH = Manufactured Home.
(2) HP = Heat Pump, Elec = Electric Heat, NG/CA = Natural Gas Furnace/Central Air, Fuels = Oil and Gas, Other = LPG and Misc.
(3) Sources: 1990 RECS (EIA 1993), Ritschard et al. (1992), Ritschard and Huang (1989).
(4) New homes are 1980-90 vintage in RECS.

| Table H.6: New Home Shell Component Prices ($1990/sq.ft. of floor area) (Screen HV-5d.1) | | | |
|---|---|---|---|
| **Component Descriptions** | **Component Level** | **National (Washington, DC)** | |
| | | **1-story** | **2-story** |
| **Ceiling** | R-0 | 0.00 | 0.00 |
| *ceiling insulation* | R-7 | 0.21 | 0.10 |
| *R-value* | R-11 | 0.33 | 0.16 |
| | R-19 | 0.47 | 0.24 |
| | R-22 | 0.52 | 0.26 |
| | R-30 | 0.65 | 0.33 |
| | R-38 | 0.83 | 0.42 |
| | R-49 | 1.03 | 0.51 |
| | R-60 | 1.21 | 0.61 |
| **Wall** | R-0 | 0.00 | 0.00 |
| *wall insulation* | R-7 | 0.18 | 0.20 |
| *R-value* | R-11 | 0.28 | 0.32 |
| | R-13 | 0.33 | 0.37 |
| | R-19 | 0.47 | 0.54 |
| | R-27 | 1.03 | 1.18 |
| | R-34 | 1.22 | 1.40 |
| **Slab Edge** | R-0 | 0.00 | 0.00 |
| *perimeter R-value* | R-5 2ft | 0.29 | 0.15 |
| *and depth* | R-5 4ft | 0.37 | 0.19 |
| | R-10 2ft | 0.57 | 0.30 |
| | R-10 4ft | 0.74 | 0.38 |
| **Floor Insulation** | R-0 | 0.00 | 0.00 |
| *underfloor R-value* | R-11 flr | 0.41 | 0.20 |
| | R-19 flr | 0.63 | 0.31 |
| | R-30 flr | 0.77 | 0.39 |
| | R-38 flr | 0.87 | 0.44 |
| | 0.8 | 0.00 | 0.00 |
| **Infiltration** | 0.7 | 0.00 | 0.00 |
| *ACH* | 0.55 | 0.19 | 0.13 |
| | 0.4 | 0.37 | 0.26 |
| **Windows** | 1.0-gla | 0 | |
| *no. of panes/design* | 2.0-gla | 0.46 | |
| | 2-gla loE | 0.69 | |
| | 2-gla loEAr | 0.77 | |
| | Spectrally Sel. | 0.76 | |
| | Superwindow | 1.06 | |
| | Heat Mirror | 1.1 | |

(1) Sources: Koomey et al. (1991b), Koomey et al. (1994b). Costs are for single-family homes.
(2) Costs normalized using average floor area for new homes: 1500 sq. ft. for 1-story, and 2200 sq. ft. for 2-story.
(3) REEPS model uses 2-story costs for national model.

The HVAC equipment vintage block data are from the 1990 RECS. The vintage block shares are shown in Table H.7. REEPS also requires data on equipment capacity by house type, which are shown in Table H.8. Another important driver in the REEPS model is the unit energy consumption of various types of HVAC equipment. For this analysis, we derive UECs from the 1990 RECS (EIA 1993) for natural gas and oil equipment, and from the LBL Residential Forecasting Database (Hanford et al. 1994) for electric heating and cooling equipment. Table H.9 shows the UECs for stock equipment. Market shares for the various HVAC systems are shown in Table H.10 and H.11 for stock and new homes, respectively. These data are from the 1990 RECS (EIA 1993) and the 1990 C-25 report (US Bureau of the Census 1991). In addition, REEPS requires data on the market share of room air conditioners in the housing stock, in order to forecast the saturation of room air units. For use in REEPS, these data are disaggregated according to the presence of central cooling equipment. Table H.12 shows the market share of room air conditioners by house type.

