LBL-31042

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ENERGY SAVINGS POTENTIAL FOR ADVANCED THERMAL DISTRIBUTION TECHNOLOGY IN RESIDENTIAL AND SMALL COMMERCIAL BUILDINGS

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July, 1991

Prepared for the
Building Equipment Divsion
Office of Building Technologies
U.S. Department of Energy

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ABSTRACT

An evaluation of the potential for energy savings in thermal distribution systems in residential and small commercial buildings has been carried out. Thermal distribution systems are the ductwork, piping, or other means used to transport heat or cooling effect from the equipment that produces the heat or cooling to the building spaces in which it is used. This evaluation was divided into four stages. First, households and small commercial buildings were broken down into specific categories relevant to thermal distribution issues; categories used in the breakdown were climate zone, building type, thermal distribution system type, and thermal distribution system location. An additional breakdown into existing buildings and new construction was used. Second, energy use per household (residential) or unit floor area (small commercial) was estimated. Third, the building stock was projected out to the year 2020, with a division into pre-1995 (existing) and post-1995 (new) buildings. 1995 was selected as the approximate date at which a new research program could begin to have significant impact on thermal distribution systems in new construction. Most buildings built before 1995 will still be in use in 2020; these, together with 25 years of new construction, were judged an appropriate mix to use as a basis for setting research priorities. Finally, energy savings from improved thermal distribution were estimated as percentages of the annual energy use projected for 2020. From these numbers, national energy-savings projections were made.

CONTENTS

EXECUTIVE SUMMARY OR TECHNICAL OVERVIEW?

Two summary documents are now presented. The first is an executive summary, while the second is a technical overview. The difference between the two is as follows. The executive summary emphasizes results that the authors believe will be useful in making management decisions concerning energy-conservation research and policy. Only a very brief outline of the technical approach is included. The technical overview, on the other hand, is intended to provide a clear picture of the technical approach, with discussion of the intermediate steps taken to arrive at the results. The executive summary is like a travel film that shows the attractive features of the destination, with just a preliminary glance at the map to enable viewers to know what part of the world they are looking at. The technical overview is like a road map with accompanying travel notes, which allows the reader to anticipate the journey in some detail without actually making it. The full report is for the determined visitor who wishes to travel the road personally.

EXECUTIVE SUMMARY

An evaluation of the potential for energy savings in thermal distribution systems in residential and small commercial buildings has been carried out. Thermal distribution systems are the ductwork, piping, or other means used to transport heat or cooling effect from the equipment that produces the heat or cooling to the building spaces in which it is used.

The approach involved four major steps. The first step was to divide the building stock into relatively homogeneous "cells" so that the possible improvements in thermal distribution for each cell could be evaluated and the resulting energy savings estimated. The hope was that a small number of cells would contain most of the buildings. In that event, a Federally sponsored research program could be targeted on these well-populated groups of buildings. This hope was in fact realized.

The cells were defined by means of a classification scheme in which five characteristics germane to thermal distribution were given two to four possible values each. The characteristics and possible values were:

	Characteristic	Possible Values (Categories)
I.	Existing Building or New Construction	1. Existing 2. New
II.	Climate Zone	1. "Frostbelt" (Northeast and Midwest Census Regions) 2. "Sunbelt" (South and West)
III.	Building Type	1. Single Family 2. Mobile Home (HUD-Code Housing) 3. Multifamily 4. Small Commercial
IV.	Thermal Distribution Type	1. Forced Air 2. Hydronic 3. Built-In Electric 4. Other or None
V.	Thermal Distribution Location	1. In Unconditioned Space (Crawlspace or Attic) 2. In Partly Conditioned Space (Basement) 3. In Conditioned Space

Each cell is then defined by the choice of one specific value for each of the five characteristics. For example, one of the cells would be: "Existing single-family housing in the Frostbelt with forced-air distribution ductwork located in a partly conditioned space."

The remaining steps in the approach are summarized as follows. Second, energy use per household (residential) or unit floor area (small commercial) was estimated. Third, the building stock was projected out to the year 2020, with a division into pre-1995 (existing) and post-1995 (new) buildings. It is

expected that research will be directed toward both existing and new buildings. To provide a rational basis for weighting program emphasis, it was decided to define "existing" buildings as those constructed in 1995 or before. 1995 was selected as the approximate date at which a new research program could begin to have significant impact on thermal distribution systems in new construction.

Finally, energy savings from improved thermal distribution were estimated as percentages of the annual energy use projected for 2020. From these numbers, national energy-savings projections were made.

Residential-Building Energy Use

For residential buildings, the procedure yielded nine cells that, together, account for 6.39 quads (1 quad=10exp15 Btu) of primary energy use for space heating and cooling in 2020. Energy savings are then estimated as a percentage of this use (see below). This level of energy use is 73% of a DOE estimate for residential space conditioning in 2010, the latest available at this time. For comparison, these same cells used 75% of the total primary energy for residential space conditioning in 1986. The projection therefore appears reasonable and perhaps conservative. The relative contributions of the eight cells to primary energy use are shown in Figure S-1.

In five cases shown in Figure S-1, both new and existing housing were combined into one cell. This was done when the energy use in new housing units was not sufficient to justify setting up a separate cell for it. Implicit in this representation is the judgment that no special program thrust is warranted for new housing of these types, but that the new housing would benefit from research conducted on existing housing of the same type.

Of the energy represented in Figure S-1, 85% is used in forced-air distribution systems, with the remainder going to hydronic systems. Also, 72% of the energy is used in existing housing, with the remainder going to new housing.

The results are fully consistent both with the long service life of existing housing and with the steady movement of U.S. population into the Sunbelt. In spite of this movement, even in 2020 nearly half of the energy use in the nine well-populated cells will be in the Frostbelt. Two reasons for this stand out. First, the average Frostbelt house uses significantly more energy for space conditioning than the typical house in the Sunbelt. Second, in the existing housing stock, disproportionately more Sunbelt than Frostbelt houses had types of distribution systems classified as "other or none," which could not be aggregated in any meaningful way into large cells.

Seven of the nine cells contain housing with forced-air distribution. If only these cells are considered, the Sunbelt's share of energy use increases to 62% of the total. In the other cells (with one minor exception) new housing was lumped with existing housing because not enough new housing was projected, in relation to the other residential cells, to justify a separate grouping. Also, no cell consisting of mobile homes was large enough to be included as a major cell. This does not imply that mobile homes are not important. Mobile homes have special characteristics that warrant their treatment in a separate analysis.

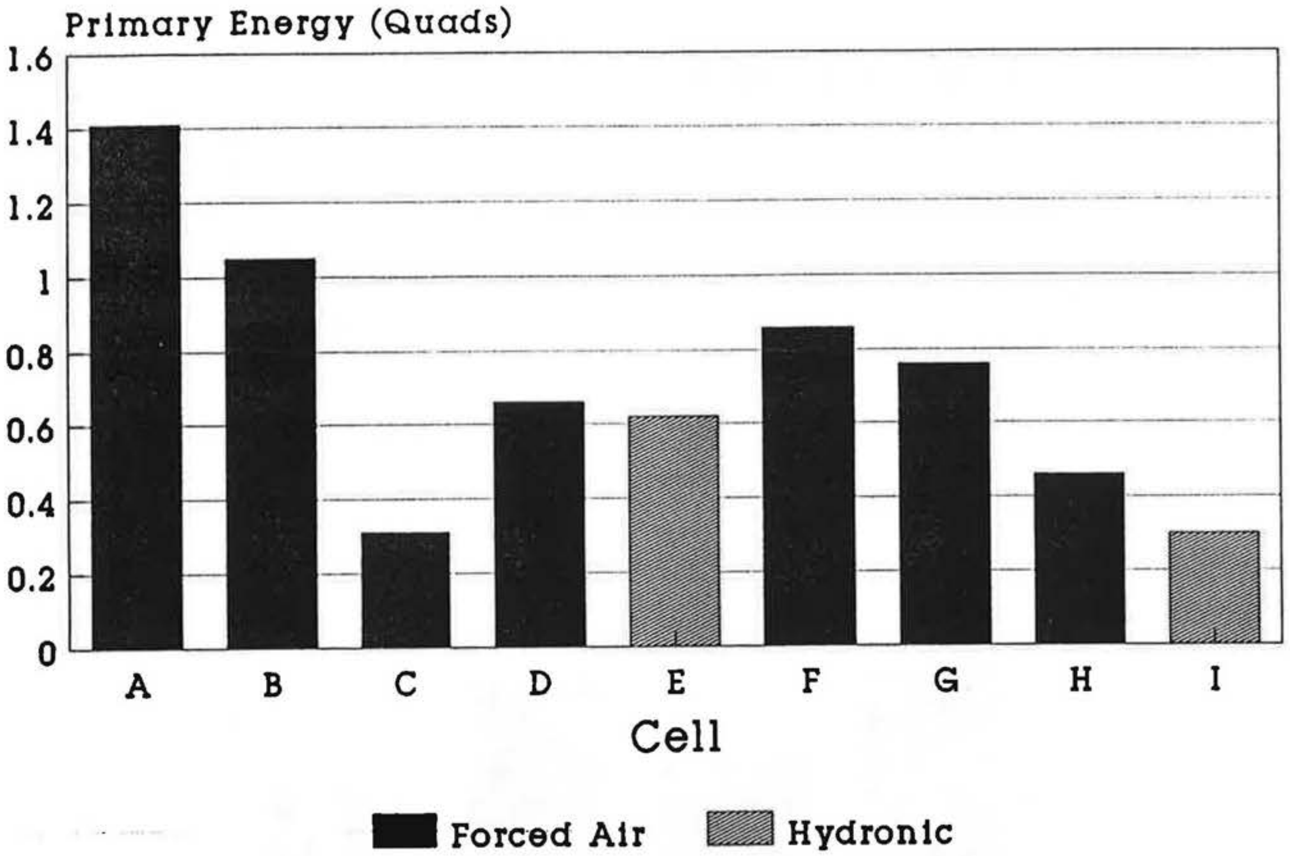

Figure S-1. Total Space Heating and Cooling Primary Energy Use by Cell for Existing and New Housing Projected to 2020. Cell Descriptions as Follows:

Cell	Existing/ New	Climate Zone	Building Type	Thermal Distribution Type	Thermal Distribution Location
A	Existing	Sunbelt	Single-Family	Forced-Air	Unconditioned Space
B	New	Sunbelt	Single-Family	Forced-Air	Unconditioned Space
C	Both	Sunbelt	Single-Family	Forced-Air	Partly Conditioned
D	Both	Sunbelt	Multifamily	Forced-Air	Any
E	Both	Frostbelt	Single-Family	Hydronic	Any
F	Both	Frostbelt	Single-Family	Forced-Air	Partly Conditioned
G	Both	Frostbelt	Single-Family	Forced-Air	Unconditioned Space
H	Both	Frostbelt	Multifamily	Forced-Air	Any
I	Existing	Frostbelt	Multifamily	Hydronic	Any

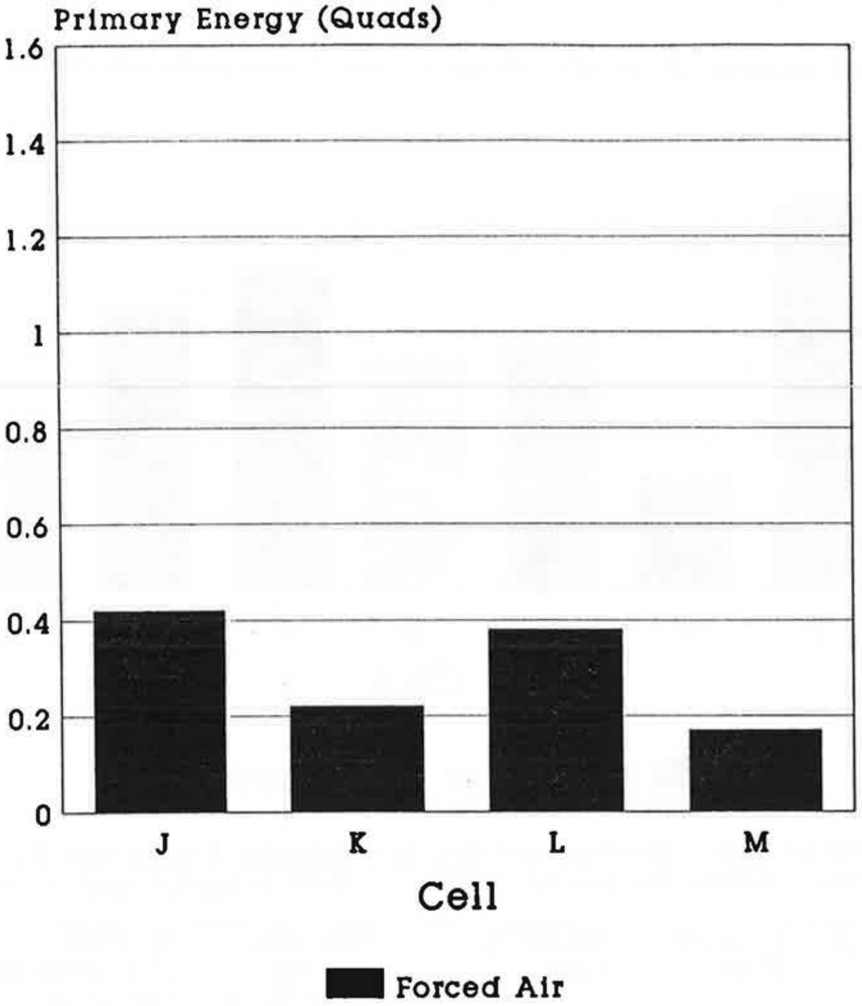

Figure S-2. Total Space Heating and Cooling Primary Energy Use by Cell for Existing and New Small Commercial Buildings Projected to 2020. Cell Descriptions as Follows:

Cell	Existing/ New	Climate Zone	Building Type	Thermal Distribution Type	Thermal Distribution Location
J	Existing	Sunbelt	Small Comm'l.	Forced-Air	Any
K	New	Sunbelt	Small Comm'l.	Forced-Air	Any
L	Existing	Frostbelt	Small Comm'l.	Forced-Air	Any
M	New	Frostbelt	Small Comm'l.	Forced-Air	Any

Commercial-Building Energy Use

In the commercial sector, the study focused on small buildings because they have several features in common with residences, whereas large commercial buildings are quite different. The dividing line between small and large buildings is believed to lie somewhere between 10,000 and 100,000 square feet of floorspace. Consistent with this study's conservative approach, it took 10,000 square feet as the upper limit for a "small" building.

In 1986, forced air was used in 69% of small commercial buildings that were heated or cooled; the market share for this type of distribution system is increasing. The present analysis yielded four cells (all forced-air) that together accounted for 1.18 quads of primary energy use in 2020. These cells used 16% of all commercial-building (large and small) space-conditioning energy in 1986, and 17% of a DOE projection to 2010 (the latest year available). Our projection therefore appears reasonable, and perhaps conservative. These cells are shown in Figure S-2.

Energy-Savings Estimates

Estimates of the energy savings that could be derived from improvements in thermal distribution were developed on a cell-by-cell basis. A distinction was made between current energy-savings potentials and full energy-savings potentials. Current savings potentials include technologies that are developed and that are reasonably well understood, at least in the buildings research community. Further efforts required to bring this category of potential to actuality will include development of more convenient diagnostics, development of verifiable accepted standards, demonstration projects, market analysis, and development of appropriate market mechanisms.

Full energy-savings potentials include the ultimate potential for savings possible by modifications to the thermal distribution systems within each cell for which we had sufficient information. Although it is unlikely that this potential would be fully realized, we expect that substantial fractions of this potential could be achieved. The efforts requried to achieve this potential will include basic technology development as well as exploratory research to improve our understanding of the processes involved and potential fixes possible. The full potential savings estimates include the current savings as a subset.

In addition, a third category, called undetermined energy-savings potential, was used for cells where we considered our present analysis too uncertain to justify a definite figure. The values presented represent our best (we think conservative) judgment of what the potentials might be.

The residential energy-savings estimates are shown in Figure S-3. The large potentials for Cells A, B, and G result from the fact that they represent forced-air systems located in unconditioned spaces--subject to the greatest losses.

The current potentials in Cells A and G (existing single-family housing with forced-air distribution systems located in unconditioned spaces, in the Sunbelt and Frostbelt, respectively) will result from a generally applied program of duct-leak reduction (by 50%) and duct insulation (to R-8), levels which can be achieved now on a retrofit basis. Research is needed to improve

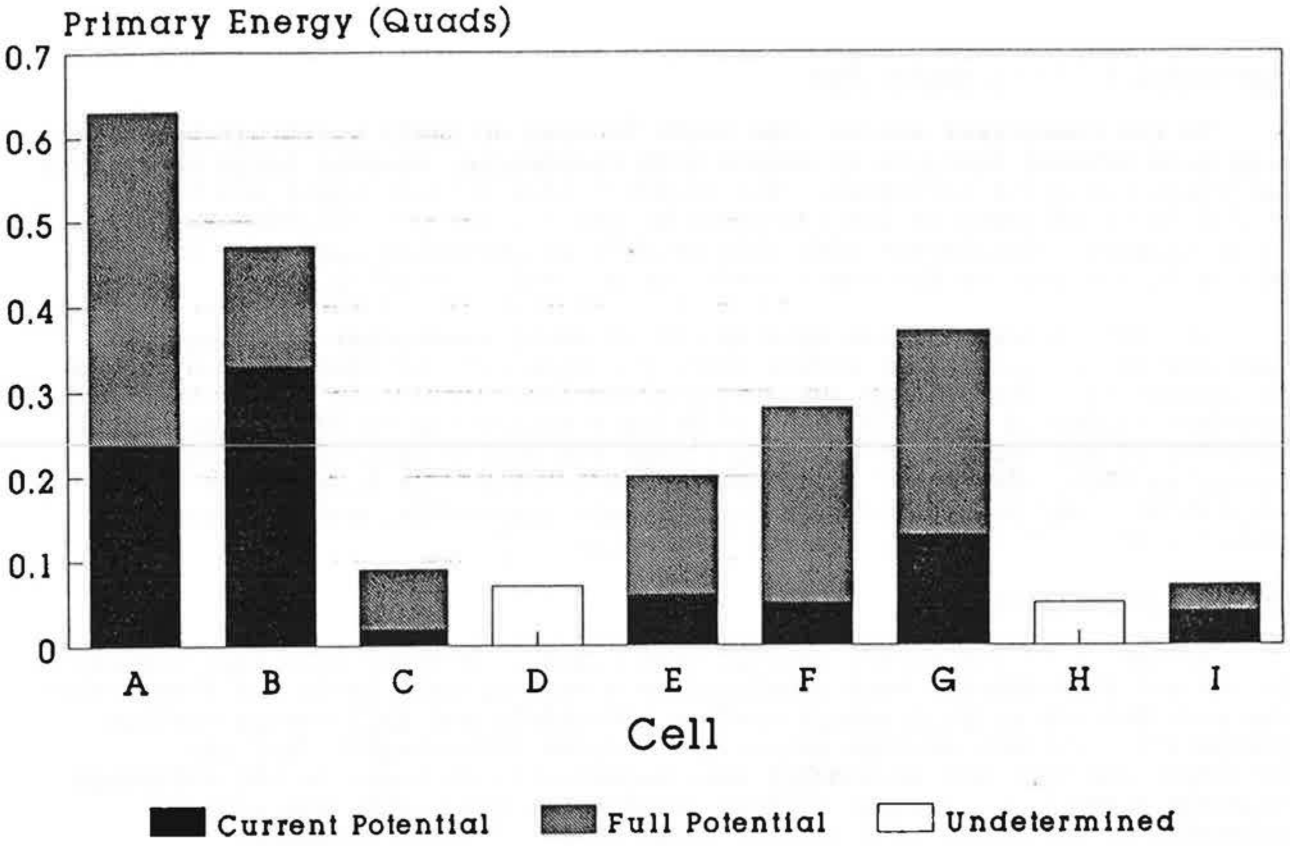

Figure S-3. Energy Savings Estimates by Cell for Existing and New Housing Projected to 2020. Cell Descriptions the Same as in Figure S-1.

the cost-effectiveness of these retrofits. In the new Sunbelt housing represented by Cell B, more aggressive action could begin within the limits of currently available technology. This would include R-12 duct insulation and leakage reduced to 20% of current levels. Also, 30% of the new houses are assumed to be zoned.

Smaller current potentials are available in Cells C, E, F, and I. The current potential for Cell F is limited because, in basement ductwork, some of the losses are effectively recovered through system interactions. It should be noted that greater savings may be expected if insulating the entire basement is included in the retrofit package; this option was not considered here because it is not, strictly speaking, a distribution-system retrofit.

The full energy-savings potentials for Cells A, B, and G envision zoned systems with no duct losses. Considerable research would be needed to achieve these potentials, especially in existing housing. For Cell F (single-family with basement ducts in the Frostbelt) the additional energy savings derive from a package of retrofits including zoning. For Cell E (single-family hydronic in the Frostbelt), the additional savings derive from proposed retrofits that would zone the houses and permit the application of efficient condensing boilers.

TECHNICAL OVERVIEW

This overview summarizes the technial approach used in the analysis. Most of the discussion here is limited to the residential sector.

As stated in the Executive Summary, the approach involved four stages. The first stage was to divide the building stock into relatively homogeneous "cells" so that the possible improvements in thermal distribution for each cell could be evaluated and the resulting energy savings estimated. The characteristics defining the cells, an understanding of which is essential if the significance of the results are to be appreciated, was discussed in the Executive Summary.

The market segmentation was begun by breaking down the 90.5 million housing units in existence in 1987 by housing type and U.S. Census region (Table 1). Next, existing single-family housing was broken down by distribution-system type and location (Tables 2-3). Then, the single-family cell populations were subtracted from corresponding totals for all housing. With a minor correction for mobile homes, this yielded the multifamily cell populations (Tables 4-7).

New housing was treated in a later section of the report. A projected annual average rate of housing construction was developed. Two data sources were compared and found to agree on the magnitude of the move to the South and West census regions (Table 16). The question of how much weight new housing should receive, relative to existing housing, was then taken up (Table 17). With these preliminary results in hand, the data were now used to develop an annual construction rate for single-family housing, broken down by distribution-system type and location (Tables 18-19). Similar breakdowns for new multifamily housing were then estimated, albeit with less confidence.

The second stage of the analysis was to estimate energy use per household for space heating and cooling. The Gas Market Survey gives numerical values for the average amount of gas used for space heating in each of the four census regions. We took this as indicative of the space-heating energy use for all fossil fuels, and we modified it in an appropriate way for electric heat. As a check, we computed the total space-heating energy use in the U.S. residential sector and compared it with the value given in DOE 1989. The totals agreed to within 2%. The discussion is in the text associated with Tables 8-12.

For space cooling we had no such direct indicator of energy use on a per-household basis. Instead, we worked backward from a national total as given in DOE 1989 to individual household usage. To do this, we converted RECS data on numbers of houses by census region, house type, and level of air conditioning to an equivalent number of centrally air-condtioned single-family houses in the South and West census regions. Dividing total usage by the number of these "full-load-equivalent" houses gives the energy use for cooling one such house. From that number, values for other house types were then determined. See Tables 13-14 for details. Table 15 summarizes the results for heating and cooling in existing housing.

Future energy conservation was taken into account by assuming that, not including advances in thermal distribution, new housing would use 40% less energy per household than existing housing. Further conservation via retrofits in existing housing was also assumed to occur in future years. (See discussion following Table 19.)

The third stage was to project the building stock out to the year 2020. This was done in order to include new and existing buildings together in an appropriate way. We used the discussion of relative weights for existing and new housing (Table 17) to decide how many years of new housing should be included in the analysis. Clearly, one year of new housing would give an inadequate picture of the impact of many years of cumulative improvements in the new housing stock. However, an arbitrarily large number of years would be inappropriate as well. On the basis of discounting, we settled upon 25 years of new housing as an appropriate measure of this segment's importance. We then developed an accounting system in which housing constructed between 1995 counted as "new" and that constructed in 1995 or before counted as "existing." The rationale was that improvements resulting from a DOE research program could begin to have a major impact on new housing at about that time. The projection accounted for attrition in existing housing due to fire, demolition, and condemnation. The projection of housing to 2020 is discussed in the sections associated with Tables 20-23.

The last step was to estimate energy savings from improved thermal distribution as percentages of the annual energy use projected for 2020. The most comprehensive effort involved simulations of Sunbelt houses with ducts in attics and crawlspaces, the types represented in Cells A and B. These simulations, with experimental results used as input parameters and reality checks, provided near-term ("current") and ultimate ("full") energy-savings potentials for these cells. The results were extrapolated to the Frostbelt to obtain estimates for Cell G.

Cell F (ducts in basements, Frostbelt) was treated by referral to results from the so-called SP-43 project carried out in the 1980's under the auspices of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers. In this project, two houses with basement ductwork in Columbus, Ohio were monitored and used to validate a computer program. The results of the computer modeling were used to estimate the extent to which duct losses are recovered through system interactions. The results from this cell were then used to evaluate the small Cell C.

Cell E (single-family hydronic, Frostbelt) was analyzed using earlier work at Brookhaven National Laboratory that proposed a simple retrofit to make possible improvements in boiler efficiency and zoning. Multifamily hydronic (Cell I) is distinguished by a high population of steam (as opposed to hot-water) systems. Several retrofits germane to such systems were used to estimate potential savings.

For the six remaining cells, represinting multifamily and small-commercial forced-air systems, insufficient information to make credible estimates was available. For these cases, best-judgment estimates based on analogy with other systems were made, taking into account likely differences between them.

In all stages of the analysis, emphasis was placed on consistency checks provided by data from different sources. A summary of these checks is given in the Introduction.

INTRODUCTION

The need for improved efficiency in thermal transport within buildings has been pointed out often.[Cummings and Tooley 1989, Gammage et al. 1986, Grot and Harrje 1981, Lambert and Robison 1989, Modera 1989, Parker 1989, Orlando and Gamze 1980, Robison and Lambert 1989] This need arises from two considerations. First, energy losses in such systems in existing buildings are perceived to be large. Second, these systems have received far less research and development effort than either the building shell itself or the lighting, appliances, and space-conditioning equipment within buildings. Although the management of the U.S. Department of Energy (DOE) has recognized the need for such research for many years, it has not had the flexibility, within the constraints imposed on it by Congress, to provide much funding for the work. During discussions with DOE management, it was suggested that one of the reasons for this lack of support has been that the potential for energy savings was not sufficiently well defined. True, previous studies had estimated large potential savings, but those estimates were based on broad-gauge considerations that did not address specific system types in sufficient detail to be credible. It is the purpose of this study to rectify that deficiency.

In order to determine whether a significant national research effort could be justified, it was judged that four things would need to be done. First, the study must segment the residential and small commercial building market into "cells" that are homogeneous with respect to characteristics that are germane to thermal distribution. Second, the energy use per building must be evaluated within each of these cells. Third, a reasonable and consistent means of giving relative weight to existing buildings and new construction needed to be devised. Finally, specific means of conserving energy through distribution system improvements need to be detailed for each cell, and the potential savings quantified. When all this had been done, the overall savings potential was calculated by multiplying the percent savings estimate for each cell by the current energy use for that cell, and summing over the cells.

Some elaboration on the third task in the above list may be in order here. It was recognized that the energy-savings opportunities available in new construction will likely be different from those that are possible in existing buildings, both in character and magnitude. Therefore, a reasonable and consistent method of accounting for new and existing buildings needed to be devised. Consideration based on discounting led us to believe that 25 years would span an appropriate number of new buildings, for the purpose of weighing relative costs and benefits of research directed toward new construction as opposed to retrofit. In order to provide a consistent set of energy-use and energy-savings estimates, we therefore decided to construct a "snapshot" of the building stock projected to the year 2020, in which buildings constructed between 1995 and 2020 are considered "new," and those constructed in 1995 or earlier are considered "existing." The year 1995 was chosen as the watershed between existing and new buildings in this context, because it was judged to be the approximate date at which a DOE research program could begin to have significant impact on thermal distribution systems in new construction.

A final item for discussion here is our decision to focus on primary rather than end-use energy. We have chosen to consider primery energy because our point of view is that of society as a whole, for which consideration of the total energy cost of an activity is appropriate, whether that energy is used on site or at a power plant. We recognize that some important factors are not captured in this approach, e.g. differences between fuels relating to energy security, environmental effects, and cost, but we view it as preferable to considering end-use energy only, which ignores not only these differences but also the thermodynamic and economic differences between electricity and fuels used on site.

Data Sources

It was beyond the scope of this study to obtain original data. We therefore had to depend on the published literature and on one unpublished data set. The principal sources of information on building populations and energy use were as follows:

1. The Residential Energy Consumption Survey (1987) published by the Energy Information Administration of the DOE. This is the most comprehensive compendium of information about how the 90.5 million family units and independent individuals within the United States are housed. This survey will be referred to as RECS in this report.

2. Data provided to Brookhaven National Laboratory by the National Association of Homebuilders. This information, given as a "snapshot" of existing and new single-family-detached housing for the year 1983, provides much greater information concerning distribution systems than does RECS. Because of the slow turnover in housing, the four-year difference between this study and RECS has not proved to be a serious problem. This study will be called "the NAHB data" in what follows.

3. The Residential Gas Market Survey: 1989, published by the American Gas Association. This survey gives information about the amount of gas used for space heating in each census region for single-family, small multifamily, and large multifamily housing. Under the assumption that gas-heat households are typical of households that rely on other fuels (with some modification for households relying on electric resistance), the information presented in this survey allowed us to calculate aggregate energy use for each space-heating fuel and compare with national figures developed by the Office of Building Technologies, DOE. In what follows, this survey will be referred to as the Gas Market Survey.

4. Data on energy use by sector published by the Energy Information Administration and disaggregated by end use under the sponsorship of the Office of Buidlings Technology, DOE. Much of this information is compiled in an Annual Report, the latest available version of which is referred to here as DOE 1989.

5. The Nonresidential Buildings Energy Consumption Survey (1986) published by the Energy Information Administration of the DOE. This is the most comprehensive compendium of information about the characterisics of the 58 billion square feet of commercial floorspace in the United States. This survey will be referred to here as NBECS.

Consistency Checks

In order to achieve the greatest possible credibility for the results, we chose wherever possible not to rely on a single source of information, particularly in the assignment of numerical values to critical parameters. This section summarizes specific instances where we were able to compare one source of information with another.

Market Segmentation. The major sources of data used to segment the housing market into homogeneous "cells" were the NAHB data and RECS. These were complementary in that NAHB gave specific information about one class of housing--single-family detached (with emphasis on forced-air distribution), whereas RECS provided less detailed but still valuable information across the whole spectrum of housing types. Some comparison of the data for consistency was possible; this is discussed in the section headed "Single-Family Housing" following Table 1. In general, the level of consistency, although not perfect, was found to be good.

A second check on consistency resides in the method used to segment the existing multifamily housing market. In this case, the single-family populations obtained with the help of the NAHB data were subtracted from the RECS totals to obtain the multifamily populations as residuals. Credibility was gained when none of the residuals was negative, and the one expected to be small (Other or None) was in fact so. This is discussed in the text surrounding Tables 4-6.

For new housing, construction rates were estimated using information in the Gas Market Survey and recent-year RECS tabulations. Projections based on this information were compared with projected numbers of households in 2010, as given in DOE 1989, and found to be in reasonable agreement. This is discussed in the section headed "Market Segmentation Procedure--New Buildings" immediately following Table 15.

Energy Use Per Household. Our method of calculating the space-heating energy use for each housing "cell" was to multiply the space-heating gas consumption per household, as given by the Gas Market Survey for each of the four U.S. Census regions, by the number of households using natural gas, as given by RECS. A variant of this procedure was then used for other space-heating fuels. The total residential space-heating energy use was then compared with the value given in DOE 1989. The agreement for each fuel was typically within ~10%. The overall agreement was within 2%. This comparison is discussed in the text following Table 11.

Residential space cooling energy was computed by dividing the national total primary-energy use, given in DOE 1989, by an aggregated equivalent number of fully air-conditioned houses, taking account variations in levels of air conditioning in the various regions of the country. This was compared with the amount of primary energy that would be used by a typical home central air conditioner running a number of hours as given in a standard chart of full-load-equivalent air-conditioner use. Our estimate of energy use was found to be 39% less than that predicted using the chart. This leads us to believe that our assumptions are within reason, and perhaps conservative. This is discussed in the text following Table 13.

Energy-Use Projections. Projected space-heating and cooling energy use, as determined in this analysis, was compared with projections in DOE 1989 for the entire residential sector. The fraction of heating and cooling energy use accounted for by the major cells under consideration was found to remain nearly constant. The fraction of households represented by these cells is increasing; therefore, the energy-use projections are viewed as within reason and, if anything, conservative. This is discussed in connection with Table 23.

CHOICE OF MARKET SEGMENTS

Choosing a market-segmentation scheme is not a trivial matter. There is no single "right answer." Because of the differences among buildings, it could be argued that a completely suitable market segmentation must consider each building individually. Obviously, such an approach is impossible. On the other hand, too coarse a segmentation may lump together buildings of such disparate nature that the results could be of little use. We therefore have to strike a middle ground, keeping the number of cells as small as possible yet striving for near homogeneity within each cell.

Also, the choice of a segmentation scheme is driven to a great extent by the type of information that is available. It does no good to set up a system of categories if no published data follow that scheme.

With these considerations in mind, the following classification scheme was used:

	Characteristic	Possible Values (Categories)
I.	Existing Building or New Construction	1. Existing 2. New
II.	Climate Zone	1. "Frostbelt" (Northeast and Midwest Census Regions) 2. "Sunbelt" (South and West)
III.	Building Type	1. Single Family 2. Mobile Home (HUD-Code Housing) 3. Multifamily 4. Small Commercial
IV.	Thermal Distribution Type	1. Forced Air 2. Hydronic 3. Built-In Electric 4. Other or None
V.	Thermal Distribution Location	1. In Unconditioned Space (Crawlspace or Attic) 2. In Partly Conditioned Space (Basement) 3. In Conditioned Space

The following comments on this classification scheme are in order.

1. The distinction between existing and new construction is driven by the fact that changes in existing buildings must be retrofit, a definite limitation on how innovative one can be. New construction can change much more radically, although there is no guarantee that it will do so.

2. We have limited the discussion to two "climate zones" that follow the census regions. While it is recognized that the designations Sunbelt and Frostbelt are not appropriate across all of the regions chosen (it puts Alaska in the Sunbelt, for example), it is nevertheless true that 69% of the

population in the South and West lives in areas with fewer than 4000 heating degree-days, while essentially all of the people in the Northeast and Midwest live in areas with more than 4000 heating degree-days.[RECS, p. 65] From the standpoint of heating energy use in the two regions, the Gas Market Survey (p. 13) quotes the average gas energy use for space heat in single-family dwellings as 105 million Btu in the Northeast and 110 million Btu in the Midwest, while for the Sunbelt the comparable figures are 55 million Btu in the South and 44 million Btu in the West.

3. The building type designations are those of RECS, with small commercial added. As will be discussed below, we believe the distinction between small and large commercial buildings, at least as far as thermal distribution is concerned, should be made on the basis of whether the chief energy conservation issue is thermal losses (small buildings) or fan power (large buildings). We do not know where the dividing line is between these two classes but believe it to lie somewhere between 10,000 and 100,000 ft^2.

4. In terms of installed units, forced air is far and away the most important residential type, even in existing housing. In new housing it comprises almost 90% of installations.[NAHB data]

5. The location of the thermal distribution system has a great impact on the effect of undesired heat and mass transfer from the system (thermal losses and leakage) on overall energy use. Forced-air distribution systems in unconditioned spaces generally suffer the most severe penalties, but even systems that are wholly within the conditioned space can still give rise to losses through system effects, e.g. increased infiltration due to differential pressurization caused by duct leakage and by suboptimal location of supply and return registers.

This classification scheme results in 192 cells (2 X 2 X 4 X 4 X 3). This is far too many to handle conveniently. It should be noted, however, that many cells will have a relatively small number of housing units or buildings in them. In other cases, cells can be combined with no loss of utility. (For example, distribution system location is most significant for forced-air systems. It is only moderately significant for hydronic systems. Built-in electric systems are all within the conditioned space.) Our approach is to identify those cells that have significant fractions of the total building stock in them, and to examine them in more detail for potential thermal-distribution system improvements.

MARKET SEGMENTATION PROCEDURE--EXISTING RESIDENTIAL BUILDINGS

We began the market segmentation with a study of existing residential buildings. RECS (p. 16) gives a breakdown of the 90.5 million households that existed in November, 1987, as shown in Table 1.

The Sunbelt (South and West census regions) has somewhat more households than the Frostbelt (54% vs. 46%), though the difference is not large on a percentage basis. This will contrast with the picture for new construction, where the Sunbelt has a distinct edge. It is also seen that by far the largest group of households lives in single-family residences. We therefore begin by considering this category in detail.

Table 1. Breakdown of Housing Types by Region in November, 1987 (Millions of Households)

House Type	Census Region				
	Northeast	Midwest	South	West	Total U.S.
Single-Family Detached	9.1	14.7	20.8	10.5	55.2
Single-Family Attached	2.0	0.9	1.5	0.9	5.3
Small Multifamily (2-4 Units)	3.2	2.6	2.2	2.0	10.1
Large Multifamily (5 or More Units)	4.1	2.8	4.2	3.8	14.9
Mobile Home	0.7	1.2	2.2	1.0	5.1
Totals	19.0	22.3	30.9	18.3	90.5

Single-Family Housing

Here we will consider all existing residential buildings occupied by one household, with the exception of mobile homes. These include single-family detached and single-family attached. Our method will be to use existing data on single-family detached to segment the market, and then prorate for all single-family housing, on the assumption that single-family-attached are not enough different from their detached counterparts to make a significant difference in the overall accounting. This procedure is justified in part by the small number of attached relative to detached housing units.

In 1985, BNL obtained data from NAHB on both existing (pre-1983) and new (constructed during 1983) single-family-detached housing. Information on thermal distribution systems more detailed than that in RECS was provided, with a special focus on forced air. These data are presented in Table 2, aggregated to a level approximating the categories discussed above.

Distribution-System Location. If we compare the categories of Table 2 with our distribution system categories, we see that we can make correspondences under the following assumptions, all of which are judged to be reasonable in the vast majority of cases:

1. In houses with basements, it is usual to place ductwork in the basement. This is more accessible than the attic and it is also closer to the usual location of the heating and cooling equipment, which is also generally placed in the basement. Although some basements are thermostatically controlled, most are not. We do not have good information on the prevalence of insulation in basements, or on mean air-infiltration values. There is good reason to believe, however, that insulation levels average less, and air-infiltration rates more than in living spaces. See, for example, Jacob et al. 1986. We therefore placed all of the houses with basements in the category "thermal distribution system in a partially conditioned space."

2. In houses with crawl spaces, the ductwork is usually placed there, although it is sometimes placed in the attic. Although some attempt is generally made to isolate the crawlspace from the exterior environment, the temperature within crawl spaces is generally much closer to that of the outside than is that of a basement. (For example, in the simulations reported in Jacob et al. 1986, the average crawlspace temperature averaged 13 F less than that in a basement.) We therefore placed all of the crawlspace houses in the category "thermal distribution system in an unconditioned space."

Table 2. Distribution of Existing (1983) Single-Family-Detached Housing into Categories per NAHB Data (Millions of Households)

Distribution System Type	House Structure	Frostbelt (Northeast and Midwest)	Sunbelt (South and West)
Forced Air	Basement	6.56	2.21
	Crawlspace	2.54	5.03
	Slab	2.27	6.52
	Bilevel	0.75	0.45
	Split Level	0.90	0.69
Hydronic	All	6.70	1.68
Built-In Electric	All	0.92	1.72
Other or None	All	4.35	13.74
Totals		24.99	32.04

3. In houses built on slabs, the usual placement of the trunk and branch ducts is in the attic, particularly in one-story houses. (One-story houses comprised 75% of the total slab-on-grade houses with forced-air distribution.) Attics are generally well ventilated to prevent overheating in the summer. We therefore placed all of the slab-on-grade houses in the category "thermal distribution system in an unconditioned space."