**Table H.7: National HVAC Equipment Vintage Blocks**
(% of heating or cooling equipment type of given age in 1990)

| ***End-Use*** | ***Technology*** | **<2YR** | **2-4YR** | **5-9YR** | **10-19YR** | **>20YR** | **Total** |
|---|---|---|---|---|---|---|---|
| **Heating** (Screen HV-3b.3) | | | | | | | |
| | Electric Furnace | 4% | 10% | 24% | 52% | 9% | 100% |
| | Gas Furnace | 8% | 15% | 20% | 31% | 26% | 100% |
| | Oil Furnace | 9% | 17% | 17% | 23% | 34% | 100% |
| | LPG Furnace | 19% | 19% | 22% | 27% | 13% | 100% |
| | Electric Heat Pump | 12% | 23% | 39% | 22% | 4% | 100% |
| | Gas Hydronics | 11% | 9% | 13% | 26% | 41% | 100% |
| | Oil Hydronics | 9% | 12% | 15% | 21% | 43% | 100% |
| | Electric Room | 8% | 11% | 19% | 33% | 29% | 100% |
| | Gas Room | 6% | 8% | 15% | 25% | 46% | 100% |
| | Other Equipment | 8% | 25% | 30% | 27% | 10% | 100% |
| **Cooling** (Screen HV-3e.3) | | | | | | | |
| | Central Air | 12% | 19% | 24% | 34% | 10% | 100% |
| | Electric Heat Pump | 10% | 26% | 39% | 23% | 2% | 100% |
| | Room Air | 13% | 23% | 31% | 27% | 7% | 100% |

(1) Source: 1990 RECS (EIA 1993).
(2) The percentages represent ownership shares for the respective vintage blocks in 1990.
(3) Heat Pump vintage shares include only heat pumps used for heating and cooling.

**Table H.8: National 1990 HVAC Equipment Average Capacity**
(kBtu/hour)

| **End-Use** | **Technology** | **SF** | **MF** | **MH** |
|---|---|---|---|---|
| Heating (Screen HV-3b.1) | | | | |
| | Electric Furnace | 60 | 25 | 60 |
| | Gas Furnace | 90 | 50 | 70 |
| | LPG Furnace | 80 | 50 | 70 |
| | Oil Furnace | 100 | 60 | 80 |
| | Electric Heat Pump | 36 | 18 | 36 |
| | Gas Hydronics | 110 | 50 | 80 |
| | Oil Hydronics | 120 | 50 | 100 |
| | Electric Room | 50 | 25 | 35 |
| | Gas Room | 40 | 35 | 40 |
| | Other Equipment | 35 | 25 | 30 |
| Cooling (Screen HV-3e.1) | | | | |
| | Central Air | 24 | 22 | 26 |
| | Electric Heat Pump | 24 | 22 | 26 |
| | Room Air | 11 | 10 | 10 |

(1) Capacity values are based on manufacturer shipment data, disaggregated by house type using the loads from Section 3 and sizing parameters from Table H.13.

| Table H.9: National 1990 Stock Average Unit Energy Consumption Estimates | | | | | |
|---|---|---|---|---|---|
| **End-Use** | **Technology** | **Units** | **SF** | **MF** | **MH** |
| **Heating** (Screen HV-3b.5) | | | | | |
| | Electric Furnace | kWh | 7,200 | 5,200 | 5,800 |
| | Gas Furnace | kBtu | 72,700 | 44,000 | 56,300 |
| | LPG Furnace | kBtu | 44,800 | 40,900 | 31,000 |
| | Oil Furnace | kBtu | 68,600 | 57,900 | 50,600 |
| | Electric Heat Pump | kWh | 5,800 | 2,500 | 2,200 |
| | Gas Hydronics | kBtu | 112,300 | 58,900 | 56,300 |
| | Oil Hydronics | kBtu | 114,400 | 54,700 | 50,600 |
| | Electric Room | kWh | 9,800 | 5,800 | 4,000 |
| | Gas Room | kBtu | 43,200 | 26,900 | 39,300 |
| | Other Equipment | kBtu | 15,100 | 9,700 | 33,500 |
| **Cooling** (Screen HV-3e.5) | | | | | |
| | Central Air | kWh | 2,800 | 1,600 | 1,900 |
| | Electric Heat Pump | kWh | 3,400 | 1,800 | 2,300 |
| | Room Air | kWh | 870 | 530 | 680 |

(1) Sources: 1990 RECS (EIA 1993) for fuel equipment, Tables B.7 and B.8 in Hanford et al. (1994) for electric heating and cooling equipment.
(2) SF = Single-Family, MF = Multifamily, MH = Manufactured Home.
(3) UECs for hydronic systems in manufactured homes are assumed to be the same as furnaces UECs.
(4) Electric Room heating UECs are higher than Electric Furnace UECs due to higher saturation in the north for room electric heaters (relative to electric furnaces).
(5) Electric Heat Pump cooling UECs are higher than CAC UECs because heat pumps are more common in warmer climates.