4. The bilevel or "raised-ranch" house has a lower story that is partly below grade level, but which nevertheless is part of the conditioned space. The ductwork is usually run along the interface between the upper and lower story, and hence is within the conditioned space.

5. In split-level houses, the portion not split is generally built on a slab or over a crawl space. Some of the ductwork will be in unconditioned spaces while some may be in the lower portion of the split (two-story) half. It is difficult to characterize this category of housing. Fortunately, the number of split-level houses is relatively small. For the purposes of this study, the split level houses will be placed in the category "thermal distribution system in an unconditioned space."

Using the data of Table 2, and assigning ductwork location according to the above considerations, we arrive at Table 3. In Table 3, we have multiplied all Table 2 values by the ratio of the RECS total of single-family houses in Table 1 to the NAHB total of single-family-detached houses in Table 2. This was done separately for each climate zone. Thus, for the Frostbelt the multiplier was 26.7/24.99 while for the Sunbelt it was 33.7/32.04.

Looking at Table 3, we note that forced-air systems comprise just under half of all existing single-family dwellings. Twenty-four of the 192 homogeneous "cells" defined earlier refer to existing single-family housing. As distribution-system location is of minor or no significance in hydronic and built-in electric systems, we combined the system locations for these to reduce the number of cells to 16. And, although we would like to do more with the "other or none" category, we do not now possess sufficient information to do so. Eliminating this category reduces the number of existing single-family cells to ten. Of these, four have six million or more houses in them. In decreasing order of numbers, these are:

- Forced-air systems, ducts in unconditioned space, Sunbelt
- Hydronic systems, Frostbelt
- Forced-air systems, ducts in partly conditioned space, Frostbelt
- Forced-air systems, ducts in unconditioned space, Frostbelt

One additional cell will be included, even though it has only 2.3 million houses. This is:

- Forced-air systems, ducts in partly conditioned spaces, Sunbelt

This cell was included is done because, when combined later on with new housing of the same type, it was projected to use more than 0.3 quads (1 quad = 10exp15 Btu) of energy for space heating and cooling in the year 2020. This level of energy use was set as a criterion for determining whether a given population of housing was sufficiently important to include it in further analysis.

Together, these units comprise 59% of the single-family houses. Another 31% of the single-family units are in the "other or none" category, which includes such things as wood stoves, free-convection furnaces, and room heaters, which should be considered in future work but which are beyond the scope of the present analysis.

Table 3. Distribution of Existing (1987) Single-Family Housing into Categories Defined in This Study (Millions of Households)

Distribution System Type	Distribution System Location	Frostbelt (Northeast and Midwest)	Sunbelt (South and West)
Forced Air	Unconditioned Space (Ducts in Attic or Crawl)	6.1	12.9
	Partly Conditioned Space (Ducts in Basement)	7.0	2.3
	Conditioned Space (Ducts in Bilevel House)	0.8	0.5
Hydronic	All	7.2	1.8
Built-In Electric	Conditioned Space	1.0	1.8
Other or None	All	4.6	14.4
Totals		26.7	33.7

Note: Table 3 values obtained from Table 2 by assigning duct location on the basis of house type and multiplying resulting values by 1.068 (Frostbelt) or by 1.052 (Sunbelt) to normalize NAHB data to RECS.

Consistency of Data Sources. It is seen that the total number of single-family-detached units given in the NAHB data is just over 57 million, while RECS gives the total as 55 million nearly four years later. Given a housing growth rate of ~1% per year, this works out to about an 8% discrepancy on a same-year basis. The source of this difference is unknown, nor is it known whether to attribute error to RECS or to NAHB. We choose to use the RECS totals as our standard, because RECS is in the public domain, and to normalize other data to RECS. That is, we will adjust the numbers in Table 2 by the ratio of the RECS total to the NAHB total, so that the results will be in agreement with RECS.

Two additional consistency checks between RECS and the NAHB data were performed. In the first check, the geographical distribution of singlefamily-detached housing as given in RECS page 16 was compared with that in the NAHB data. The percentage of houses in each of the four U.S. Census regions differed by no more than 1% between the two sources.

The second check compared fueluse statistics for singlefamily (detached plus attached) housing as given in RECS page 45 with those of NAHB. In this case NAHB gave percentages for gas, electric, and oil use that were 3, 4, ans 2 percentage points less than RECS, contributing to an "other or none" component of 24% for NAHB vs. 15% for RECS. It is possible that this difference lies in a systematic difference in treatment of houses with more than one heating system.

No direct comparison of the two sources with respect to thermal-distribution system type was possible because RECS did not break down single-family housing with respect to this variable.

Multifamily

The treatment of multifamily buildings will necessarily be less precise than that for single-family residences, because the available data are less precise. Particularly in cases where the number of households in a particular class is small, it will be necessary to make judgments that are not supported by hard information. The approach will be to subtract the single-family totals for each category from the overall totals as given in RECS. Following this, further subtractions will be made for mobile homes to obtain a residual of households in multifamily buildings.

The calculations described in this section are summarized in Table 4. We begin with the totals of non-single-family dwelling units from RECS for the Frostbelt and Sunbelt, as summarized in Table 1. These totals are displayed in Line 1 of Table 4.

Next, we obtain the totals of households with forced-air distribution systems, for each climate zone, from page 29 of RECS. These totals were entered on Line 2. Forced air is assumed to comprise the following RECS categories: natural gas, central warm-air furnace; electricity, central warm-air furnace; electricity, heat pump; fuel oil, central warm-air furnace; and LPG, central warm-air furnace. (Where RECS gave a non-value [Q] for any census region and category, a proxy value was calculated by subtracting the other three regions from the total for that category. It was felt that this would be a better procedure than assuming a zero for these cases.)

Next, the number of forced-air distribution systems serving non-single-family dwelling units was obtained by subtracting the single-family values from Table 3 (entered here on line 3) from the totals. The result was entered on Line 4.

A similar procedure was followed to obtain the number of hydronic systems in non-single-family households. Hydronic was assumed to comprise the following RECS categories: natural gas, steam or hot water system; and fuel oil, steam or hot water system. The results appear on Line 7.

A similar procedure was also followed to obtain the number of built-in electric systems in non-single-family households. Built-in electric is a single category in RECS. The results appear on Line 10.

Finally, with the numbers in hand for forced air, hydronic, and built-in electric, the "other or none" category was obtained by subtracting these from the totals for non-single-family on Line 1.

One remaining task remains to be done with these values: mobile homes must be filtered out. We do not, unfortunately, have good, detailed data on mobile homes. RECS provided data on mobile homes, but without the necessary crosscuts to make the subtractions exactly. Hence, the following procedure was used.

First, the number of mobile homes using wood or kerosene as the main heating fuel is given by RECS, page 45, as 0.8 million. These will mostly fall in the "other or none" category, and the number is nearly the same as the "other or none" total for both climate zones in Table 4. Thus, we conclude that, after subtracting out mobile homes, few cases are left of multifamily dwellings with distribution systems in the "other or none" category.

Table 4. Distribution-System Characteristics of Existing (1987) Non-Single-Family Buildings, Including Mobile Homes (Numbers in Millions of Households)

Building Set Description	How Obtained or Source	Frostbelt (Northeast and Midwest)	Sunbelt (South and West)
1. Total Non-Single-Family (Note 1)	RECS p. 16	14.6	15.4
2. Total Forced Air	RECS p. 29	21.1	28.4
3. Single-Family Forced Air	Table 3	13.9	15.7
4. Non-Single-Family Forced Air	(2) - (3)	7.2	12.7
5. Total Hydronic	RECS p. 29	13.6	1.9
6. Single-Family Hydronic	Table 3	7.2	1.8
7. Non-Single-Family Hydronic	(5) - (6)	6.4	0.1
8. Total Built-In Electric	RECS p. 29	1.9	3.6
9. Single-Family Built-In Electric	Table 3	1.0	1.8
10. Non-Single-Family Built-In Elec.	(8) - (9)	0.9	1.8
11. Non-Single-Family Other or None	(1)-(4)-(7)-(10)	0.1	0.8

Note 1. Non-Single-Family in this table includes mobile homes.

Once this is done, dividing the remaining mobile homes into the forced-air, hydronic, and built-in-electric categories is more difficult. One significant piece of information gleaned from RECS (page 46) is that 1.3 million mobile homes have central air conditioning. Since nearly all central air-conditioning systems in the United States are associated with forced-air distribution, this sets a minimum on the number of forced-air systems in mobile homes. Another important datum (RECS page 45) is that 2.9 million mobile homes are heated with either natural gas or LPG. Some of these may be room heaters with no central distribution system. However, our accounting system has left little room in the "other or none" category for non-single-family dwellings after the wood- and kerosene-using mobile homes were subtracted out. Relatively few mobile homes have hydronic distribution systems. It is therefore concluded that most of these 2.9 million mobile homes have forced-air distribution systems.

In RECS, page 46, it is stated that 1.0 million mobile homes use electricity for heating. We believe that most of these are electric baseboard or other type of built-in electric, as opposed to heat pumps.

Finally, 0.4 million mobile homes are heated with oil. Use of hydronic heating in mobile homes is probably concentrated in these units, since oil heat and hydronics are both heavily represented in the same region, the Northeast.

On the basis of these considerations, the mobile homes were divided into distribution-system categories as follows: forced-air, 2.9 million; hydronic, 0.4 million; built-in electric, 1.0 million; and other or none, 0.8 million. They were distributed by region on the same percentage basis as the overall fuel/distribution-system combinations in RECS, page 65, except for the "other or none" category, which was placed mostly in the Sunbelt due to the small Frostbelt residual for this category in Table 3. When this was done, the total of mobile homes for the Frostbelt was higher by 0.3 million than the total number of mobile homes for the region as given by RECS page 16, with a corresponding deficiency for Sunbelt mobile homes. This was rectified by transferring 0.3 million mobile homes with forced air from the Frostbelt to the Sunbelt. The results of this distribution are given in Table 5.

Table 5. Mobile Homes by Distribution Category
(Millions of Homes)

	Frostbelt	Sunbelt
Forced-Air	1.1	1.8
Hydronic	0.4	0.0
Built-In Electric	0.3	0.7
Other or None	0.1	0.7
Totals	1.9	3.2

These numbers were subtracted from the corresponding categories (4, 7, 10, and 11) in Table 4. The results are given in Table 6.

Of the 192 "cells" defined earlier, 24 refer to existing multifamily buildings. Lacking information on the location of distribution systems in multifamily housing, we have had to combine these, even for forced-air. This reduces the number of cells from 24 to 8. Of these, three stand out in Table 6 as having significant numbers of households. In decreasing order of numbers, they are:

- Forced-air systems, Sunbelt
- Forced-air systems, Frostbelt
- Hydronic systems, Frostbelt

Table 6. Distribution-System Characteristics of Multifamily Buildings (Numbers in Millions of Households)

Building Set Description	How Obtained or Source	Frostbelt (Northeast and Midwest)	Sunbelt (South and West)
1. Non-Single-Family Forced Air	Table 4, l. 4	7.2	12.7
2. Mobile Homes with Forced Air	Table 5	1.1	1.8
3. Multifamily Forced Air	(1) - (2)	6.1	10.9
4. Non-Single-Family Hydronic	Table 4, l. 7	6.4	0.1
5. Mobile Homes with Hydronic	Table 5	0.4	0.0
6. Multifamily Hydronic	(4) - (5)	6.0	0.1
7. Non-Single-Family Built-In Elec.	Table 4, l. 10	0.9	1.8
8. Mobile Homes with Built-In Elec.	Table 5	0.3	0.7
9. Multifamily Built-In Electric	(7) - (8)	0.6	1.1
10. Non-Single-Family Other or None	Table 4, l. 11	0.1	0.8
11. Mobile Homes with Other or None	Table 5	0.1	0.7
12. Multifamily, Other or None	(10) - (11)	0.0	0.1

Mobile Homes

Mobile homes, both existing and new, comprise another 48 of our 192 cells. The number of existing (1987) mobile homes is given in RECS as 5.1 million (Table 1). Since these are split among distribution system types (cf. Table 5), it is unlikely that any cell of mobile homes will have enough units to merit consideration as a major group. This does not mean that mobile homes are unimportant; however, because of their relatively small numbers and dispersal among distributionsystem types, they will not be considered further here.

Existing Buildings Summary

We are now in a position to state that most of the existing households can be placed in seven of the "cells" defined by our classification scheme. The numbers are given in Table 7.

Table 7. Cell Populations, Existing (1987) Housing

Cell Description	Number of Households (Millions)
Single-Family, Forced-Air, Ducts in Unconditioned Space, Sunbelt	12.9
Multifamily, Forced-Air, Sunbelt	10.9
Single-Family, Hydronic, Frostbelt	7.2
Single-Family, Forced-Air, Ducts in Partly Conditioned Space, Frostbelt	7.0
Single-Family, Forced-Air, Ducts in Unconditioned Space, Frostbelt	6.1
Multifamily, Forced-Air, Frostbelt	6.1
Multifamily, Hydronic, Frostbelt	6.0
Single-Family, Forced-Air, Ducts in Partly Conditioned Space, Sunbelt	2.3

Taken together, these eight cells include 88% of households that are not in mobile homes or in the "other or none" category with respect to distribution system type.

ENERGY USE PER HOUSEHOLD--EXISTING RESIDENTIAL BUILDINGS

As discussed in the introduction, the second step in estimating energy savings potential, after market segmentation, is estimating per-household energy use. For space heating, two independent sources of information were used, which permitted a cross-check on the validity of the estimates. The Gas Market Survey provided values for average gas usage for space heating in each of the four U.S. census regions. Basing the usage for all fuels on that for gas, total consumption figures were developed for the U.S. as a whole. These were compared with values given in DOE 1989, p. 3-4. Space cooling energy use was evaluated with the help of DOE 1989 and RECS.

Space Heating--Natural Gas

The Gas Market Survey, page 13, gives average fuel usage for gas-heat households. The usage is broken down into heating and baseload, where baseload means gas used for purposes other than space heating, i.e. ranges and ovens, clothes dryers, water heaters, and other gas appliances. Gas usage is given for single-family and for multifamily households in each census region. A combined average usage for all households is given as well.

Table 8 shows a computation of the national annual residential gas usage for space heating. The computation uses gas-heat housing populations from RECS, page 65, together with the combined average gas usage for space heating from the Gas Market Survey. The total of 3.15 quads is to be compared with the total of 2.87 quads of natural gas for residential space heating given in DOE 1989. The 9% difference is judged to be within the expected levels of error in the two studies. We therefore feel confident in using the individual-household gas-usage figures from the Gas Market Survey in our energy savings analysis.

Table 8. Computation of Annual U.S. Natural Gas Usage for Space Heating in Residential Buildings

U.S. Census Region	Number of Gas-Heated Households (Millions)	Average Space-Heat Gas Use per Household (Million Btu)	Total Space-Heat Gas Use in Region (Quads)
Northeast	8.1	86.5	0.70
Midwest	16.6	87.9	1.46
South	13.6	46.1	0.63
West	11.8	30.1	0.36
Totals	50.1		3.15

Note: 1 Quad = 10exp15 Btu

Space Heating--Other Fuels

We were not able to obtain information on other fuels comparable to that in the Gas Market Survey. We therefore postulated that the energy use for space heating is essentially independent of the fuel used. There are reasons to doubt that this is strictly true. Electrically heated homes, for example, have traditionally been insulated to a higher level than homes heated by fossil fuels. Differences between types of thermal distributions systems no doubt also exist. Nevertheless, we found that this assumption produced good agreement with the primary energy usages reported in DOE 1989, according to the computations described below.

Oil. Fuel oil used for space heating was handled in the same way as natural gas, with the explicit assumption that the average oil use per household is the same as for natural gas. Table 9 shows how the result, 0.87 quads, was obtained. This is to be compared with the 1.00 quads given in DOE 1989, for a difference of 13%. Given the small numbers involved, relative to gas, this percentage difference is not a great cause for concern.

Table 9. Computation of Annual U.S. Fuel Oil Usage for Space Heating in Residential Buildings

U.S. Census Region	Number of Oil-Heated Households (Millions)	Average Space-Heat Oil Use per Household (Million Btu)	Total Space-Heat Oil Use in Region (Quads)
Northeast	7.7	86.5	0.67
Midwest	1.5	87.9	0.13
South	1.3	46.1	0.06
West	0.4 (Note 1)	30.1	0.01
Totals	10.9		0.87

Note 1: Value obtained by subtraction of other 3 regions from total in RECS
Note 2: 1 Quad = 10exp15 Btu

LPG. Liquefied petroleum gas (LPG) was, like oil, handled in the same way as natural gas, with the explicit assumption that the average LPG use per household is the same as for natural gas. Table 10 shows how the result, 0.25 quads, was obtained. This is to be compared with the 0.39 quads given in DOE 1989 for LPG and coal. We were not able to subtract out the coal; however, the numbers appear consistent and are relatively small in any case.

Table 10. Computation of Annual U.S. LPG Usage for Space Heating in Residential Buildings

U.S. Census Region	Number of LPG-Heated Households (Millions)	Average Space-Heat LPG Use per Household (Million Btu)	Total Space-Heat LPG Use in Region (Quads)
Northeast	0.2 (Note 1)	86.5	0.02
Midwest	1.3	87.9	0.11
South	2.1	46.1	0.10
West	0.6	30.1	0.02
Totals	4.2		0.25

Note 1: Value obtained by subtraction of other 3 regions from total in RECS
Note 2: 1 Quad = 10exp15 Btu

Electric Heat. In the case of electric heat, some adjustments were necessary that were not needed in the case of fossil fuels. Electric heating differs from fossil-fuel heating in several important respects. The first of these is that no heat is lost through an on-site chimney. Therefore, those losses that occur with on-site use of fossil fuels needed to be subracted out in order to obtain a "base heating load" for the housing unit. For the purposes of this exercise, the average on-site efficiency of existing gas heating systems was estimated to equal 0.7. Therefore, the average gas usage figures of Table 8 were multiplied by 0.7 to obtain the average base heating loads of Table 11.

The second difference is the fact that many electric heating systems use heat pumps. These heat pumps bring in some "free" energy from the outside ambient, in addition to the electrical energy required for their operation. The amount of free energy is represented by a coefficient of performance (COP), which is the ratio of heat delivered to electricity consumed by the heat pump, where both are presented in the same units. For the purposes of this exercise, the populations of electrically heated buildings given in RECS page 65 were used, with the proportion of heat pumps stated therein (25%), with an assumed average COP of 2.0. The RECS data did not provide sufficient accuracy to apportion the heat pumps other than on a national-average basis, although it is known that a relatively high proportion of the heat pumps exists in the South. The small number of electric-heat households in the colder regions should minimize any errors from this procedure. With these assumptions, the average COP of all electric heating (built-in, central furnace, and heat pump) was determined to be 1.27. The base heat loads in Table 11 were therefore divided by this factor to obtain an average electric energy use per household.

The third consideration is the difference between end-use electricity and the primary energy needed to run the central power plant. This difference appears as waste heat rejected at the power station. In DOE 1989, an average heat rate of 11500 Btu/kWh is used to represent the fuel input needed to generate one kilowatt of electricity. Since the Btu equivalent of a kW is 3410, this means that the end-use electricity requirement must be multiplied by 11500/3410 or 3.37 to obtain the primary energy needed for electric heating. This calculation is shown in the next column of Table 11.

Finally, the primary energy per household is multiplied, for each region, by the number of electric-heat households. The results are given in the last column of Table 11 and summed. The total of 1.71 quads compares with the value of 1.81 quads given in DOE 1989. The difference is 6%.

Table 11. Computation of Annual U.S. Primary Energy Usage for Electric Space Heating in Residential Buildings

Census Region	Number of Electric-Heat Households (Millions)	Average Base Heating Load (Million Btu) (Note 1)	Electric Energy Use Per Household (Million Btu)	Primary Energy Use Per Household (Million Btu)	Total Primary Energy Use (Quads)
Northeast	2.1	60.6	48.4	163	0.34
Midwest	1.4	61.5	49.2	166	0.23
South	10.6	32.2	25.8	87	0.92
West	3.8	21.1	16.9	57	0.22
Totals	17.9				1.71

Note 1: Base heating loads obtained as gas usage in Table 8 divided by 0.7 (See text for this and other factors used in computations.)
Note 2: 1 Quad = 10exp15 Btu.

Overall, the total primary energy use for residential space heating was 5.98 quads as estimated using the Gas Market Survey figures as a starting point, and 6.07 quads as given in DOE 1989, a difference of 2%. Considering that the latter figure includes a small amount of coal use, the overall agreement is remarkably good.

Energy Use in Forced-Air Systems

One question that might be raised at this point is as follows. How can the agreement between the calculated energy use and the DOE 1989 values be this good if, as may be inferred from our later discussion, forced-air systems use more energy than others? Haven't we assumed implicitly that all distribution-system types use the same amount of energy, on average?

We have two responses to this. The first relates to the calculations just completed. Over 80% of the primary energy for space heating is used in gas and electric systems. As given in RECS page 65, forced-air distribution is used in 63% of gas-heat systems and in 64% of electric-heat systems. Because these fractions are nearly the same, the averaging of forced-air with other distribution systems in the Gas Market Survey statistics will be reflected properly in the electric-heat computations as well.

The second response is that, yes, the estimates for energy use in forced-air systems that we will proceed to develop are probably too low. Yet, we prefer to err on the side of conservatism than to open ourselves to charges of begging the question by making assumptions that depend on our conclusions. The energy-use estimates for forced-air systems should be regarded as lower bounds, subject to possible upward revision as information becomes more refined.

Primary Energy Ratio

This section considers how the mix of energy sources for each thermal-distribution system type will affect our estimate of that system's primary energy requirements as a function of climate zone. The basic assumption will be that each housing unit can be assumed to use a number of Btu's for space heat as given in the Gas Market Survey, modified to reflect the amount of electric heating in the mix of end uses. We emphasize that the differences in primaryenergy use that appear between forced-air and hydronic systems reflect only the higher proportion of electric-heat households in the forced-air distribution group. Electric heat uses more primary energy than gas. No difference in distribution-system efficiency is assumed <u>a priori</u>. Since electric heat is mostly confined to the Sunbelt (South and West), this procedure will result in a significant modification only for that climate zone.

We begin by defining a Primary Energy Ratio (PER) as follows:

$$\mathrm{PER} = \frac{\text{Actual primary energy used}}{\text{Primary energy use assuming all units are gas-fired}} \tag{1}$$

An expression for PER in terms of the populations of various kinds of heating systems is given as follows:

$$\mathrm{PER} = \frac{\mathrm{GAS} + \mathrm{OIL} + \mathrm{LPG} + 0.7 \times 3.37 \times (\ \mathrm{ERH} + \mathrm{HTP}\ /\ 2.00\ )}{\mathrm{GAS} + \mathrm{OIL} + \mathrm{LPG} + \mathrm{ERH} + \mathrm{HTP}} \tag{2}$$

where GAS, OIL, and LPG are the numbers of households heating with gas, oil, and LPG, respectively. ERH is the number of households with electric-resistance heat (e.g. electric warm-air furnace). HTP is the number of households heated with electric-powered heat pumps. The factors in Equation 2 are the same as those used in developing Table 11.

For hydronic systems, the above procedure results in a PER of 1.00, very nearly, since the number of electrically heated hydronic systems is negligible. For forced air, use of the populations given in RECS page 65, resulted in a PER of 1.05 in the Frostbelt and 1.32 in the Sunbelt.

As mentioned earlier, this treatment ignores any difference in energy efficiency between thermal-distribution types. To the extent that forced-air systems experience higher thermal losses than others, this accounting will result in low estimates for forced-air systems.

We arrive at the results for space-heating energy use in single-family and multifamily buildings in the two climate zones, as illustrated in Table 12.

Space Cooling

So far, the analysis has considered space heating only. In order to include the impact on space cooling energy use, we first note that as far as thermal distribution is concerned, we will only need to consider forced-air systems, since in small buildings, hydronic systems are not often used to transport cooling.

Our method of evaluating space-cooling energy use involves relating each type of building and climate zone to one case as a standard. The base case is the single-family house with central air conditioning in the Sunbelt. Other house types, air-conditioning system types, and climate zones are related to the base case by the use of multipliers whose values lie between zero and one. That is, the base case is the heaviest cooling energy user; others use less. These multipliers are then used to find the number of households, equivalent to the base case, that would be needed to equal the actual energy use for cooling in residences. Then, dividing the total primary energy used for residential cooling by this number of base-case households, the primary energy use for one such household is determined. Then, using the multipliers, primary energy use for other cases of interest can be calculated.

Climate Zone. In order to get an approximate ratio between typical air-conditioning energy needs in the two climate zones, a chart of cooling-load hours [ARI 1981] was referred to. Cooling-load hours for the Frostbelt ranged from <400 to 1000, with 700 hours representing a median line passing through major population centers such as New York and Chicago. The range for the Sunbelt is much broader: ~500 hours in the intermountain West to >2800 hours in southern Florida. It was judged that 1500 to 2000 hours would represent a reasonable average, describing high-population locales such as Atlanta, New Orleans, Dallas, and Phoenix. Lower numbers in California are balanced by higher numbers in Houston and Miami. Estimating a 2.5 to 1 ratio for cooling between the two zones, we set the multipliers as: Sunbelt, 1.00; Frostbelt, 0.4.

House Type. Cooling loads for multifamily housing are expected to be lower than those for single-family, because of the generally smaller floor area. We expect that the ratio of cooling energy needed for these two types of buildings would be roughly equivalent to a similar ratio for heating energy. The ratio of heating energy for single-family dwellings to that for multifamily is ~0.6 for both climate regions (see Table 12). We assume that mobile homes are similar to multifamily dwellings, because of their similar floor space. We therefore set the multipliers as: Single Family, 1.0; Multifamily/Mobile Home, 0.6.

Table 12. Calculation of Space-Heating Primary Energy, by Building Type, Distribution System Type, and Climate Zone

Climate Zone	Frostbelt		Sunbelt	
Building Type	Single-Family	Multi-Family	Single-Family	Multi-Family
Average Gas Use (Note 1) (Million Btu)	107	67	52	31
Primary Energy Ratio				
Forced-Air (Note 2)	1.05		1.32	
Hydronic	1.00		N/A (Note 3)	
Primary Energy Use Per Household, Space Heating (Million Btu)				
Forced-Air	112	70	69	41
Hydronic	107	67	N/A	N/A

Note 1: From Gas Market Survey
Note 2: Energy use in forced-air systems may be underestimated, since the only difference in end-use energy considered here is that between heat pumps and electric-resistance heat.
Note 3: Hydronic systems are not significant in the Sunbelt

Air-Conditining System Type. RECS divides the housing universe into central air conditioning, room-unit air conditioning, and no air conditioning. Central air-conditioning systems tend to use more energy than houses with room units, because some rooms may not have air conditioners and because not all the room units need be operated. We make the assumption here that a house with room units will use approximately half the cooling energy of one with a central air-conditioning system. The multipliers are therefore: Central Air, 1.0; Room Units, 0.5; No Air Conditioning, 0.0.

Cooling Energy-Use Calculation. RECS page 31 gives data on air conditioning systems by census region, while RECS page 46 gives data on air conditioning systems by building type. No crosscuts are given. We therefore assumed statistical independence of the two variables and constructed a matrix, which is displayed in Table 13.

Table 13. Populations of Residential Buildings with Various Types of Air-Conditioning Systems (Millions of Households)

Each matrix element contains three numbers, representing central air conditioning, room-unit air conditioning, and no air conditioning, in that order.

	Total U.S.	Single-Family	Multi-Family	Mobile Homes
Total U.S.	30.7	22.7	6.7	1.3
	26.9	16.3	8.7	1.9
	32.9	21.4	9.5	1.9
Frostbelt (Northeast and Midwest)	10.2	7.5	2.2	0.4
	15.3	9.3	4.9	1.1
	15.9	10.3	4.6	0.9
Sunbelt (South and West)	20.5	15.2	4.5	0.9
	11.6	7.0	3.8	0.8
	17.1	11.1	4.9	1.0

We now multiplied each number within the body of the matrix by each appropriate multiplier. For example, the 9.3 million single-family homes in the Frostbelt with room units was multiplied by 1.0 for single-family, 0.4 for the Frostbelt, and 0.5 for having room units, to obtain 1.86 million equivalent single-family Sunbelt households with central air-conditioning.

If the whole matrix is treated in this way and the results summed, we find the nation's residential air conditioning equivalent to 29.5 million single-family Sunbelt houses with central air. (Because of the large number of single-family Sunbelt houses with central air conditioning, this result is not very sensitive to changes in the multipliers. A 50% increase or decrease in the smaller member of any pair of multipliers would result in only ~10% change in the 29.5 million-household equivalent central-air figure.) Using the value of 1.08 quads of primary energy for residential air conditioning (all electric), we obtain a primary-energy use of 37 million Btu for air conditioning in each of these houses. Using the multipliers, we can then obtain similar energy-use values for other housing types of interest, as shown in the first two rows of Table 14.

A check on the values in Row 2 of Table 14 can be made as follows. For the Sunbelt, a typical 2.5 ton (30,000) Btu/h air conditioner with a Seasonal Energy Efficiency Ratio (SEER) of 10 Btu/Wh, running for 1750 hours, will use

$$\frac{30{,}000 \text{ Btu/h} \times 1750 \text{ h}}{10 \text{ Btu/Wh} \times 1000 \text{ W/kW}} = 5250 \text{ kWh}$$

of electricity for cooling. At the heat rate of 11,500 Btu/kWh cited in DOE 1989 (cf. Table 11), this translates to 61 million Btu of primary energy. Many, if not most residences probably cool fewer hours than the ARI chart would indicate. Still, as a benchmark, it indicates that our estimate of 37 million Btu is within reason, and perhaps conservative.

One additional factor needs to be accounted for, which is that not all forced-air distribution systems come with central air conditioning. If we compare the populations of single-family and multifamily houses with central air conditioning (as shown in Table 13) with the populations of these same housing types with forced-air distribution (as shown in Tables 3 and 6), we find that in the Frostbelt, 7.5 of 13.9 million single-family houses with forced-air distribution have central air conditioning, or 54%. In the same region, 2.2 of 6.1 million multifamily units with forced-air distribution have central air conditioning, or 36%. In the Sunbelt, the comparable figures are: single-family, 15.2 of 15.7 million houses, or 97%; multifamily, 4.5 of 10.9 million units, or 41%.

This information allows us to recognize, by using one more multiplier, that not all forced-air distribution systems provide cooling. This multiplier is equal to the fraction of forced-air systems that are used to provide cooling. The average per-household primary-energy use for cooling delivered via the forced-air distribution system is then computed by multiplying the primary energy use per cooling household (row 2 of Table 14) by this fraction. The results are shown in the third and fourth rows of Table 14.

Table 14. Calculation of Space-Cooling Primary Energy, by Building Type and Climate Zone for Forced-Air Distribution Systems (See Note)

Climate Zone	Frostbelt		Sunbelt	
Building Type	Single-Family	Multi-Family	Single-Family	Multi-Family
Multiplier	0.33	0.20	1.00	0.60
Primary Energy Use Per Household, Space Cooling, (Million Btu)	15	9	37	22
Central-Air/ Forced-Air Population Ratio	0.54	0.36	0.97	0.41
Average Primary Energy Use Per Household for Space Cooling Delivered via the Forced-Air Distribution System	8	3	36	9

Note: Hydronic systems are not generally used for cooling in small buildings.

Total Energy Use by Cell

Returning now to the seven well-populated cells displayed in Table 7, we are in a position to determine the total primary energy used by each for space heating and cooling delivered via the thermal distribution system. The number of households in each cell, taken from Table 7, is multiplied by the primary energy use per household for space heating (Table 12) and for space cooling (Table 14). The results are displayed in Table 15.

In summary, we see that these eight cells have captured 75% of the 6.07 quads [DOE 1989] of primary energy used for residential space heating, and 71% of the 1.08 quads used for residential space cooling.

Table 15. Energy Use by Cell Populations, Existing (1987) Housing

Cell Description	Number of Households (Millions)	Space Heating Primary Energy per Household (Million Btu)	Space Heating Total Primary Energy (Quads)	Space Cooling Primary Energy per Household (Million Btu)	Space Cooling Total Primary Energy (Quads)
Single-Family, Forced-Air, Ducts in Unconditioned Space, Sunbelt	12.9	69	0.89	36	0.46
Single-Family, Forced-Air, Ducts in Partly Conditioned Space, Sunbelt	2.3	69	0.16	36	0.08
Multifamily, Forced-Air, Sunbelt	10.9	41	0.45	9	0.10
Single-Family, Hydronic, Frostbelt	7.2	107	0.77	0	0.00
Single-Family, Forced-Air, Ducts in Partly Conditioned Space, Frostbelt	7.0	112	0.78	8	0.06
Single-Family, Forced-Air, Ducts in Unconditioned Space, Frostbelt	6.1	112	0.68	8	0.05
Multifamily, Forced-Air, Frostbelt	6.1	70	0.43	3	0.02
Multifamily, Hydronic, Frostbelt	6.0	67	0.40	0	0.00
Totals	58.5		4.56		0.77

Note: 1 quad = 10exp15 Btu

MARKET SEGMENTATION PROCEDURE--NEW RESIDENTIAL BUILDINGS

Assessing energy use in new buildings presents one difficulty not present with existing buildings--it requires one to foretell the future course of the construction industry. Nevertheless, an imperfect forecast is usually better than no forecast at all, in that it provides a benchmark against which calculations can be made, and which can be corrected as unfolding time provides additional information.

With this in mind, we first consider a projection of the national rate of housing construction, and then consider how this might be broken down by the categories used in the discussion of existing housing. The Gas Market Survey, page 3, provides a concise statement of private housing starts during the years 1982 through 1989, along with projections for 1990-92. The set of past years included in these data is probably representative in that it includes the recession year of 1982 along with the boom years 1983-87. The average number of single-family starts was 1.03 million, while the average of the three projected years is 1.05 million. We assumed this not to include mobile homes. For multifamily, the average for 1982-89 was 0.53 million, while the average for 1990-92 is projected at 0.36 million.

Additional information can be gleaned from RECS page 20. It shows that single-family houses (not including mobile homes) were constructed during the period 1980 through November 1987 at the rate of 0.90 million per year, and during the period 1975 through November 1987 at the rate of 1.07 million per year. Multifamily housing was constructed at the rate of 0.37 million annually since 1980 and 0.43 million annually since 1975. Mobile homes were constructed at the rate of 0.15 million per year since 1980 and 0.17 million annually since 1975.

Finally, DOE 1989 projects that 118.5 million households will exist in the United States in 2010. In past work, an attrition rate (due to loss by fire, condemnation, or voluntary demolition) of 0.64% per year was estimated, based on U.S. census data (see Note below).[Andrews and Krajewski 1985] If this is accepted, then the average annual construction rate between 1987 and 2010 must be given by R in the equation

$$(2010\ \text{HOUSEHOLDS}) = (1987\ \text{HOUSEHOLDS})\ (1-0.0064)\text{exp}23 + 23\ R \qquad (3)$$

Note: The numbers of occupied housing units in 1960 and 1980, repectively, were 53.0 million and 80.1 million.[Census 1982, p. 757] Subtracting mobile homes (0.8 million and 3.8 million, respectively) [Census 1982, p. 751] leaves 52.2 million and 76.3 million. The number of housing starts in the 20-year period was 32.3 million.[Census 1982, p. 747] Subtracting the increase in occupied units (24.1 million) from this leaves an attrition of 8.2 million over 20 years. The average attrition per year is then 1/20 of this divided by the average base, or 8.2/(20 X 64.2) = 0.0064. This is permanent (non-mobile-home) housing. Mobile homes no doubt have a higher attrition rate, but because of their small representation in the housing mix, they will not affect the overall attrition rate very much. For example, assuming a 2% attrition rate for mobile homes would increase the overall attrition to 0.71% annually. A 3% attrition for mobile homes would increase the overall rate to 0.77%.

The increase in households from 90.5 million to 118.5 million during this period then leads to R = 1.75 million per year.

Taking all of this information into account, we deem it reasonable to follow the DOE projection by allocating new housing at the rate of 1.1 million units per year for single family housing and 0.45 million annually for multifamily. Mobile homes are projected to be constructed at the rate of 0.20 million units annually. These values are slightly higher than the near-term projections discussed two paragraphs above, but appear reasonable if one assumes that new construction will proceed, on average, as a constant percentage of an increasing base.

The Move to the Sunbelt

The locale of new construction is decidedly skewed toward the South and West census regions. Table 16, which displays data taken from RECS page 16, shows this dramatically. In contrast to existing housing, which is divided more or less evenly between the Frostbelt and Sunbelt, new construction is heavily weighted toward the Sunbelt, particularly toward the South census region. Data supplied by NAHB on new single-family detached housing for the year 1983 appear consistent with this weighting, as shown by the percentages in the third row of Table 16. We will therefore use these data as indicators of the current trends in new construction.

How Many Years?

One question that we will need to consider is how many years of new construction to use in making energy-savings estimates. Clearly, we should not take just one year; this would ignore the cumulative effect of improved thermal distribution on many years of construction. We may not, however, take an arbitrarily large number of years, either, even though the benefits of the improvements will be available for a long time to come and even though, eventually, new housing will largely replace existing housing.

Table 16. Allocation of Housing Units by Census Region (See Note)
(Percent of Row Totals)

Years Constructed	Census Region			
	Northeast	Midwest	South	West
All Existing Stock	21	25	34	20
1980 - 1987	14	15	48	23
NAHB New Housing Data for 1983	11	15	52	22

Note: The first two rows of data are from RECS page 16.

The approach we have chosen to take is one based on discounting. Future payoffs of currently funded research should be reduced in value at some rate that reflects the time value of money. This is equivalent to saying that we will consider a certain number of years' construction in evaluating the effectiveness of improvements. For a discount rate i, the present value of a long-term stream of benefits beginning with the present is equal to the inverse of the discount rate, or 1/i. If the stream of benefits will not begin for some number k of years, this value must be decreased by the factor (1-i) to the power k. This factor, by which one year's benefit must be multiplied to obtain this present worth, is given in Table 17 as a function of several values of i and k.

Table 17. Present-Worth Factors of a Long-Term Stream of Benefits

Time Delay for Benefits to Start	Discount Rate (Percent) 3	4	5
0	33	25	20
5	28	20	15
10	24	17	12

Even within this relatively narrow range of discount rates and delay times, the present-worth factor varies by a factor of three. Clearly, there is some subjectivity in assigning a relative importance to improvements in new vs. existing construction. Since research is a societal function, it appears reasonable to assign a relatively low real discount rate to it, of the order of 3 percent. From the plan for the program, it is estimated that significant benefits will be available within five years. Clearly, not all new housing will take advantage of this research right away, but then it is also true that not all existing housing will take advantage of new retrofit options. Nevertheless, it is technical potentials that we will be discussing, i.e. what could be achieved through this research, and not predictions of what will actually be achieved. The actual outcome will depend strongly on historical developments and social choices that are beyond the control of the DOE and its National Laboratories. It therefore seems reasonable to take a time delay of ~5 years and to use a present-worth factor of 25 in evaluating the energy use, and, later, the energy-savings potential for thermal distribution systems in new construction.

Single-Family

Information similar to that obtained from NAHB for existing single-family-detached housing was obtained at the same time for new single-family-detached housing constructed during 1983. These data are presented in Table 18, aggregated into the same format as Table 2.