**Table H.10: National Existing Home HVAC System Shares (Screen HV-3a.1)**
**(% of house-type with given HVAC system)**

| **System No.** | **Cooling/Heating Combination** | **Housing type** | | |
|---|---|---|---|---|
| | | **SF** | **MF** | **MH** |
| 1 | Central Air/Electric Furnace | 5.5% | 15.2% | 6.8% |
| 2 | Central Air/Gas Furnace | 23.6% | 13.2% | 13.1% |
| 3 | Central Air/LPG Furnace | 1.2% | 0.1% | 7.0% |
| 4 | Central Air/Oil Furnace | 1.5% | 0.1% | 0.6% |
| 5 | Central Air/Gas Hydronics | 0.5% | 0.6% | 0.0% |
| 6 | Central Air/Oil Hydronics | 1.0% | 0.2% | 0.0% |
| 7 | Central Air/Other | 0.9% | 0.0% | 0.4% |
| 8 | Electric Heat Pump | 6.9% | 5.7% | 1.8% |
| 9 | No Central Air/Gas Furnace | 19.2% | 10.2% | 23.1% |
| 10 | No Central Air/LPG Furnace | 3.8% | 0.2% | 15.3% |
| 11 | No Central Air/Oil Furnace | 4.9% | 1.3% | 4.8% |
| 12 | No Central Air/Gas Hydronics | 4.7% | 19.4% | 0.0% |
| 13 | No Central Air/Oil Hydronics | 4.2% | 9.5% | 0.0% |
| 14 | No Central Air/Electric Room | 6.6% | 12.6% | 13.1% |
| 15 | No Central Air/Gas Room | 9.0% | 10.1% | 1.7% |
| 16 | No Central Air/Other | 6.6% | 1.7% | 12.2% |
| | *Totals* | 100% | 100% | 100% |

(1) Source: 1990 RECS (EIA 1993).

| Table H.11: National New Home HVAC System Shares (Screen HV-4a) (% of house-type with given HVAC system) | | | | |
|---|---|---|---|---|
| System No. | Cooling/Heating Combination | Housing type | | |
| | | SF | MF | MH |
| 1 | Central Air/Electric Furnace | 6.7% | 16.6% | 11.6% |
| 2 | Central Air/Gas Furnace | 46.9% | 26.9% | 17.0% |
| 3 | Central Air/LPG Furnace | 0.6% | 0.8% | 14.8% |
| 4 | Central Air/Oil Furnace | 0.0% | 0.0% | 0.0% |
| 5 | Central Air/Gas Hydronics | 0.1% | 0.0% | 0.0% |
| 6 | Central Air/Oil Hydronics | 0.2% | 0.0% | 0.0% |
| 7 | Central Air/Other | 0.4% | 0.0% | 1.2% |
| 8 | Electric Heat Pump | 22.9% | 26.0% | 3.3% |
| 9 | No Central Air/Gas Furnace | 10.8% | 8.7% | 22.7% |
| 10 | No Central Air/LPG Furnace | 0.7% | 0.8% | 15.1% |
| 11 | No Central Air/Oil Furnace | 1.4% | 0.0% | 4.0% |
| 12 | No Central Air/Gas Hydronics | 1.0% | 5.5% | 0.0% |
| 13 | No Central Air/Oil Hydronics | 3.5% | 0.9% | 0.0% |
| 14 | No Central Air/Electric Room | 3.1% | 10.6% | 1.0% |
| 15 | No Central Air/Gas Room | 0.4% | 2.8% | 0.5% |
| 16 | No Central Air/Other | 1.1% | 0.6% | 8.9% |
| | *Totals* | 100% | 100% | 100% |