Table 18. Distribution of New Single-Family-Detached Housing (Year of Construction 1983) into Categories per NAHB Data (Thousands of Households)

Distribution System Type	House Structure	Frostbelt (Northeast and Midwest)	Sunbelt (South and West)
Forced Air	Basement	78	50
	Crawlspace	14	77
	Slab	45	427
	Bilevel	18	29
	Split Level	14	38
Hydronic	All	19	6
Built-In Electric	All	41	20
Other or None	All	4	18
Totals		233	665

In a format similar to that used for existing single-family housing, we now present the data such that forced-air systems are described by duct location relative to the conditioned space, and we also normalize to a predicted average construction rate of 1.1 million units annually. The results are presented in Table 19.

The salient facts that emerge from this table, in addition to the shift of new contruction to the Sunbelt, as discussed above, are:

o Forced-air systems have come to dominate the market, with 88% of new houses.

o One cell in particular--forced-air systems in the Sunbelt with ducts in unconditioned space--has captured over 60% of the entire new housing market.

Table 19. Distribution of New Single-Family Housing into Categories Defined in This Study (Thousands of Houses Per Year)

Distribution System Type	Distribution System Location	Frostbelt (Northeast and Midwest)	Sunbelt (South and West)
Forced Air	Unconditioned Space (Ducts in Attic or Crawl)	89	664
	Partly Conditioned Space (Ducts in Basement)	96	61
	Conditioned Space (Ducts in Bilevel House)	22	36
Hydronic	All	23	7
Built-In Electric	Conditioned Space	50	25
Other or None	All	5	22
Totals		285	815

Note: Table 19 values obtained from Table 18 by assigning duct location on the basis of house type and multiplying resulting values by 1.225 to normalize NAHB data to Gas Market Survey projection.

Primary Energy Per Household

In evaluating energy use in new housing, an additional factor that needs to be accounted for is the likelihood that, even without advances in thermal distribution, space conditioning in new housing is going to be more energy-efficient than in existing housing. This will be brought about chiefly by improvements in space-conditioning equipment, building materials, window technology, and construction practice. DOE 1989 projects a drop in primary energy consumption per household from 176 million Btu in 1986 to 160 million Btu in 2010. If we assume that the 16-million Btu drop is entirely due to heating and cooling (with other factors balanced by increased use of appliances), then the total energy conservation during this period would amount to 20% of the current 80 million Btu per household (7.15 quads divided by 90.5 million households) used for residential space heating and cooling. It is reasonable to expect that new housing will conserve more than existing housing. In the absence of more definitive data, we will assume 40% conservation in new housing and 10% conservation in existing housing, relative to the values given in Tables 12 and 14, which will yield a total consistent with 20% conservation overall. Because most new housing with forced-air distribution will have central air conditioning, for space-cooling energy the values in the second rather than the fourth row of Table 14 will be used.

Using this procedure and considering 25 years of new housing, only one "cell" emerged with importance comparable to the seven cells of existing single-family housing, namely the big one discussed in connection with Table 19. In addition, four smaller cells represent housing of types identical to those of cells listed in Table 7 for existing housing. These are included on the theory that advances in thermal distribution that are applicable to existing housing will carry over into new housing as well. The energy-use characteristics of these cells are displayed in Table 20. Five-sixths of the new single-family housing units are captured in the four single-family cells in that table.

New Multifamily Housing

Owing to lack of available data on distribution systems, new multifamily was the most difficult sector for us to analyze. An attempt was made to estimate the characteristics of new multifamily housing using a subtraction procedure similar to that displayed in Table 4, taking RECS data from 1975 through 1987 as representative of new housing. This procedure, however, had certain impediments that made it unworkable:

o The numbers in RECS for these recent years are small enough to introduce significant errors into a subtraction process.

o The necessary crosscuts were not available for the given subset of RECS data.

o RECS showed a significant fraction (13%) in categories other than forced-air, hydronic, or built-in electric, whereas the NAHB single-family data showed only 2% outside these categories. The subtraction process then results in a large fraction (32%) of new multifamily in the "other" category, a result we do not believe, in view of Table 6, where essentially no existing multifamily units were in the "other" category.

One possible explanation for this discrepancy may be that RECS has a significant number of new single-family houses heated with wood, whereas NAHB does not. It is likely that houses with both wood stoves and ducts were counted as forced air by NAHB, whereas RECS may have counted most of them as primary wood burners.

If the "other or none" category is ignored, the new multifamily housing units break down as follows:

o Forced Air, 64%

o Hydronic, 16%

o Built-In Electric, 20%

These percentages must be regarded as extremely tentative. Nevertheless, it does appear that a large proportion of new multifamily housing is equipped with forced-air distribution of some sort.

Concerning other characteristics, the following information for multifamily housing units constructed between 1975 and 1986, was gleaned from Amols et al. 1988:

- 73% were constructed in the Sunbelt.
- 74% of those in the Sunbelt were heated electrically, the remainder with gas.
- 86% of those in the Sunbelt had air conditioning.

None of these facts should be a surprise. Unfortunately, they do not enable us to tell anything concerning the thermal distribution characteristics. We know that electric strip heaters and package terminal air conditioners are often used in apartments, whereas this combination is unusual in single-family housing, especially new housing.

The best we are able to do towards arriving at an energy-use estimate for any homogeneous set of multifamily housing is to consider the number of forced-air units in the Sunbelt to be estimated by the product of the 64% forced-air and the 73% in the Sunbelt, as found immediately above, multiplied by the 0.45 million-unit-per-year projection arrived at earlier in this section. This equals 0.210 million units annually, or an equivalent 5.3 million units over 25 years. The same procedure for multifamily forced-air in the Frostbelt yields 1.9 million households. No attempt was made to estimate new multifamily hydronic systems; these are expected to be small in number, however. The energy-use consequences for these cells are derived on the appropriate lines of Table 20.

Notes to Table 20

Note 1: For single-family, Table 19 values were multiplied by 25. For multifamily, see text above.
Note 2: Table 12 values reduced by 40%.
Note 3: Table 14 (second row) values reduced by 40%.
Note 4: 1 quad = 10exp15 Btu.

Table 20. Annual Energy Use by Cell Populations, New Housing Constructed Between 1995 and 2020. (Notes to this Table on Preceding Page)

Cell Description	Number of Households (Note 1)	Space Heating		Space Cooling	
		Primary Energy per Household (Note 2)	Total Primary Energy	Primary Energy per Household (Note 3)	Total Primary Energy
	(Millions)	(Million Btu)	(Quads)	(Million Btu)	(Quads)
Single-Family, Forced-Air, Ducts in Unconditioned Space, Sunbelt	16.6	41	0.68	22	0.37
Single-Family, Forced-Air, Ducts in Partly Conditioned Space, Sunbelt	1.5	41	0.06	22	0.03
Multifamily, Forced-Air, Sunbelt	5.3	25	0.13	13	0.07
Single-Family, Hydronic, Frostbelt	0.6	64	0.04	0	0.00
Single-Family, Forced-Air, Ducts in Partly Conditioned Space, Frostbelt	2.4	67	0.16	9	0.02
Single-Family, Forced-Air, Ducts in Unconditioned Space, Frostbelt	2.2	67	0.15	9	0.02
Multifamily, Forced-Air, Frostbelt	1.9	42	0.08	5	0.01
Totals	29.0		1.30		0.52

Notes to this table are on the preceding page.

A CONSISTENT TREATMENT OF EXISTING AND NEW HOUSING

The purpose of this section is to complete the analysis of residential energy use by bringing together the discussions of existing and new housing into a single consistent treatment. Keeping in mind the argument that ~25 years of new housing should be considered in energy savings projections, and that the benefits of a DOE research program in thermal distribution will begin seriously to be felt about 1995, we have elected to take the following approach:

1. Bring the populations of existing housing in 1987, as shown in Table 7, forward to 1995 by the addition of 8 years of additional housing distributed as shown in Table 19. It is also necessary to account for attrition in existing housing. At this point the "existing" housing stock is frozen, subject only to 25 more years of attrition, to bring it out to 2020.

2. Add 25 years of new housing, representing 1995-2020, distributed as shown in Table 19.

We believe that this procedure will provide a reasonable projection of the various cell populations in "snapshot" form for 2020, and therefore a sound basis for setting research priorities.

The method we have adopted recognizes the factor of attrition among existing housing units, caused by several factors such as loss by fire, condemnation, and voluntary demolition. This was discussed earlier when we considered the impact of assumptions concerning new construction rates on the projected numbers of households in future years. The attrition rate of 0.64% annually, developed in that section, will be used here. In bringing the existing housing stock forward from 1987 to 1995, we multiplied the Table 7 cell populations by (1-0.0064)exp8, or 0.95, and then added 8 times the annual production of new housing for that cell, as given in Table 19. The resulting populations were then multiplied by (1-0.0064)exp25, or 0.85, to bring them out to the year 2020. The results are shown in Table 21.

In the same way that the 1987 cell populations for existing housing were used to develop the energy-use estimates of Table 15, we now use the 2020 cell populations for pre-1995 "existing" housing, which we just derived in Table 21, to develop energy-use estimates. The computations, exactly like those of Table 15, are illustrated in Table 22. These are our projections for space-heating and cooling energy use for the eight major cells, as of 2020, for housing units constructed in 1995 or earlier.

Table 21. Cell Populations, Existing Housing Brought Forward to 2020 (Millions of Households)

Cell Description	Number of Households in 1987 (Note 1)	Annual New Households Added (Note2)	Number of Households in 1995	Number of Households in 2020
	X 0.95 + 8 X	=	X 0.85 =	
Single-Family, Forced-Air, Ducts in Unconditioned Space, Sunbelt	12.9	0.664	17.6	14.9
Single-Family, Forced-Air, Ducts in Partly Conditioned Space, Sunbelt	2.3	0.061	2.7	2.3
Multifamily, Forced-Air, Sunbelt	10.9	0.210	12.0	10.2
Single-Family, Hydronic, Frostbelt	7.2	0.023	7.0	6.0
Single-Family, Forced-Air, Ducts in Partly Conditioned Space, Frostbelt	7.0	0.096	7.4	6.3
Single-Family, Forced-Air, Ducts in Unconditioned Space, Frostbelt	6.1	0.089	6.5	5.5
Multifamily, Forced-Air, Frostbelt	6.1	0.078	6.4	5.5
Multifamily, Hydronic, Frostbelt	6.0	0.019	5.9	5.0
Totals	58.5		65.5	55.7

Note 1: From Table 15.
Note 2: From Table 19 (singlefamily) or text (multifamily).

Table 22. Energy Use by Cell Populations for Pre-1995 ("Existing") Housing Projected to 2020.

Cell Description	Number of Households (Millions)	Space Heating		Space Cooling	
		Primary Energy per Household (Note 1) (Million Btu)	Total Primary Energy (Quads)	Primary Energy per Household (Note 2) (Million Btu)	Total Primary Energy (Quads)
Single-Family, Forced-Air, Ducts in Unconditioned Space, Sunbelt	14.9	62	0.92	33	0.49
SingleFamily, ForcedAir, Ducts in Partly Conditioned Space, Sunbelt	2.3	62	0.14	33	0.08
Multifamily, Forced-Air, Sunbelt	10.2	37	0.38	8	0.08
Single-Family, Hydronic, Frostbelt	6.0	96	0.58	0	0.00
Single-Family, Forced-Air, Ducts in Partly Conditioned Space, Frostbelt	6.3	101	0.64	6	0.04
Single-Family, Forced-Air, Ducts in Unconditioned Space, Frostbelt	5.5	101	0.56	6	0.03
Multifamily, Forced-Air, Frostbelt	5.5	63	0.35	3	0.02
Multifamily, Hydronic, Frostbelt	5.0	60	0.30	0	0.00
Totals	53.4		3.87		0.74

Notes to Table 22
1. Table 12 values reduced by 10%.
2. Table 14 (line 4) values reduced by 10%.
3. 1 quad = 10exp15 Btu

New (Post-1995) Housing Projected to 2020.

For the 25 years of post-1995 housing included in the 2020 housing stock, we use the estimates for 25 years of new housing given in Table 20. Because this housing is so new, its attrition rate should be very low; for the purpose of this analysis we ignore it.

Energy-Use Summary, Residential Housing in 2020.

Table 23 summarizes the energy-use projections for housing in a form that should be useful to DOE management and others concerned with energy policy. Nine cells are defined, each of which uses at least 0.3 quads for space heating and cooling. One group of housing, single-family forced-air in the Sunbelt, with ducts in unconditioned spaces, was split into separate cells for existing (pre-1995) and new (post-1995) housing. Other new housing cells from Table 20 used 0.2 quads or less for both heating and cooling and therefore were judged sufficiently small that they should be combined with their existing-housing counterparts in Table 21. The implied judgment is that no special program thrusts should be put in motion for new housing in these cells, but that the benefits of research on existing housing in these cells would apply to new housing as well.

In Table 23, where existing and new housing have been combined into a single cell, this has been so indicated. For one cell (multifamily, hydronic, Frostbelt) we were not able to estimate new housing; however, the amount of new housing in this cell is believed to be sufficiently low that the results will not be affected very much.

In Table 15 it was found that eight cells represented 5.33 quads of primary energy for space heating and cooling in existing buildings, or 75% of the 7.15 quads expended for these end uses. DOE 1989 page 3-14 gives a forecast of 8.7 quads for residential heating and air conditioning in 2010. The heating and cooling energy used by nine cells representing the same housing types in 2020 is 6.43 quads, or 74% of the 8.7 quads estimated for 2010. Note that the nine cells in the 2020 projection represent the same housing categories as the eight cells for the 1987 data; the only difference is that for one category, existing and new housing were separated into distinct line items. Even assuming no increase in the DOE estimate for residential space heating and cooling energy between 2010 and 2020, the percentage for the cells under consideration has decreased slightly despite the rapid addition of forced-air systems and the increased use of air conditioning. This indicates that the projections given in Table 23 are within reason, and probably conservative.

Table 23. Total Space Heating and Cooling Energy Use by Cell Populations for Existing and New Housing Projected to 2020.

Letter Designation	Cell Description	Existing and/or New Housing	Projected Energy Use (Quads) Heating	Cooling	Total
A	Single-Family, Forced-Air, Ducts in Unconditioned Space, Sunbelt	EXISTING	0.92	0.49	1.41
B	Single-Family, Forced-Air, Ducts in Unconditioned Space, Sunbelt	NEW	0.68	0.37	1.05
C	Single-Family, Forced-Air, Ducts in Partly Conditioned Space, Sunbelt	EXISTING + NEW	0.20	0.11	0.31
D	Multifamily, Forced-Air, Sunbelt	EXISTING + NEW	0.51	0.15	0.66
E	Single-Family, Hydronic, Frostbelt	EXISTING + NEW	0.62	0.00	0.62
F	Single-Family, Forced-Air, Ducts in Partly Conditioned Space, Frostbelt	EXISTING + NEW	0.80	0.06	0.86
G	Single-Family, Forced-Air, Ducts in Unconditioned Space, Frostbelt	EXISTING + NEW	0.71	0.05	0.76
H	Multifamily, Forced-Air, Frostbelt	EXISTING + NEW	0.43	0.03	0.46
I	Multifamily, Hydronic, Frostbelt	EXISTING	0.30	0.00	0.30
	Totals		5.17	1.26	6.43

SMALL COMMERCIAL BUILDINGS

We include small commercial buildings in our discussion of thermal distribution systems because they have many aspects in common with residential buildings. Large commercial buildings, by contrast, have quite different characteristics. The following major differences between large and small buildings relate specifically to thermal distribution:

1. In small buildings, the major efficiency issue in thermal distribution is thermal losses (heat transfer and leakage), whereas in large buildings it is fan power.

2. The heating and cooling requirements of small buildings tend to be dominated by heat gains and losses through the building envelope (perimeter losses), whereas for large buildings energy gains within the interior of the building tend to dominate (core effects).

3. The sizing, types, and operating parameters of heating and cooling equipment are different for large buildings than they are for small buildings. This can have a significant impact on the choice and operating modes of thermal distribution systems.

4. Economies of scale in large buildings permit design choices that are less often considered for small buildings. Variable air volume and cold air distribution are two examples of these.

NBECS pp. 51 and 53 gives the following information on the number of buildings and total floorspace as functions of floor area per building:

Table 24. Number of Buildings and Total Floorspace by Individual-Building Floor Area (1986)

Floorspace Category (ft^2)	Number of Buildings (Thousands)	Total Floorspace (Million ft^2)
1,001 to 5,000	2,220	6,209
5,001 to 10,000	931	6,861
10,001 to 25,000	557	9,119
25,001 to 50,000	242	8,661
50,001 to 100,000	123	8,559
100,001 to 200,000	52	7,191
200,001 to 500,000	23	6,737
Over 500,000	6	4,893
Totals	4,154	58,229

We see that about half the buildings are in the smallest size category, but nearly half the floorspace is in buildings larger than 50,000 ft^2. The average area is 14,000 ft^2.

We do not know where the dividing line between small and large buildings should be drawn, but believe that in general it should be somewhere between 10,000 ft^2 and 100,000 ft^2 total floor area. The energy-conservation issues associated with thermal distribution systems in large buildings need to be explored as carefully as those for small buildings. Because of the small-building emphasis of this study, we have chosen to concentrate on the subset of buildings with floor areas 10,000 ft^2 or less. For these buildings, technology developed for the residential sector will find direct applications, abeit with some modification. As buildings get larger, design choices become more varied, and a study directed specifically toward larger buildings is appropriate.

Energy Use in Commercial Buildings

DOE 1989 states that in 1986, commercial buildings used a total of 11.73 quads of primary energy, of which 3.80 quads were for space heating and 1.11 quads for space cooling. Small buildings (<10,000 ft^2) had 22% of the total commercial floorspace. Assuming energy use to prorate roughly by floorspace, this means that small commercial buildings will use 0.85 quads for space heating and 0.25 quads for space cooling. Amols et al. 1988 shows a growth rate for energy use in commercial buildings of slightly more than 2% per year between 1975 and 1985. DOE 1989 p. 3-14 projects that primary energy use for space heating in commercial buildings will rise to 5.0 quads by 2010, while air-conditioning energy use will grow to 1.9 quads. The total of 6.9 quads represents a 1.5% annual growth rate over 1986 for this sector.

Determining reasonable values for primary energy use per square foot for heating and cooling required some analysis. We would have preferred to work with data on small buildings only. However, since all the necessary information on this subset was not available, we chose instead to develop average energy-use values for all commercial buildings and to assume that these are approximately valid for those under 10,000 ft^2.

Our approach was as follows:

1) Determine the number of heated (or cooled) square feet for all commercial buildings in each climate zone.

2) Determine the ratio of heating (or cooling) primary energy use in the Frostbelt to that in the Sunbelt.

3) Combine these results with the overall energy use figures given above to obtain an energy-use figure per unit heated (or cooled) area.

NBECS page 44 gives breakdowns, by census region, of fraction of floorspace that is heated or cooled, with categories of 100%, 51-99%, 1-50%, and 0%. Assuming the heating or cooling fractions for the second and third categories to be at the midpoints of the two ranges (75% and 25%, respectively), the Frostbelt had 23.4 billion heated square feet and 12.8 billion cooled square feet, while the Sunbelt had 23.0 billion heated square heat and 17.9 billion cooled square feet.

No direct information on the ratio of energy use for heating or cooling between the Frostbelt and Sunbelt was found. The breakdowns by region contained, for example, in Amols et al. 1988 were for total energy use, not heating or cooling energy use. In the residential case, the average heating energy use in the Sunbelt, per unit area, was 63% as great as in the Frostbelt. This was determined using the primary energy data in Tables 8-11 together with residential square-footages given in RECS page 16. We judged it a better procedure to base our Frostbelt/Sunbelt breakdown on residential space conditioning than to use commercial-building total energy. We therefore posited a value of 0.6 for the Sunbelt/Frostbelt ratio of primary energy use for heating, per unit area. In a similar manner, we set 0.4 as the Frostbelt/Sunbelt ratio of primary energy use for cooling.