Source: 1990 RECS (EIA 1993); 1990 C-25 report (US Bureau of the Census 1991).
(1) RECS data are based on sub-sample of homes built 1980 to 1990.
(2) SF and MF fuel shares are based on C-25 data, using RECS for relative weighting of equipment types.
(3) MH electric and gas room heating shares have been limited to ≤1% based on conversations with MH manufacturers (Boghosian 1994). The RECS shares (in excess of 1%) for these heating types have been allocated to other non-CAC heating systems.

| Table H.12: 1990 National Stock Room Air Conditioner Market Shares (Screen HV-3c.4) (% of central cooling-type with RAC) | | | |
|---|---|---|---|
| Central Cooling System | Housing type | | |
| | SF | MF | MH |
| Central Air | 7.7% | 1.4% | 5.6% |
| Heat Pump | 3.5% | 0.0% | 0.0% |
| No Central Air | 47% | 49% | 44% |

Source: 1990 RECS (EIA 1993).

In order to calculate national decision models, we must estimate the cost of HVAC equipment, which in turn requires estimates of equipment size. Equipment is usually sized to meet the peak load; Table H.13 presents the parameters used to calculate national average peak load. This load is subsequently used to estimate equipment sizing parameters, which are presented in Table H.14. These parameters indicate the extent to which HVAC equipment is oversized for meeting the peak load. The cost of HVAC equipment is calculated using the same equation as the regional models because this equation was based on national data (the resulting costs vary from the regional models, however, due to different equipment sizes).

| Table H.13: Peak Thermal Load as a Function of Annual Load for National Model | | |
|---|---|---|
| **Heating** | **slope** (kBtuh/kBtu) | **intercept** (kBtuh) |
| Single-Family | 0.527 | 8.197 |
| Multifamily | 0.436 | 6.787 |
| **Cooling** | **slope** (kBtuh/kBtu) | **intercept** (kBtuh) |
| Single-Family | 2.029 | -1.862 |
| Multifamily | 1.597 | -1.218 |
| (1) Values are based on regressions using DOE-2 results with thermal shell packages of varying thermal integrity.<br>(2) Values presented here are weighted-averages of regional values in Table 5.1. | | |

| Table H.14: National Equipment Sizing Parameters | | | |
|---|---|---|---|
| | **SF** | **MF** | **MH** |
| **Heating** | | | |
| Electric Furnace | 1.76 | 1.60 | 1.81 |
| Gas Furnace | 2.06 | 1.89 | 2.07 |
| Oil Furnace | 2.15 | 1.99 | 2.18 |
| Electric Heat Pump | 1.48 | 1.46 | 1.62 |
| Gas Hydronics | 2.39 | 1.94 | n/a |
| Oil Hydronics | 2.44 | 2.08 | n/a |
| Electric Room | 1.80 | 1.65 | 1.72 |
| Gas Room | 1.54 | 1.61 | 1.61 |
| Other Equipment | 1.90 | 1.97 | 2.01 |
| **Cooling** | | | |
| Central Air | 1.00 | 0.84 | 1.07 |
| Electric Heat Pump | 1.29 | 1.03 | 1.42 |
| Room Air | 0.65 | 0.55 | 0.68 |
| No Air | | | |
| (1) Developed from thermal shell assumptions (RECS 1990), peak load estimation relation, and data on the size of recent shipments of the various equipment types (AHAM 1991, ARI 1991, GAMA 1992).<br>(2) A sizing parameter of 1.0 implies that the size of the equipment is exactly sufficient to meet the peak load, while a sizing parameter of 1.80 implies that the capacity of the equipment is 80% larger than required to exactly meet peak load. | | | |

## H.2 Decision Models

The national HVAC model employs the same decision equations and parameters as the regional models because the parameters for these equations have all been calculated using national data. Refer to Section 6 of the main report for the methods and data used in specifying the HVAC decision models.

One may question the accuracy of the regional model market share forecasts, because they use the same decision parameters as the national model. While both use the same decision model, the purchase results will differ because the disaggregated (regional) models capture dependencies in the structure of consumer decision-making that are not apparent in the aggregated model due to the non-linear nature of the consumer choice models. The purpose of distinguishing between North and South models is thus not to account for differences in consumption, for this could be more easily accomplished in a spreadsheet model. Rather, the purpose is to recognize that the circumstances under which decisions are made are inherently different in the two regions due to differences in important factors such as climate, gas availability, and construction practices. Thus we believe that there are no significant regional differences in consumers' decision *criteria*, but that the different decision *environment* will lead to different purchase decisions. By applying the decision models separately to the North and South regional data, the dependent variables (consumer purchase decisions) will more accurately reflect the actual environment in which decisions are made. The same principle is applicable to the distinction between small and large single-family homes, because the decision environments are inherently different in the two cases. The market share data from RECS bear this out, with significantly different HVAC system market shares for large and small homes, reflecting both typical construction practices and the economics of particular equipment choices. Both regional and house-type disaggregations point to the fact that REEPS is not simply a tool for assessing end-use consumption, but rather a tool for assessing consumer *decision-making*. The resulting end-use consumption is merely a consequence of the decisions modeled during the course of the forecast.

### H.3 Model Execution in REEPS

One of the advantages of the national HVAC model is that it can be run simultaneously with the national appliance models developed by LBL (see companion report, LBL #34046). In practice to use the regional REEPS model requires running three separate models in REEPS: North HVAC, South HVAC, and appliances. The national model saves time in two ways. First, the national model only has one set of REEPS input files, so it takes less time to change model parameters in order to forecast the effect of policies. In most cases these model changes are not a significant burden, but when modeling several scenarios or policies the extra time and possibility for mistakes can be significant with the regional (2-model) version. The second advantage of the national model is that it avoids the need to aggregate forecast results after model execution. These features of the national model are most useful in quick-reaction policy modeling situations.

### H.4 Choosing the Appropriate Model

When faced with the option of using two alternative models, the question inevitably arises: What benefits can one gain from the added effort required to run the regional models rather than the national model? Use of the two regional models can sometimes amount to two or more times the amount of work compared to the national model. Furthermore, some analyses require only highly aggregated numbers which obscure the original detail of the regional models. Thus the analyst needs a benchmark or indicator to identify those cases for which the regional models significantly improve the results.

First, total base-year consumption by end-use is *not* a useful benchmark for identifying differences in the models' results. Since REEPS is calibrated to the Unit Energy Consumption values, the base-year consumption can *always* be reproduced when the UECs are based on a consistent single source, namely RECS. Thus, because the UEC input data for the two models are from the same source, the base-year end-use consumption would be roughly the same. The base-year consumption is mainly useful as a mechanical check as to whether the number of households, market shares, etc. have been entered correctly and consistently.

Another possible indicator for comparison is the end-use consumption over the forecast period. The end-use consumption by itself is not a sufficient basis for comparison, but should be compared in conjunction with the other key variables: Thermal Integrity, Thermal Shell Shares, HVAC System Market Shares, Efficiency, Usage, and Stock Turnover. If these variables yield similar results in both models, then the model results are not sensitive to the 2-region disaggregation under the given exogenous assumptions. Since the comparison is often conducted for a reference or base case, however, one cannot be certain the comparison would be as favorable when the exogenous variables include a drastic change, such as a price shock, a set of stringent standards, or the introduction of an advanced technology that is expected to gain considerable market share. These circumstances require more caution in using the models interchangeably.

Although there is no way to know *a priori* whether a particular set of runs will be sensitive to the disaggregation, there are a few rules of thumb which can be used to narrow the set of parameters used in comparing the models.

(1) Mechanically check base-year end-use consumption numbers when there is a possibility of differences in conventions between the national and regional models. In other words, if exogenous variables are changed in structure or value, the comparison can reveal numerical or structural mis-specifications.

(2) Compare the relevant forecast variables for a 20-year period for the national and regional models whenever there are significant departures from the base case. In other words, the comparison provides a measure of the sensitivity of the model results to those cases which serve as jumping-off points for other analyses. For example, the comparison could be made for a business-as-usual case, a max. tech. case, and a minimum life-cycle cost case in order to determine model sensitivity across a range of scenarios.

(3) When the policies are concerned only with one area of improvement, such as efficiency improvements in heating and cooling equipment, the national model will generally suffice. On the other hand, when the relationship among different improvements is considered, such as between thermal shell and equipment efficiency, the disaggregated model is preferable.