For heating, then, the primary energy use per Frostbelt square foot, averaged over all buildings, large and small, is:

$$\frac{3.80 \times 10^{15}}{(23.4 + 0.6 \times 23.0) \times 10^{9}} = 102{,}000\ \text{Btu/ft}^{2}.$$

The Sunbelt value then works out to 60% of this, or 61,000 Btu/ft^2.

For cooling, we elected to use only the electric cooling primary energy in the numerator, rather than the total for electric and gas cooling. Our rationale for this is twofold. First, small buildings use a negligible amount of gas cooling. Second, there is good reason to believe that large buildings will require more cooling energy per square foot than small ones, because of heat buildup in the core. Primary energy use per Sunbelt square foot is then:

$$\frac{1.11 \times 10^{15}}{(17.9 + 0.40 \times 12.8) \times 10^{9}} = 48{,}000\ \text{Btu/ft}^{2}.$$

For the Frostbelt, the value is 40% of this, or 19,000 Btu/ft^2.

Existing Buildings

Referring to Table 24, there were 13.1 billion square feet of floorspace in small (<10,000 ft^2) commercial buildings in 1986. According to NBECS p. 187, 11.7 billion ft^2 were heated or cooled. The same source yields a breakdown into distribution system types as shown in Table 25. As can be seen from this table, nearly 70% of small commercial buildings that are heated or cooled have ducted forced-air distribution systems. We will therefore concentrate on this distribution system.

NBECS does not give data on the distribution of small buildings with forced-air distribution into census regions. However, it does give regional breakdowns of all buildings with forced air (page 42), and of small buildings regardless of distribution system (page 44). The Frostbelt held 45% of all commercial-building floorspace served by ducted forced air, with 63% of heating-only floorspace, 40% of heating-and-cooling floorspace, and (surprisingly) 60% of cooling-only floorspace. The split of small buildings between the two climate zones (44% in the Frostbelt) was similar to that of all buildings (48% in the Frostbelt). We therefore do not think that the lack of a crosscut will skew the results significantly, and we adopt the assumption of statistical independence, that the splits of forced-air systems between climate zones, given for all building sizes, will apply to the subset of small buildings. We therefore divided the three categories of forced-air systems from Table 25 between the Frostbelt and Sunbelt in accordance with the above ratios, to arrive at the figures shown in Table 26.

Table 25. Thermal Distribution Systems in Small (<10,000 ft^2) Commercial Buildings

Classification		Floorspace (Billion ft^2)
All Buildings in Class		13.1
Heated or Cooled Buildings		11.7
With Ducted Forced Air		8.1
Heating Only	2.1	
Cooling Only	0.4	
Heating/Cooling	5.6	
With Steam or Hot Water Radiators or Baseboards		1.4
With Fan-Coil Units		0.9
With Heating Panels		0.6

Table 26. Forced-Air Thermal Distribution in Small Commercial Buildings, by Region, Year 1986

Application (Heating or Cooling)	Floorspace (Billion ft^2)	
	Frostbelt	Sunbelt
Heating Only	1.3	0.8
Cooling Only	0.2	0.2
Heating and Cooling	2.2	3.4
Totals	3.7	4.4

We now derive the primary energy use in existing (1986) small commercial buildings with forced-air distribution, as shown in Table 27.

Table 27. Calculation of Space-Conditioning Primary Energy Use in Existing (1986) Small Commercial Buildings with Forced-Air Distribution.

Region	Application	Building Area (Billion ft^2)	Primary Energy per Unit Area (Million Btu)	Primary Energy Total in Region (Quads)
		X	=	
Frostbelt	Heating Only	1.3	0.102	
	Cooling Only	0.2	0.019	
	Heating/Cooling	2.2	0.121	
	Total			0.40
Sunbelt	Heating Only	0.8	0.061	
	Cooling Only	0.2	0.048	
	Heating/Cooling	3.4	0.109	
	Total			0.43

Note: 1 Quad = 10exp15 Btu

We thus have identified two "cells" of existing small commercial buildings that used 0.40 and 0.43 quads of primary energy, respectively, in 1986. We will now turn to new buildings, and then project to 2020 in a manner similar to that done for residential buildings.

New Buildings

Comparing NBECS 1979 page 23 with NBECS 1986 page 82, we are able to obtain an estimate for the rate at which floorspace is added to the building stock. During the years 1980-86, a total of 9.9 billion ft^2 were constructed. The total square footage in place during the period ranged from 54.8 billion in 1979 (NBECS 1979) to 58.2 billion in 1986. The average annual construction rate during the period is equal to the amount constructed divided by the average in place and by the number of years, or

$$\text{ANNUAL CONSTRUCTION} = \frac{9.9}{0.5\ (58.2 + 54.8)} \times \frac{1}{7} = 0.025, \text{ or } 2.5\%.$$

In addition to construction rate, we need an estimate either of the attrition rate or the net increase in floorspace. DOE 1989 page 4-21 shows a projected increase in commercial floorspace of from 58.2 billion ft^2 in 1986 to 93.4 billion ft^2 in 2010. This represents a 2.0% average annual increase.

The difference between the 2.5% construction rate and the 2.0% average annual increase in floorspace implies a 0.5% attrition rate for commercial floorspace, which is of the same order of magnitude as the 0.64% attrition rate in the residential sector discussed earlier.

Making the above assumptions, we arrive at a new commercial construction rate of 0.025 X 58.2 X 10^9 - 1.45 billion ft^2 per year for all buildings, large and small. Everything else being equal, the annual increase in floorspace of small buildings with forced-air distribution would be:

- In the Frostbelt, 0.025 X 3.7 X 10^9 - 92 million ft^2 per year.
- In the Sunbelt, 0.025 X 4.4 X 10^9 - 110 million ft^2 per year.

Everything is not equal, however. Three factors in particular need to be accounted for if the projections are to be realistic. These are: an increase in the proportion of buildings with ducts, a decrease in the proportion of small buildings, and a shift of new construction to the Sunbelt.

Increase in Use of Forced Air. NBECS page 89 provides data on the proportion of buildings with ducts as a function of building age. This information is summarized in Table 28.

Table 28. Floorspace Served by Ducted Forced-Air Distribution, by Year Constructed (Billion Square Feet).

	Year Constructed	
	before 1974	1974-1986
With Ducts	25.4	14.7
Without Ducts	14.8	3.4

Note: Includes all sizes of commercial buildings.

The proportion of buildings with ducts among all the buildings is 69% of the total, but for the last 13 years in the sample, this rises to 81%. We therefore include a factor of 81/69 or 1.17 to modify our baseline estimates for new construction, developed above, to account for this factor.

Decrease in Proportion of Small Buildings. NBECS page 91 provides data on the proportion of buildings with ducts as a function of building age. This information is summarized in Table 29.

Table 29. Commercial Floorspace for Small and Large Buildings, by Year Constructed (Billion Square Feet).

	Year Constructed before 1974	 1974-1986
<10,000 ft^2	9.2	3.9
>10,000 ft^2	30.9	14.2

Note: Includes all distribution types.

The proportion of small buildings overall is 22% of the total, but for the last 13 years in the sample, this drops to 21%. We therefore include a factor of 21/22 or 0.95 to modify our baseline estimates for new construction, developed above, to account for this factor.

The Shift to the Sunbelt. NBECS page 92 provides data on the proportion of buildings in each climate zone as a function of building age. This information is summarized in Table 30.

Table 30. Commercial Floorspace in Frostbelt and Sunbelt, by Year Constructed (Billion Square Feet).

	Year Constructed before 1974	 1974-1986
Frostbelt	20.0	7.7
Sunbelt	19.9	10.4

Note: Includes all distribution types and building sizes.

The proportion of buildings in the Frostbelt overall is 48% of the total, but for the last 13 years in the sample, this drops to 43%. For the Frostbelt we therefore include a factor of 43/48 or 0.90 to modify our baseline estimates for new construction, developed above, to account for this factor. The corresponding factor for the Sunbelt is 57/52 or 1.10.

Annual Added Floorspace. Using the above factors, we arrive at modified estimates of the floorspace added each year to the stock of small commercial buildings with forced-air distribution, as follows:

- Frostbelt: 1.17 X 0.95 X 0.90 X 92 million = 92 million ft^2/yr
- Sunbelt: 1.17 X 0.95 X 1.10 X 110 million = 134 million ft^2/yr

Annual Primary Energy Use. For these new buildings, we now estimate the annual energy use of 25 years of construction, in line with the methodology employed in the residential case. We assume 40% conservation relative to present energy-use figures, and we assume that all these buildings will be both heated and cooled by 2020. The annual primary energy use for 25 years of new small buildings with forced air is then:

- Frostbelt: 25 X 92 X 10^6 X 0.6 X 121,000 = 0.17 quads annually
- Sunbelt: 25 X 134 X 10^6 X 0.6 X 109,000 = 0.22 quads annually

Existing Buildings Projected to 2020.

We project the existing small-commercial building stock forward to 2020 in the same way as the residential stock. The Table 26 floorspace values for the two climate regions are multiplied by 0.995exp9, or 0.96, and then 9 times the annual construction is added to the result. This gives the floorspace in 1995. Then, 25 years of attrition are accounted for by multiplying that value by 0.995exp25, or 0.88, to project the floorspace of pre-1995 buildings in 2020. The calculation and results are shown in Table 31.

Table 31. Floorspace of Existing (pre-1995) Small Commercial Buildings Brought Forward to 2020 (Billions of Square Feet)

Cell Description	Floorspace in 1986	Annual Addition of New Floorspace	Floorspace in 1995	Floorspace in 2020
	X 0.96 + 9 X		=	X 0.88
Small Commercial, Forced-Air, Frostbelt	3.7	0.092	4.4	3.9
Small Commercial, Forced-Air, Sunbelt	4.4	0.134	5.4	4.8
Totals	8.1		9.8	8.7

The primary energy used to heat and cool this floorspace is computed as follows. It is assumed that conservation measures other than thermal distribution improvements will contribute a 20% conservation over current practice. As with new buildings, it is also assumed that essentially all existing buildings with ducts will be both heated and cooled by 2020. The space-heating primary-energy usages are then determined by multiplying projected square footage by unit energy consumption, or:

- Frostbelt: 3.9 X 10^9 X 0.8 X 121,000 - 0.38 quads annually

- Sunbelt: 4.8 X 10^9 X 0.8 X 109,000 - 0.42 quads annually

Energy-Use Summary, Small Commercial Buildings in 2020

Four "cells" of small commercial buildings were identified, all with ducted forced-air distribution. The primary-energy use for these cells are given in Table 32.

Table 32. Total Space Heating and Cooling Energy Use by Cell Populations for Existing and New Small Commercial Buildings Projected to 2020.

Letter Designation	Cell Description	Existing or New	Projected Energy Use, Space Heating (Quads)
J	Small Commercial, Forced-Air, Sunbelt	EXISTING	0.42
K	Small Commercial, Forced-Air Sunbelt	NEW	0.22
L	Small Commercial, Forced-Air, Frostbelt	EXISTING	0.38
M	Small Commercial, Forced-Air, Frostbelt	NEW	0.17
	Total		1.19

Note: 1 quad = 10exp15 Btu

The total projected primary energy use for space conditioning in small commercial buildings with ducted forced-air distribution in the year 2020 is 1.19 quads per year. This compares with 0.8 quads for this sector in 1986, a 48% increase. DOE 1989 page 3-14 projects an increase for all commercial-building space conditioning from 4.9 quads in 1986 to 6.9 quads in 2010. This is a 41% increase over a smaller number of years. A parabolic extrapolation of DOE 1989 projections to 2020 yields 7.6 quads for commercial space conditioning, a 55% increase over 1986. (A linear extrapolation would yield a still-larger figure.) The small-building projections derived above are therefore consistent with current expectations for the commercial sector as a whole.

ENERGY SAVINGS POTENTIAL

Having developed a set of building classifications (cells) that includes the majority of the small-building stock using Thermal Energy Distribution (TED) systems, and having in turn developed estimates for the primary energy use within each of those cells, we now turn to estimating the energy savings potential associated with TED improvements on a cell by cell basis. Both the full technical potential, as well as the potential of some of the more obvious scenarios, are estimated for each cell. Based on Tables 23 and 32, there are nine residential cells and four commercial-building cells for which potential energy savings must be estimated. Consistent with those tables, the savings potential estimates are derived for cells A through L for the year 2020 in the sections that follow. The savings estimates are based on the best available information, however there is a wide range in the degree of confidence in the individual cell savings estimates. Both the detail, quality, and proximity-to-market of the technologies (and in some cases potential technologies) examined, vary substantially both between market sectors (cells) and within market sectors (i.e., between the various technology options in a given cell). The way we have chosen to deal with this diversity is to divide the derived estimates into three categories. Although it is not always clear into which category each of the technologies examined should fit, a first cut at this was undertaken. The three chosen categories are:

1. *Current Potential*: This category includes technologies that are developed, and that are reasonably well understood, at least in the buildings research community. The efforts required to achieve this potential will include development of more convenient diagnostics, development of verifiable accepted standards, demonstration projects, market analysis, and development of appropriate market mechanisms. These estimates are are printed in **boldface** within the tables presented for each cell.
2. *Full Potential*: This category includes what we considered to be the ultimate potential for savings possible by modifications to the thermal distribution systems within each cell for which we had sufficient information. Although it is unlikely that this potential would be fully realized, we expect that substantial fractions of this potential could be achieved. The efforts required to achieve this potential will include basic technology development, as well as exploratory research to improve our understanding of the processes involved and potential fixes possible. The *Current Potential* is a subset of this category. These estimates are are printed in *italics* within the tables presented for each cell.
3. *Undetermined Potential*: This category includes cells for which we considered our present analysis to be unacceptably uncertain, but which represent enough energy through thermal distribution systems that they can not be ignored. The efforts required for the entries herein are basic data gathering and analyses upon which defensible potential estimates could be based, although additional literature searches and subsequent analyses could prove fruitful in some instances. This category does not include any of the others as a subset, and should be viewed as potentially

additive.

Some general points should be kept in mind when examining the cell-by-cell analyses of energy savings potential that follow. First, three distinct techniques were used to make the cell savings estimates: 1) a simulation tool developed at LBL (Modera 1991), 2) the results of simulations with a previously developed tool, SP43 (Jacob et. al. 1986), and 3) hand calculations based on published laboratory or field investigations. We generally attempted to assure that all the cells were treated as consistently as possible, although additional work to further improve consistency is probably justified. In the instances where estimates of the impacts of particular measures or particular physical phenomena could not be obtained for a given cell with the predominant analysis tool for that cell, transfers of estimates from one cell to another were generally made in a conservative manner (e.g., one that tends to underestimate the size of the effect). Another assumption in our analyses that results in an underestimation of the savings potential is that average per-building energy use and percentage savings were used for all cells. As distribution-system inefficiencies and energy use are expected to be positively correlated, the use of average values results in an underprediction of the impacts of those inefficiencies, and therefore of the savings potential. On the overestimation side of the coin, with the exception of hydronic systems and partly-conditioned duct systems in single-family frostbelt houses, no attempt was made to estimate the impact of distribution-system improvements on heating or cooling equipment efficiency, the effect of which is a slight overstatement of the available savings. Another issue that is not taken into account is the energy implication of the fans and pumps associated with air or water distribution (These systems generally account for 1-5% of space-conditioning energy use in the small buildings under examination). Finally, although interactive effects were examined in a few cases (e.g., simulations for Cell A), we generally assumed that if more than one efficiency-improvement measure were applied to a given building within a cell (e.g., duct sealing and zone conditioning), the benefits would be sequential rather than additive. Namely, a 15% savings on top of a 25% savings results in a 36% rather than a 40% savings potential. This assumption, that all measures have a constant percentage impact that is independent of the energy demand to which they are applied, implies that we generally ignore any synergistic effects between measures, and that the only interactive effects considered in most cases were the energy demand reductions resulting from previous measures. In summary, although a number of effects were not examined in this study, many of which should be taken into account in future updates to this document, the numbers presented should provide reasonable (to conservative) estimates of the overall savings potential, as well as cell-by-cell comparisons that can help guide future efforts in this area.

(Cell A) *Single-family forced-air ducts in unconditioned spaces in the sunbelt (Existing buildings):* This building classification has recently been studied more extensively than any of the the others. Savings estimates can be obtained from: 1) published estimates in the literature, 2) measured savings for limited samples that received some type of TED retrofit, and 3) from detailed simulations of expected performance conducted specifically for this document (as yet unpublished). The numbers derived herein are based principally on the simulation results, however the simulation results are compared for consistency with earlier estimates and with measured performance parameters (whenever possible). As the majority of the results in this section are based upon simulation results, a brief summary of the reality checks employed is probably in order. These include:

1. The assumed envelope leakage is based upon a database of envelope leakage measurements on 750 houses (Modera 1986).
2. The assumed duct leakage is based upon a database of leakage measurements on over 250 houses (Cummings 1990, Modera 1986, Modera 1989, Modera 1991).
3. The changes in whole building infiltration rate due to system operation were compared with changes measured in a 31-house field study with tracer gasses (Modera 1991).
4. The simulated envelope pressure differentials created by running the duct system with the internal doors closed were compared with pressure differentials measured in a 31-house field study (Modera 1991).
5. The energy losses due to conduction from the ducts were compared with the losses measured in a 31-house field study, and the simulated losses were found to be less than the measured losses (Modera 1991).

The simulations used to estimate energy savings potential were based upon a combination of DOE-2, an hourly building energy load calculation model, and MOVECOMP, a non-linear air-flow network simulation model. These two large simulation codes were combined with several interface and post-processing programs to produce integrated as well as hour-by-hour estimates of energy use.

The savings potential estimates are based upon simulations of a base-case building that uses wall furnaces and room air-conditioners driven by a central thermostat (or alternatively, a 100% efficient distribution system). The chosen building is a 1540 ft^2 single-story ranch with a vented crawlspace and attic. The single-zone savings potential is then computed by comparing the base-case building with a "typical" forced-air distribution-system installation. This "typical" system has supply ducts in the attic and return ducts in the crawlspace, a configuration whose summer efficiency is between the least efficient extreme of attic supply/return, and the most efficient extreme of crawlspace supply/return in an unvented crawlspace (the chosen case is closer to the most efficient extreme). The system has typical duct leakage (140 cm^2) and typical insulation (R-4 english). The AFUE of the furnace and the SEER of the air conditioner were assumed to be equal to those assumed for the base-case (AFUE=0.85, SEER=10). Based upon annual simulations for a poorly-insulated (R-11 ceiling, R-0 walls, single-pane windows) house in Sacramento, California, it was found that the base-case house used 30% less energy for heating, and 23% less energy for cooling, when compared to the "typical" house.

Building Envelope To examine the importance of the building envelope on the percentage savings, annual simulations were also performed for a well-insulated (R-30 ceiling, R-19 walls, double-pane windows) house in the same climate, from which it was found that the base-case house used 33% less energy for heating, and 23% less energy for cooling, when compared to the "typical" house. Based upon a comparison of the heating and cooling energy-use profiles of the well-insulated and poorly insulated houses, the principal reason for the difference in the duct-system implications in the two cases seems to be the difference in operating conditions between the two cases. More specifically, the well-insulated house has heating loads only under more extreme weather conditions, implying a lower average duct efficiency. On the other hand, due its larger cooling-load fraction due to internal gains, and its longer time constant, the well-insulated house has more hours requiring cooling, and less peaked cooling loads, even though the overall cooling energy consumption for the well-insulated and poorly-insulated base-case houses is the same. Due to this lower correlation of the cooling load of the well-insulated house with weather conditions, more duct operation occurs during higher-efficiency periods, resulting in a higher average duct efficiency during the cooling season. Surprisingly, although the degree of coupling between the house and the buffer zones is expected to have some impact, namely that a larger fraction of the duct losses go towards reducing the building load in the poorly-insulated house, this has not yet been confirmed.