(4) If the only issue is fuel price sensitivity, the national model will probably suffice because the regional sensitivity to fuel price is small, and fuel price forecasts are often not available by region anyway. The same point applies to other exogenous variables that are not available independently by region, such as housing starts.

As these rules of thumb suggest, the main distinction between the national and regional models is methodological and does not always show up in the end-use consumption totals. Thus some care is necessary in choosing the appropriate model(s) where disaggregated models are available.

### H.5 National HVAC Model Summary

Certain applications of forecasting models do not require regional detail or do not allow the time needed to produce detailed regional results. For these cases, we have developed an aggregated, national REEPS HVAC model. The model was developed using the same methodology as the regional models, and the modeling structure differs only in minor aspects. despite their similarities, however, we do not expect that the models will yield identical results. A future report in this series will investigate the differences in model results between the national and regional REEPS HVAC models.

## APPENDIX I: REDUCED-FORM THERMAL INTEGRITY COST CURVES

One of the features of the REEPS 2.1 model that most distinguishes it from other end-use forecasting models is the thermal shell model documented in Section 3. The detailed treatment of the physical building characteristics allows for accurate modeling of changes in space conditioning loads. For those end-use forecasting models, such as the LBL Residential Energy Model, that do not treat the thermal shell in detail, we have developed reduced-form cost vs. efficiency curves. Tables I.1-I.3 and Figures I.1-I.3 document these relationships for new shells of the three housing types in the national model (single-family, multifamily, and manufactured homes). It is interesting to note that the curves have similar forms for all three housing types (due to the same shell measure for the corresponding points on each curve), but the magnitude of cost increases and thermal integrity improvements differ. Also keep in mind that the thermal integrity improvements shown in the figures are relative to shell package #1, which is essentially uninsulated. These results do not imply that space conditioning load for typical new shells can be reduced by 70-80%. Note that these curves are not used in the REEPS model, but are only provided for use in other modeling applications.

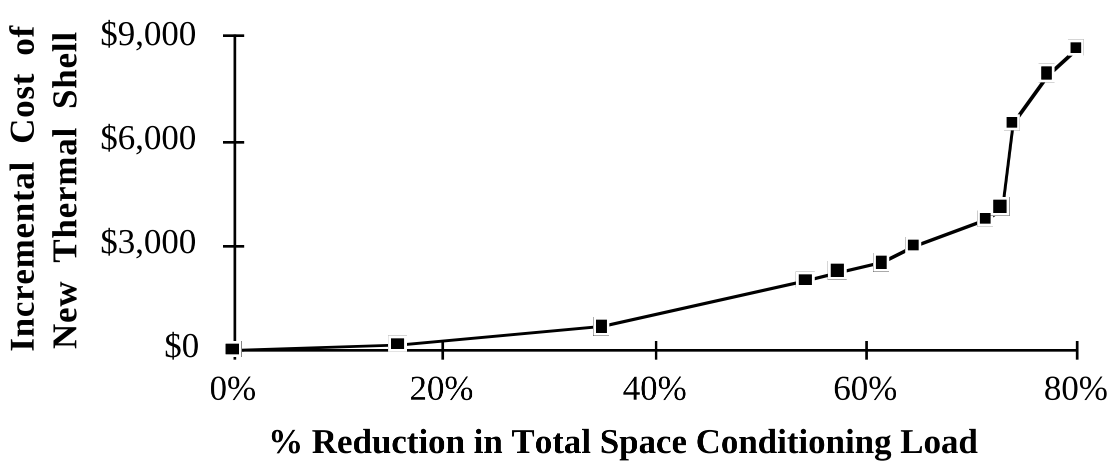
The analysis documented in this Appendix is based on the new construction thermal shell components and prices presented in Sections 3.1 and 3.4. The space conditioning loads are based on the national shell packages described in Appendix H.

**Table I.1: New Single-Family National Average Price for Thermal Integrity Improvements**

| | Heating Load | | Cooling Load | | Total Load | | | |
|---|---|---|---|---|---|---|---|---|
| Shell Package | Annual Load (MMBtu) | % Decr. From Pkg. 1 | Annual Load (MMBtu) | % Decr. From Pkg. 1 | Annual Load (MMBtu) | % Improvement From Pkg. 1 | % Improvement From Prev. Pkg. | Incremental Shell Price (1990$) |
| 1 | 110.4 | 0% | 21.9 | 0% | 132.3 | 0% | 0% | $0 |
| 2 | 93.7 | 15.1% | 17.9 | 18.2% | 111.6 | 15.7% | 15.7% | $181 |
| 3 | 71.3 | 35.4% | 14.5 | 33.9% | 85.8 | 35.2% | 19.5% | $687 |
| 4 | 48.2 | 56.4% | 12.5 | 43.1% | 60.7 | 54.2% | 19.0% | $2,036 |
| 5 | 44.6 | 59.7% | 11.9 | 45.9% | 56.4 | 57.4% | 3.2% | $2,309 |
| 6 | 40.0 | 63.7% | 11.0 | 49.8% | 51.0 | 61.4% | 4.1% | $2,533 |
| 7 | 36.8 | 66.7% | 10.3 | 52.9% | 47.1 | 64.4% | 3.0% | $3,066 |
| 8 | 28.8 | 74.0% | 9.2 | 58.0% | 38.0 | 71.3% | 6.9% | $3,770 |
| 9 | 26.5 | 76.0% | 9.4 | 57.0% | 35.9 | 72.9% | 1.5% | $4,129 |
| 10 | 25.6 | 76.8% | 8.8 | 59.6% | 34.5 | 73.9% | 1.1% | $6,552 |
| 11 | 21.9 | 80.1% | 8.2 | 62.6% | 30.1 | 77.2% | 3.3% | $7,997 |
| 12 | 18.5 | 83.2% | 8.0 | 63.3% | 26.6 | 79.9% | 2.7% | $8,714 |

Sources: (1) Space conditioning loads based on shell characteristics and loads described in Appendix H. Loads are calculated using DOE-2 simulations.
(2) Shell component prices are from Koomey et al. (1991b), Koomey et al. (1994b).

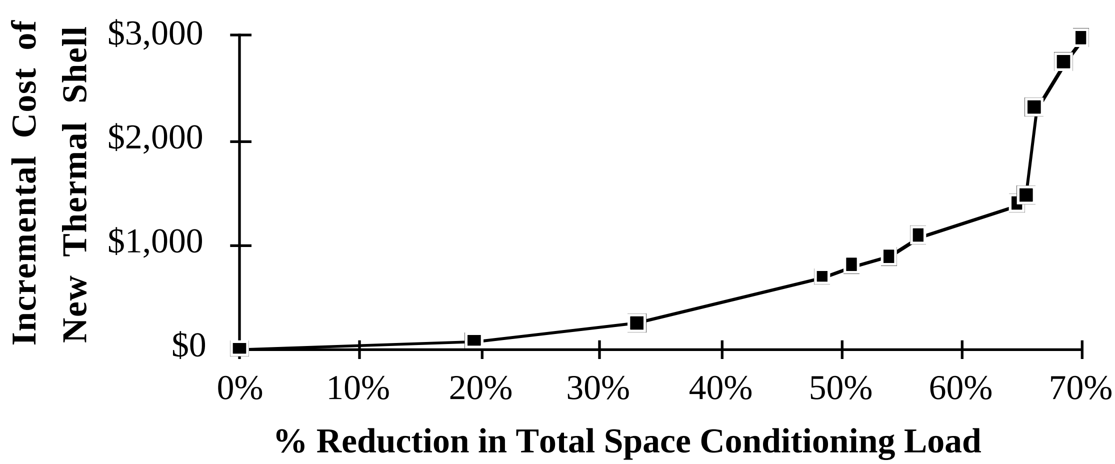
**Figure I.1: Single-Family Thermal Shell Integrity vs. New Construction Cost**