As a result of the well-insulated/poorly-insulated house comparison, it was tentatively assumed that the UA-value of the house did not have a large impact on the percentage difference between the typical house (i.e., duct system) and base-case house (i.e., no ducts) performance, and the average percentage is used for the calculations in this report. This assumption would have to be re-examined when trying to evaluate the performance of various design and retrofit options, as the direction and magnitude of the UA-value effects are dependent on the season, climate and type of inefficiency (i.e., duct leakage versus duct conduction versus flow imbalance (see below)). Another envelope issue that should be examined more carefully is the effect of attic and crawlspace venting on duct-system performance, as the recovery of heating-season duct losses should be larger in a house with less buffer-zone venting.

Balanced Returns As the simulations did not take into account the effect of closed interior doors on distribution system performance, several additional simulations were performed to estimate the size of this effect. The effect in question is the extra air infiltration (and subsequent space conditioning loads) due to interzonal pressure differentials created by the distribution system. These pressure differentials stem from the common practice of installing supply registers in each room, but only installing a single central return. When internal doorways are closed, the envelope pressure differentials created are typically on the order of 5-10 Pa. To estimate the overall impact of this effect, simulations were performed using typical internal door undercuts, and the resulting pressure differentials were compared with those measured in a 31-house field study in California. Including this effect, the typical poorly-insulated house uses 1.7% more cooling energy, and 1.3% more heating energy than the typical house used in the open-internal-door simulations. The equivalent figures for the well-insulated house were 2.2% more cooling energy, and 1.1% more heating energy than the open-internal-door well-insulated house. Although this effect seems to be relatively small, its magnitude is presently underestimated relative to other house constructions and other climates, as the extra infiltration in the simulated houses comes from buffer zones in a mild climate, which are at temperatures relatively close to that inside. Moreover, the use of a crawl-space house is particularly conservative relative to this effect, as a slab-on-grade house should be more significantly impacted by flow imbalances, particularly in the summer.

Duct Dynamics The effect of thermal mass in the ducts also has to be estimated. This effect stems from the fact that after the furnace or A/C turns off, there is energy stored in the ducts, some of which ultimately reaches the conditioned space, the rest of which is lost to outdoors via the unconditioned space. For a typical furnace, the distribution fan continues to run after the furnace has turned off, thereby recovering much of this energy, however doing so also increases the on-time of the furnace fan, and thereby increase the time period associated with increased air infiltration due to duct leakage and pressure imbalances. Also, during the heating season (and much of the cooling season in California), very little of the energy stored in attic supply ducts will be recovered after the fan turns off, as the air flow, and therefore the heat flow, will be from the house to the ducts. Based upon these considerations, our assumptions that 50% of the energy stored in the ducts is lost during the cooling season, and that 25% of the energy stored in the ducts is lost in the heating season, although not strictly correct, are relatively conservative (i.e., they are more likely to understate the losses). The simulation results were corrected by assuming that each hour of system operation contains 2.5 furnace cycles or 1.25 A/C cycles, and that the entire mass of the supply ducts is at a temperature halfway between the room and supply plenum temperature. The choice of the furnace cycles per hour was based upon the number of cycles per hour obtained in the validation of the SP43 model of furnace performance (Jacob et. al. 1986a), and the A/C cycles were based on a field study of heat pumps (Parken et. al. 1985). Including this effect, and conservatively assuming that the ducts are all the modern flexible fiberglass/plastic kind, the typical house in our simulations should use an additional 3% more cooling energy, and 6% more heating energy than the base-case house for both well-insulated and poorly-insulated (it should be noted that system sizing can play an important role relative to this effect).

To arrive at a savings estimate for sunbelt houses with ducts in unconditioned spaces, two more issues had to be dealt with: 1) the effect of duct location on duct-system energy implications, and 2) the effect of climate on duct-system energy implications. In both cases, when extrapolating from our attic-supply/crawlspace-return test house in Sacramento CA to the entire population, the duct inefficiencies increase.

Duct Location Concerning the effect of duct location on duct efficiency, the choice of a crawlspace return and attic supply ducts is conservative. Earlier research has shown that placing the return in the attic has a large negative effect on duct efficiency in the summer (Modera 1989), a situation that is very common in sunbelt houses due to the prevalence of slab-on-grade construction. The use of attic returns does not have a significant effect on winter duct performance, as attic temperatures do not vary considerably from crawlspace temperatures in the winter (although this does depend somewhat on construction and climate). Locating both supply and return ducts in the crawlspace would improve summer duct efficiency by reducing conduction losses, and should not have a large impact on winter performance. To further examine the magnitude of the impact of attic returns in the summer, simulations were performed for the typical well-insulated house with an attic return, the results of which indicated a 28% increase in air conditioning consumption over the crawlspace-return situation.

Climate Effects Concerning the effects of climate on duct-system energy implications, the duct efficiencies obtained in the simulations of the typical well-insulated house with a crawlspace return and attic supplies in Sacramento CA were plotted against outdoor temperature in Figures 1 and 2. Figure 1 is a plot of the furnace-mode duct efficiencies calculated for each hour of the heating season (October through April), whereas Figure 2 is a plot of the air-conditioning-mode duct efficiencies calculated for each hour of the cooling season (May through September). Both figures indicate a monotonic dependence of duct efficiency on outdoor temperature, with duct efficiency decreasing essentially linearly with increasingly severe outdoor conditions (lower outdoor temperatures in the winter, or higher outdoor temperatures in the summer). As Sacramento is a mild climate, even by sunbelt standards, Figures 1 and 2 indicate that duct efficiencies will generally be lower than those obtained from the Sacramento simulations. Moreover, the simulations presently do not account for latent load implications, an effect that is expected to be significant under summer conditions in the sunbelt, and even under summer conditions in much of the frostbelt.

Although all of the interactions between house construction, duct location and climate have not been investigated, the middle-of-the-road to conservative assumptions employed for the purposes of this analysis can be used to provide a reasonable estimate of the total savings potential available. The total savings potential was thus computed using the following assumptions:

1. The housing stock can be described by the average of the poorly-insulated and well-insulated simulated houses.
2. One half of the sunbelt houses with unconditioned ducts have attic returns, and those houses use 28% more cooling energy.
3. Heating-season duct performance is negligibly dependent on duct location.
4. Sacramento duct-system efficiencies are applicable to the entire sunbelt.
5. Dynamic effects are a constant percentage of base-case use (3% for cooling and 6% for heating, based on plastic flex ducts).
6. Pressure imbalance effects are a fixed percentage (the average of the poorly and well insulated hose percentages) of typical house use (2% for cooling, 1% for heating).

Based upon these assumptions, the overall savings potential values chosen to describe the existing housing stock in the sunbelt with ducts in unconditioned spaces are 35% for heating, and 34% for cooling.

To estimate the savings potential of a duct-system improvement scenario that could be readily accomplished with current technologies, a doubling of duct insulation value coupled with a 50% reduction in duct leakage was evaluated. A 50% reduction in duct leakage is in between the results of two recent field studies of duct sealing, one of which resulted in sealing approximately 25% of the duct leaks (Robison 1989), the other in sealing 68% of the leaks (Cummings 1990). To analyze the impacts of the chosen scenario, an additional simulation of the poorly-insulated house with R-40 ducts was performed, the purpose of which was to separate the effects of duct leakage from duct conduction. This simulation indicated that approximately 40% of the inefficiencies (excluding imbalances and dynamics) were due to duct conduction. Based upon this work, the percentage and absolute heating energy savings potential for 100% efficiency, and for various partial-improvement retrofit options are summarized in Table 33, and the analogous values are presented in Table 34 for cooling.

Zone Conditioning In addition, the extra savings potential that could be achieved by using zone conditioning is also included in Tables 33 and 34. The chosen savings potential presented for zone conditioning (15% of single-zone consumption) is based upon work done by Lawrence Berkeley Laboratory, the California Energy Commission, and others (Modera 1990). It should be noted that the estimated savings potential for zone-conditioning is lower for the sunbelt houses compared to the frostbelt houses (for which 20% savings is used). This difference is due to the larger expected impacts of zoning under more extreme weather conditions (see Cell E).

Table 33: Heating Energy Savings Potential for existing single-family houses with forced-air ducts in unconditioned spaces in the sunbelt **(Cell A)**

Retrofit	Savings [%]	Total Potential↓ [quads]
System Replacement Eff. = 100%	35	0.32
Zoned 100% Efficient Systems	*45*	*0.41*
R-8 Duct Insulation	7	0.06
Airtight Ducts*	20	0.18
Balanced Return	1**	0.01
50% Tighter Ducts, R-8 Insulation	**17**	**0.16**

↓ Based upon Table 23

* Assumed to eliminate the cycling losses in addition to leakage losses.

** Probably underestimated (see text).

Table 34: Cooling Energy Savings Potential for existing single-family houses with forced-air ducts in unconditioned spaces in the sunbelt **(Cell A)**

Retrofit	Savings [%]	Total Potential↓ [quads]
System Replacement Eff. = 100%	34	0.17
Zoned 100% Efficient Systems	*44*	*0.22*
R-8 Duct Insulation	6	0.03
Airtight Ducts*	19	0.09
Balanced Return	2**	0.01
50% Tighter Ducts, R-8 Insulation	**16**	**0.08**

↓ Based upon Table 23

* Assumed to eliminate cycling losses in addition to leakage losses.

** Probably underestimated (see text).

(Cell B) *Single-family forced-air ducts in unconditioned spaces in the sunbelt (New buildings):* The savings estimates for new construction in the sunbelt are based upon the same simulations used for existing construction, except the current-potential scenario includes R-12 rather than R-8 insulation, 80% sealed ducts rather than 50% sealed ducts, balanced returns, and 30% of the houses using 90% efficient zone conditioning. The assumption for the current potential that 30% of the houses (twice the estimated present rate in California) could receive 90% efficient zone conditioning is based upon two preliminary assumptions: 1) that the present state of the art in zone conditioning is only suitable to larger houses, and 2) that 100% efficient systems are not presently commercially available (other than no distribution system). Also, the well-insulated construction results are used instead of the average of poorly-insulated and well-insulated construction. These results are summarized in Tables 35 and 36.

Table 35: Heating Energy Savings Potential for new single-family houses with forced-air ducts in unconditioned spaces in the sunbelt **(Cell B)**

Retrofit	Savings [%]	Total Potential↓ [quads]
100% Efficient Single Zone	37	0.25
R-12, 80% Tighter Ducts with Balanced Returns*	28	0.19
Zoned 100% Efficient Systems	*46*	*0.31*
30%: Zoned, (90% efficient), 70%: R-12, 80% Tighter Ducts with Balanced Returns**	**32**	**0.22**

↓ Based upon Table 23

* Assumed to eliminate cycling losses in addition to leakage losses.

** Assumes that zone-conditioning is applied to the average house, rather than to the largest houses, as is presently the case.

Table 36: Cooling Energy Savings Potential for new single-family houses with forced-air ducts in unconditioned spaces in the sunbelt **(Cell B)**

Retrofit	Savings [%]	Total Potential↓ [quads]
100% Efficient Single Zone	34	0.13
R-12, 80% Tighter Ducts with Balanced Returns*	26	0.10
Zoned 100% Efficient Systems	*44*	*0.16*
30%: Zoned, (90% efficient), 70%: R-12, 80% Tighter Ducts with Balanced Returns**	**30**	**0.11**

↓ Based upon Table 23

* Assumed to eliminate cycling losses in addition to leakage losses.

** Assumes that zone-conditioning is applied to the average house, rather than to the largest houses, as is presently the case.

(Cell C) *Single-family forced-air ducts in partly conditioned spaces in the sunbelt (New and existing buildings):* The savings estimates for single-family houses with forced-air ducts in partially conditioned spaces is derived principally from the duct analyses performed as part of a research program cofunded in the 1980's by ASHRAE, DOE and GRI, that focused on ducts in partly conditioned spaces in the frostbelt (Jacob et. al. 1986), combined with some of the results from Cell A. A complete discussion of these analyses can be found in Cell F. In general, the assumed retrofits were the same as those for the frostbelt: insulation and sealing of ducts, system balancing and zoning. The heating and cooling savings were assumed to be equal, on a percentage basis, to the heating savings derived for the frostbelt. It was also assumed that that balanced-return systems presently exist in only 10% of the existing houses in this cell, that the percentage savings attributable to zoning is 15%, and that the percentage savings attributable to balanced returns is 1%, the latter two assumptions being consistent with Cell A. The primary energy use attributable to this cell is 0.31 quads (Table 23), and the savings estimates are summarized in Table 37. The full potential savings is computed as (1-(0.75*0.80*0.85 + 0.25*0.85))*0.31, equals 0.086 quads or 28%.

Table 37: Energy Savings Potential for new and existing single-family houses with forced-air systems in partly conditioned spaces in the sunbelt **(Cell C)**

Retrofit	Savings [%]	Fraction of Houses [-]	Total Potential↓ [quads]
100% Efficient Single Zone	21	0.75	0.05
80% Tighter, R-5 Insulation Ducts	**8**	**0.75**	**0.02**
Zoning	15	1.0	0.08
Zoned 100% Efficient Systems	*28*	*1.0*	*0.09*

↓ Based upon Table 23

(Cell D) *Multifamily forced-air ducts in the sunbelt (New and Existing buildings):* Although telephone interviews could be used to characterize the building stock in this cell, and existing simulation tools could be modified to estimate the potential savings associated with improving the efficiency of thermal energy distribution in these buildings, the scope of the present study has not yet included these efforts. At this stage we will assume that the savings achievable in these buildings is 10%, lower than any of the other cells examined. The rationale for making such a low estimate is that zoning is probably not a viable option, and a reasonable fraction of the ductwork might be in conditioned spaces. On the other hand, other sources of TED inefficiency could very well exist in these buildings. This estimate is one of the most uncertain of those presented in this document.

(Cell E) *Single-family hydronic distribution in the frostbelt (Existing buildings):*

Our analysis has considered several retrofit actions that could improve the overall efficiency of hydronic systems. These are:

- Insulate piping that passes through unconditioned or partly conditioned spaces.

- Implement a low flow-rate option to permit the use of a condensing boiler.
- Establish a zone control strategy.

Each of these options is now considered.

Insulate Piping As a base case for study, we assumed a hydronic loop running around the periphery of a 1500 ft^2 house, of dimensions 50 ft by 30 ft, with 200 ft of 0.75 in. I.D. pipe constituting the hydronic loop. Of this pipe, half is assumed to be finned tubing above the floor, and the other half is bare pipe in the basement. These assumptions give a heating capacity for the loop of just under 50,000 Btu/hr at full load. A typical operating condition of 15,000 Btu/hr heating load and three cycles per hour then yielded an operating protocol of 4 minutes circulator on followed by 16 minutes circulator off. The thermal losses from the bare pipe were then calculated to equal 18% of the thermal output from the boiler. Assuming the installation to be the typical case where the connecting pipes are located in a basement, it is reasonable to assume that half of these losses are recovered through system effects. (The basement temperature is higher that it otherwise would be, thus inhibiting heat loss through the house floor. See, for example, Jacob et al. 1986.) In this case, the net losses are 9%. A further calculation showed that these losses could be reduced to approximately 4% if the pipes were insulated to R-3. A net gain of 5% is thus projected.

Low-Flow Option with Condensing Boiler In a previous study of hydronic systems in residential housing, (Krajewski and Andrews 1983) the question of how to incorporate high-efficiency boilers that condense the water vapor in the flue gases was analyzed. In natural gas combustion, approximately 10% of the thermal output is in the form of heat of vaporization of the water vapor in the flue gas. A condensing boiler extracts a significant portion of this heat by cooling the flue gas to a low enough temperature to cause much of this vapor to condense. The difficulty is that condensation does not begin until the flue gas is cooled below 136 F, even under stoichiometric conditions. Since excess air is required, condensing does not begin until an even lower temperature is reached. Standard hydronic system designs use return-water temperatures of approximately 150 F. This is too hot to effect the required heat exchange with the flue gases. (Furnaces, by contrast, use return air form the house at approximately 70 F, cool enough to bring the flue-gas temperature down to approximately 100 F or less.) The solution proposed was to reduce the flow rate in the hydronic loop sufficiently that the return-water temperature would drop to approximately 100 F. The boiler can now condense.

Two immediate objections to this proposal needed to be addressed. The first was that with the lower flow rate, the ability of the system to deliver heat is reduced from the 50,000 Btu/hr typical of 3- to 4-gallon/minute systems to 30,000 Btu/hr. This latter figure is, however, still higher than most houses would require on all but the coldest days of the year. Many are so overdesigned, that the lower value would be adequate even on the most extreme heating day. If not, a two-speed circulator could be used to step up the flow rate for those few hours when a higher rate is needed. The higher flow rate could also be used for morning pickup in cases where a night setback strategy is used.

The second objection is more telling. It is that, with a lower flow rate, the heating units that are near the end of the loop (i.e., near the return to the boiler) will get a much smaller fraction of the total heat output than they did before the flow rate was reduced, because the water in them will be in the 100-120F temperature range rather than the 150-180 F range for which they were designed. The solution proposed here is to incorporate a reversing valve into the system. Each time the circulator is activated, the direction of flow through the hydronic loop would be reversed. Thus, those heating units that were shortchanged on one on-period of the system would be compensated on the next, because instead of being near the end of the line (cool end) they would be near the beginning (hot end).

Installation of such a system would require no reworking of the hydronic loop itself, other than installing the reversing valve, the necessary controls, and (possibly) the two-speed circulator at the boiler location. The expected energy savings can be estimated by comparing the annual fuel use efficiency (AFUE) of a typical boiler under standard design conditions with that possible for a condensing boiler. For the standard boiler, we assume 80% AFUE, consistent with current standards. Condensing furnaces typically have AFUE's in the 90-95% range. Condensing boilers have somewhat lower AFUE's, reflecting the difficulty of attaining low flue-gas temperatures. If the return-water temperature were reduced sufficiently, gas-fired condensing boilers should perform almost as well as furnaces. We therefore assume a 92% AFUE. The percent savings is then calculated from the ratio 80/92 = 0.87, or a 13% improvement. Note that although the savings accrue from the installation of a better boiler, they are not possible without the improvement in thermal distribution. This improvement should be readily retrofittable, although it is not now standard practice.

It should be noted that condensing is now a practical option mainly for gas-fired systems. With oil, the onset of condensing occurs approximately 10 F lower than for gas, because there is less water vapor in the flue gas from oil combustion than from gas (6% vs. 10%). Because there is less water vapor in the flue gas, the benefit from condensing is less. Also, with oil the condensate is more aggressively corrosive, because of oil's sulfur content. Finally, the smaller oil-heat market has encouraged less development of condensing systems for oil than for gas. Specifically, no oil-fired condensing boilers are now on the residential market.

Against these considerations is the strong support that the oil-heat industry has been giving to reasonable conservation options. The fact that research and development is needed to bring this efficiency improvement to oil-fired hydronic systems need not be an insurmountable barrier, although the incremental benefit relative to the best non-condensing oil-fired boilers may be somewhat less, because oil-fired systems can reach a higher efficiency without condensing. Oil-fired systems are about 2% more efficient than gas-fired ones at the same flue-gas temperature. (Andrews, et al. 1984)

In view of the above considerations, we will place the gas-fired systems in the current potential category, while the oil-fired systems will be placed in the full energy-savings potential category, with a 10% improvement in AFUE, compared with the 12% improvement we have assumed for gas.

Zoning Splitting a house into two or more zones, each controlled by its own thermostat, is a well-known means of saving energy. One of the points raised in favor of built-in electric heat is that each room can be controlled individually, with unused rooms turned down in temperature. In new hydronic systems, too, zoning is relatively simple, requiring only that each zone have its own hydronic loop with circulator controlled by its own thermostat.

Given that relatively few new houses are being built with hydronic systems, we naturally are driven to question whether zoning might be retrofitted. We have proposed two methods of doing this.

The first method is straightforward. Simply split the existing loop into two or more loops, running the necessary additional piping to the points where the breaks are made and installing the additional circulator(s). The cost-effectiveness of this retrofit obviously will by system-dependent. For some systems, the breakpoint will be easily accessible and near the boiler. For other systems, this retrofit may be precluded by characteristics of the as-installed configuration.