| Table I.2: New Multifamily National Average Price for Thermal Integrity Improvements | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Heating Load | | Cooling Load | | Total Load | | | |
| Shell Package | Annual Load (MMBtu) | % Decr. From Pkg. 1 | Annual Load (MMBtu) | % Decr. From Pkg. 1 | Annual Load (MMBtu) | % Improvement From Pkg. 1 | % Improvement From Prev. Pkg. | Incremental Shell Cost (1990$) |
| 1 | 45.4 | 0% | 13.9 | 0% | 59.4 | 0% | 0% | $0 |
| 2 | 36.0 | 20.7% | 11.7 | 15.9% | 47.7 | 19.6% | 19.6% | $100 |
| 3 | 29.1 | 35.9% | 10.6 | 24.0% | 39.7 | 33.1% | 13.5% | $270 |
| 4 | 21.4 | 52.9% | 9.2 | 34.0% | 30.6 | 48.5% | 15.4% | $714 |
| 5 | 20.2 | 55.6% | 9.0 | 35.7% | 29.1 | 51.0% | 2.5% | $803 |
| 6 | 18.6 | 59.0% | 8.6 | 38.0% | 27.3 | 54.1% | 3.1% | $897 |
| 7 | 17.5 | 61.5% | 8.4 | 39.7% | 25.9 | 56.4% | 2.3% | $1,083 |
| 8 | 13.2 | 71.0% | 7.8 | 43.9% | 21.0 | 64.7% | 8.3% | $1,398 |
| 9 | 12.8 | 71.8% | 7.7 | 44.4% | 20.5 | 65.4% | 0.7% | $1,497 |
| 10 | 12.6 | 72.2% | 7.6 | 45.6% | 20.2 | 66.0% | 0.6% | $2,309 |
| 11 | 11.4 | 74.9% | 7.3 | 47.3% | 18.8 | 68.4% | 2.4% | $2,762 |
| 12 | 10.6 | 76.6% | 7.2 | 48.2% | 17.9 | 69.9% | 1.5% | $2,978 |

Sources: (1) Space conditioning loads based on shell characteristics and loads described in Appendix H. Loads are calculated using DOE-2 simulations.
(2) Shell component prices are from Koomey et al. (1991b), Koomey et al. (1994b).
(3) Space conditioning loads and shell costs are per apartment unit.

**Figure I.2: Multifamily Thermal Shell Integrity vs. New Construction Cost**



| Table I.3: New Manufactured Home National Average Price for Thermal Integrity Improvements | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Heating Load | | Cooling Load | | Total Load | | | |
| Shell Package | Annual Load (MMBtu) | % Decr. From Pkg. 1 | Annual Load (MMBtu) | % Decr. From Pkg. 1 | Annual Load (MMBtu) | % Improvement From Pkg. 1 | % Improvement From Prev. Pkg. | Incremental Shell Cost (1990$) |
| 1 | 93.5 | 0% | 18.7 | 0% | 112.2 | 0% | 0% | $0 |
| 2 | 72.7 | 22.3% | 13.4 | 28.2% | 86.1 | 23.3% | 23.3% | $250 |
| 3 | 57.8 | 38.2% | 10.9 | 41.5% | 68.7 | 38.8% | 15.5% | $631 |
| 4 | 36.1 | 61.4% | 10.2 | 45.5% | 46.2 | 58.8% | 20.0% | $1,896 |
| 5 | 33.3 | 64.3% | 9.6 | 48.4% | 43.0 | 61.7% | 2.9% | $2,092 |
| 6 | 29.9 | 68.0% | 8.9 | 52.3% | 38.8 | 65.4% | 3.7% | $2,316 |
| 7 | 27.7 | 70.4% | 8.4 | 54.8% | 36.1 | 67.8% | 2.4% | $2,684 |
| 8 | 21.9 | 76.6% | 7.6 | 59.5% | 29.4 | 73.8% | 5.9% | $3,246 |
| 9 | 18.7 | 80.0% | 7.9 | 57.8% | 26.6 | 76.3% | 2.5% | $3,742 |
| 10 | 18.5 | 80.2% | 7.6 | 59.3% | 26.1 | 76.7% | 0.5% | $5,301 |
| 11 | 15.9 | 83.0% | 7.1 | 62.1% | 23.0 | 79.5% | 2.8% | $6,285 |
| 12 | 12.7 | 86.4% | 7.1 | 62.0% | 19.8 | 82.3% | 2.8% | $6,935 |

Sources: (1) Space conditioning loads based on shell characteristics and loads described in Appendix H. Loads are calculated using DOE-2 simulations.
(2) Shell component prices are from Koomey et al. (1991b), Koomey et al. (1994b).

**Figure I.3: Manufactured Home Thermal Shell Integrity vs. New Construction Cost**