A second approach to zoning will, in some cases be made possible by the low-flow approach discussed above. If the hydronic loop is configured (or can be easily reconfigured) such that all the rooms of one zone are reached first, and then all the rooms of a second zone, then a two-zone system can be implemented in connection with the low-flow option, without adding any circulators. In this case, whichever zone is to be set back in temperature will be placed at the end of the line nearest the boiler return, while the zone that is to set up in temperature will be placed nearest the supply from the boiler. Should this setting allow the setback zone temperature to drop too far, the flow direction can be reversed temporally. A simple control strategy would determine the direction of flow to favor the zone whose temperature is below its own setpoint.

The energy savings potential for a zoning strategy depends on the nature of the strategy itself and on the thermal characteristics of the house. In general, the larger and less well insulated a house is, the more it can benefit from zoning. This is because zoning strategies generally involve changes in the temperature of the zoned subspaces at certain time in the diurnal cycle. The time a structure takes to respond to changes in the temperature setpoint is proportional to the product of the level of insulation and the thermal mass of the house (resistance-capacitance product). As a benchmark, we refer to studies of zoning carried out at Oak Ridge National Laboratory (ORNL) and Brookhaven National laboratory (BNL). For typical Frostbelt locations, a study at Oak Ridge National laboratory predicted possible energy savings from zoning ranging up to 44% in Chicago and 55% in Knoxville (Moyers and Nephew 1984). Brookhaven National

Laboratory predicted savings of 32% in Kansas City (Andrews and Krajewski 1985, page 56). These predictions were for aggressive zoning strategies in which portions of the house are allowed to drop in temperature to as low as 50F when unoccupied. However in evaluating the savings that could be obtained from improved thermal distribution, we need to take into account the savings obtainable from night setback, which does not require any changes in the distribution system. The SP-43 project derived an average benefit of 13% energy savings from night setback in three northern cities for forced air from zoning (over and above night setback) which appears reasonable in the light of the above-referenced overall projections. We therefore project a 20% improvement in energy efficiency that is made possible specifically via changes in the thermal distribution system.

Energy Savings Potentials In this section we evaluate the overall energy savings potential for thermal distribution improvements in existing single-family housing with hydronic distribution in the Frostbelt. In order to do this, we will need to take account of the following factors.

1. Savings from insulating piping are limited to the extent that systems already have insulated pipes. We make the assumption here that half of the houses in this cell have their below-grade piping insulated, while the other half do not. We place this retrofit in the current potential category.
2. Savings from low-flow condensing are now limited to systems that use gas. The NAHB data for 1983 show 3.8 million hydronic systems in the Frostbelt with gas-fired boilers, out of a total of 6.7 million systems. Thus, 57% of the systems will be placed in the current potential category, while the remaining 43% (which use oil-fired boilers) are in the full potential category.
3. We have no data on the number of these houses that could be zoned. As we placed zoning in the full potential category, we assumed that all of the houses in this cell could be zoned using relatively straightforward means, such as provision of an additional circulator, or using more advanced techniques, such as the flow-reversal scheme discussed above.

The savings potentials for this cell are summarized in Table 38, and are based on the heating energy usage for this cell of 0.62 quads from Table 23. The current potential is computed as (1-0.95*0.25-0.95*0.87*0.25-0.87*0.32-1.0*0.18)*100, which equals 10% or 0.062 quads. Similarly, the full potential is computed as (1-0.80*0.88*0.5-0.80*0.88*0.95*0.5)*100, which equals 31% or 0.195 quads.

Table 38: Heating Energy Savings Potential for existing single-family houses with hydronic systems in the frostbelt **(Cell E)**

Retrofit	Savings [%]	Fraction of Houses [-]	Total Potential↓ [quads]
Insulate Piping in Unconditioned Space	5	0.5	0.02
Low-flow Condensing Boiler (Gas)	13	0.57	0.05
Current Potential (Above Retrofits Where Applicable)	**10**	-	**0.06**
Low-flow Condensing Boiler (Oil)	11	0.43	0.03
Zoning	20	1.0	0.12
Full Potential (All Applicable Retrofits)	*31*	-	*0.20*

↓ Based upon Table 23

(Cell F) *Single-family forced-air ducts in partly conditioned spaces in the frostbelt (New and existing buildings):*

Our analysis of this cell relies heavily on results obtained in a project initiated by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) with funding support from DOE and the Gas Research Institute. This project, performed by Battelle-Columbus laboratories during the years 1982 - 1988, measured the performance of forced-air systems in two houses with basement ductwork in Columbus, Ohio. The primary purpose of the project was to assess the extent to which improvements in furnace efficiency resulted in comparable percentage improvements in overall system performance, as measured by a figure of merit called System Index that is proportional to the inverse of fuel consumed on an annual basis. One of the factors also investigated in that project was duct efficiency, including the interaction between duct losses and overall building load.

One of the principal difficulties associated with estimating the energy savings potential for this cell (and Cell C) was to assure that the estimates were consistent with (or at least comparable to) the estimates for the other major cells, namely those examined with the LBL air-distribution model (Cells A,B and G). To overcome this difficulty, some understanding of how the two models compare, and some means of reconciliation of the differences was needed. In brief, the major differences between the two types of analyses are: 1) the LBL analyses use a crawlspace house with 100% efficient distribution (e.g. no-distribution/single-zone-thermostat) as a base case, whereas the SP43 work uses a basement house with "typical" ducts, insulated basement walls, and uninsulated basement ceiling, as a base case, 2) the LBL model deals explicitly with overall leakage/flow implications, including localized return and supply leakage as well as unbalanced-return effects, whereas the SP43 model assumes a fixed air infiltration rate, assumes that return leakage is equal to supply leakage, and ignores unbalanced-return effects, 3) the SP43 model simulates duct dynamics (using sheet-metal ducts), furnace cycling, furnace efficiency and electricity-use directly, whereas the LBL model estimates the effects of duct dynamics and does not consider furnace efficiency changes or fan electricity consumption, and 4) the LBL model treats cooling, whereas the reported SP43 model results do not.

The first step in reconciling the two models was to reanalyze the SP43 results so as to compare different options with the 100% efficient distribution case. The principal difficulty in doing this was to properly account for the duct energy losses that are indirectly returned to the house (e.g., by warming the basement). No explicit calculation of such a factor was reported; however, recomputing an energy balance based upon the data from the SP43 project (Jacob, et al. 1986) it was found that in basements with no insulation, those with walls insulated to R-8, and those with R-11 ceiling insulation as well as R-8 wall insulation, the fractional amount of energy returned to the house varied between 42 and 57%. Based upon these fractions, the effects of going from the "typical" duct installation in SP43 (R-0 ducts with 10% supply and return leakage) to a 100% efficient distribution system could be determined (see Table 39).

Table 39: Fractional basement energy-loss recovery and resulting impact of installing 100% efficient distribution in a basement house (based on SP43 simulation results).

Basement Ceiling Insulation [h ft^2 °F/Btu]	Basement Wall Insulation [h ft^2 °F/Btu]	Duct-Loss Recovery [%]	$I_{100\%}/I_{typical}$ * [-]
0	0	49	1.27
0	8	57	1.19
11	8	42	1.28

* System index as defined in SP43 project (portion of total energy input that supplies the net load of the intentionally conditioned space) for a 100% efficient distribution system, divided by that for the "base-case" duct system used in the SP43 calculations (i.e., no duct insulation and 10% supply and return leakage).

The results in Table 39 are used to estimate the savings potential associated with installing 100% efficient distribution systems in basement houses. This is accomplished by assuming (for lack of any better information) that one third of the existing basement housing stock in the frostbelt falls into each of the three categories in Table 39, the result being an average potential savings of 20% ((1/1.27 + 1/1.19 + 1/1.28)/3 X 100). It should be noted that the potential energy savings could be considerably higher if basement insulation were included as part of, or in lieu of, the measures taken to improve distribution-system efficiency.

Balanced Returns To be consistent with the estimates of savings potential made with the LBL model (Cells A, B and G), the issue of unbalanced return-air flows has to be included. The savings estimates associated with the eliminating the extra air-infiltration impacts of closing interior doors are based upon the simulations performed for Cell A. The savings potential associated with eliminating this effect was chosen to be higher for frostbelt homes than for sunbelt homes due to the larger relative temperature differentials associated with air infiltrating from buffer zones and outside in the more extreme climates. It was also assumed that only about half of the houses will be amenable to return balancing, the ineligible houses being those with previously-balanced systems.

Current Potential The current-potential estimate for this cell is based upon the assumption that ducts in basement houses are typically configured as in the SP43 base case (i.e., uninsulated with 10% balanced supply and return leakage). It should be noted that, although it does not seem unreasonable, we do not have any confirmation that the SP43 base case is typical. It is also assumed that the ducts can generally (75% of the time) be easily accessed for sealing and insulating. Concerning access for sealing, those that are enclosed in the basement ceiling are most likely associated with finished basements, which should probably be considered to be part of the conditioned space under those conditions. The ducts are assumed to be 80% sealed and insulated to R-5, the savings estimate for this being based on the results of two of the scenarios analyzed within the SP43 project. This retrofit raises duct efficiency to approximately 76% from between 57% and 61%, which in turn results in an energy savings potential of 8% on average.

Zoning The potential for zone conditioning in this sector was determined by using the 20% savings estimate used for hydronic systems in the frostbelt, and assuming that all of the houses in this cell would be amenable to zoning, either by retrofit or by inclusion into new construction. In reality there will be limitations on zoning in retrofit, where the installation of new dampered returns could prove prohibitively expensive or impractical.

Full Potential To estimate the full potential for this cell, it is assumed that 100% efficient systems could be retrofitted into 75% of the stock, the remaining 25% of the stock assumed to have finished basements, which are assumed to be equivalent to ducts within the conditioned space, and are therefore only eligible for the 20% savings associated with zoning. It is also assumed that the savings due to return-air balancing is included in the savings associated with zoning. The primary energy use attributable to this cell is 0.86 quads (Table 23), and the full potential savings is computed as (1-(0.75*0.80*0.80 + 0.25*0.80))*0.86, equals 0.275 quads or 32%. The results are shown in Table 40.

Table 40: Heating Energy Savings Potential for new and existing single-family houses with forced-air systems in partly conditioned spaces in the frostbelt **(Cell F)**

Retrofit	Savings [%]	Fraction of Houses [-]	Total Potential↓ [quads]
100% Efficient Single Zone	22	0.75	0.14
80% Tighter, R-5 Insulation Ducts	**8**	**0.75**	**0.05**
Balanced Returns	2*	0.5	0.01
Zoning	20	1.0	0.17
Zoned 100% Efficient Systems	*32*	-	*0.28*

↓ Based upon Table 23

* Probably underestimated (see *Balanced Returns* text for Cell A).

(Cell G) *Single-family forced-air ducts in unconditioned spaces in the frostbelt (New and existing buildings):* The savings estimates for houses with ducts in unconditioned spaces in the frostbelt are based upon the same simulations used for existing construction in the sunbelt, except that heating and cooling are combined to create a single table (due to the small size of the cooling energy use and the small difference between heating and cooling performance). The effect of zoning was assumed to be the larger value used for the frostbelt (20%), and the effect of return balancing was also assumed to be the larger value used for the frostbelt (2%). These results are summarized in Table 41. The impact of a larger fraction of unvented crawlspaces in this region was assumed to be compensated for by the lower expected duct efficiencies associated with the more severe climate, however this issue clearly merits further investigation.

Table 41: Energy Savings Potential for new and existing single-family houses with forced-air ducts in unconditioned spaces in the frostbelt **(Cell G)**

Retrofit	Savings [%]	Total Potential↓ [quads]
System Replacement Eff. = 100%	35	0.27
Zoned 100% Efficient Systems	*48*	*0.37*
R-8 Duct Insulation	7	0.05
Airtight Ducts*	20	0.15
Balanced Return	2**	0.01
50% Tighter Ducts, R-8 Insulation	**17**	**0.13**

↓ Based upon Table 23

* Assumed to eliminate the cycling losses in addition to leakage losses.

** Probably underestimated (see *Balanced Returns* text for Cell A).

(Cell H) *Multifamily forced-air ducts in the frostbelt (New and Existing buildings):* As for forced-air multifamily buildings in the sunbelt (Cell D), telephone interviews could be used to characterize the building stock in this cell, and existing simulation tools could be modified to estimate the potential savings associated with improving the efficiency of thermal energy distribution in these buildings. The present study has not yet included these effort. At this stage we will assume that the savings achievable in these buildings is 10%, lower than any of the other cells examined, following the same rationale used for the sunbelt buildings. This estimate is also one of the most uncertain of those presented in this document.

(Cell I) *Multifamily hydronic in the frostbelt (Existing buildings):* In general, this cell contains three types of distribution systems, single-pipe steam distribution, two-pipe steam distribution, and hot water distribution. Of the three, single-pipe steam is the most inefficient, hot water the most efficient. The retrofits included for this sector are: 1) steam-flow balancing for single-pipe steam buildings, 2) steam to hot water conversion for two-pipe and single-pipe steam buildings, 3) outdoor temperature reset and cutout for hot-water buildings, and 4) Thermostatic Radiator Valves (TRV) for hot-water buildings.

In a single-pipe steam building, the boiler is connected to the radiators in the zones via single pipes through which steam flows in one direction, and condensate flows in the other. Thermostatic valves on steam lines and radiators allow the air within the system to escape as the steam trys to push its way through the system, and close when the high-temperature steam reaches the valve. Steam-flow balancing in single-pipe steam buildings is accomplished by changing the air vents of steam lines, steam risers, and radiators. The problem being solved is that of apartments close to the boiler room tending to get much more heat than those furthest from the boiler room, due to the fact that the radiators in the close apartments are filled with steam much more quickly than those in the far apartments. As a result, in order to maintain comfort in the furthest apartments, the thermostat setting is raised, windows are opened in the close apartments, and a large fraction of the heating energy is wasted. Increasing the air-flow capacity of the vents on the furthest runs (and therefore reducing steam resistance of those runs) provides much more uniform heat delivery.

Converting a building from steam to hot-water distribution has been shown to be very effective in reducing energy consumption (Goldman et.al. 1988), however the only demonstrations of this have been in two-pipe steam buildings, for which it is much less expensive to make the conversion from steam to hot water. This is because the existing condensate return lines from each radiator in a two-pipe steam building can be converted to hot-water returns, which is not the case in single-pipe steam buildings. It is possible to make these conversions in single-pipe steam buildings, however the costs have been considered to be excessive.

Two options are considered for buildings heated with hot water, the first being to install a reset/cutout controller that changes the temperature of the water in the circulating loop in response to changes in outdoor temperature, the term cutout corresponding to turning off the boiler completely whenever the outdoor temperature rises above a specified value. The other option for hot-water buildings, which can be coupled with outdoor cutout/reset, is to use TRVs to adjust the flow to a given zone based upon the temperature sensed by the valve in that zone.

The savings estimates for this cell are relatively conservative, as they are based upon actual measured savings for technologies that have been demonstrated (Goldman et.al. 1988, Biederman and Katrakis 1990). The "current potential" estimates are based upon outdoor reset/cutout controls being installed in three-quarters of the available building fraction, steam to hot water conversion being employed in one fifth of the available fraction (e.g., two-pipe steam only), and steam balancing being employed in three quarters of the available fraction. The "full potential" estimates are based upon outdoor reset/cutout controls being installed in the full available fraction, and steam to hot water conversion being employed in the full available fraction. To consistent with the other cells, this cell should be updated with a 100% efficiency analysis.

Table 42: Heating Energy Savings Potential for existing multifamily buildings with hydronic systems in the frostbelt **(Cell H)**

Retrofit	Savings [%]	Fraction of Buildings [-]	Total Potential↓ [quads]
Steam Balancing	15	0.7	0.03
Steam to Hot Water Conversion	25	0.7	0.05
Outdoor Reset (water)	9	0.3	0.01
Thermostat Radiator Valves (water)	15	0.1	0.01
Current Potential (Presently Applicable Retrofits)	**14**	-	**0.04**
Full Potential (All Applicable Retrofits)	*22*	-	*0.07*

↓ Based upon Table 23

Cells J,K,L and M)*Small-commercial forced-air ducts in the sunbelt and frostbelt (New and Existing buildings):* Although there may be some information within the literature that could be used to quantify the potential savings associated with improving the efficiency of thermal energy distribution in small commercial buildings, the scope of the present study did not include such a literature search and analysis. Moreover, it is equally likely that primary data collection might be necessary to make reliable estimates of the energy savings potential for these cells. At this stage we will assume that the savings achievable in TED systems in new small commercial buildings is 20%, and that the savings potential in existing buildings is 10%, both of which are lower than the average savings potential for new and existing residential buildings, respectively.

SAVINGS POTENTIAL SUMMARY

For each of the market cells A through L, potential energy savings estimates have been derived in the previous sections. Based upon these estimates, summaries of the various entries into the *Current-Potential*, *Full-Potential*, and *Undetermined-Potential* categories have been compiled, and are presented in Tables 43 through 45.

Table 43: **Current** Energy Savings Potential of Improved Efficiency of Thermal Energy Distribution in Small Buildings

Cell	Description	Savings [%]	Potential [quads]
A	Existing Single-Family Unconditioned Forced-Air (Sunbelt)	17	0.24
B	New Single-Family Unconditioned Forced-Air (Sunbelt)	31	0.33
C	Exist + New Single-Family Part conditioned Forced-Air (Sunbelt)	6	0.02
E	Exist + New Single-Family Hydronic (Frostbelt)	10	0.06
F	Exist + New Single-Family Part conditioned Forced-Air (Frostbelt)	6	0.05
G	Exist + New Single-Family Unconditioned Forced-Air (Frostbelt)	17	0.13
I	Exist + New Multifamily Hydronic (Frostbelt)	14	0.04
All	**Total**		**0.87**

Table 44: **Full** Energy Savings Potential of Improved Efficiency of Thermal Energy Distribution in Small Buildings

Cell	Description	Savings [%]	Potential [quads]
A	Existing Single-Family Unconditioned Forced-Air (Sunbelt)	45	0.63
B	New Single-Family Unconditioned Forced-Air (Sunbelt)	46	0.47
C	Exist + New Single-Family Part Condition Forced-Air (Sunbelt)	28	0.09
E	Exist + New Single-Family Hydronic (Frostbelt)	31	0.20
F	Exist + New Single-Family Part Condition Forced-Air (Frostbelt)	32	0.28
G	Exist + New Single-Family Unconditioned Forced-Air (Frostbelt)	48	0.37
I	Exist + New Multifamily Hydronic (Frostbelt)	22	0.07
All	**Total**		**2.11**

Table 45: **Undetermined** Energy Savings Potential of Improved Efficiency of Thermal Energy Distribution in Small Buildings

Cell	Description	Savings [%]	Potential [quads]
D	Exist + New Multi-Family Forced-Air (Sunbelt)	10	0.07
H	Exist + New Multi-Family Forced-Air (Frostbelt)	10	0.05
J	Existing Small Comm. (Sunbelt)	10	0.04
K	New Small Comm. (Sunbelt)	20	0.04
L	Existing Small Comm. (Frostbelt)	10	0.04
M	New Small Comm. (Frostbelt)	20	0.03
All	**Total**	**12**	**0.27**

CONCLUSIONS

Two major conclusions can be drawn from the analyses presented in this study. First, these analyses have shown that the potential energy savings associated with improving thermal energy distribution systems in small buildings is large, ranging from 0.87 to 2.38 quads, and possibly more. However, despite the apparently large energy savings potential uncovered, this study also pointed out the relatively poor understanding and characterization of many of the key issues, which leads to the second conclusion. Namely, based upon the large variability in the quality and quantity of information available for the various market sectors identified, this study has made it clear that is that there is a need both for better data and for leadership in this area. In particular, the development of a consistent analysis methodology and yardstick by which competing technologies within a cell, or even between cells, can be fairly compared, would represent an important first step towards achieving the potential energy savings identified in this study.

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