RESIDENTIAL ENERGY CONSUMPTION DETAILED GEOGRAPHIC ANALYSIS

SUMMARY REPORT

Department of Housing and Urban Development

Office of the Assistant Secretary for Policy Development and Research

ENERGY CONSERVATION

RESIDENTIAL ENERGY CONSUMPTION
DETAILED GEOGRAPHICAL ANALYSIS

HIT-650-11

Summary Report

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Taghi Alereza

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I. INTRODUCTION

Based on the events of the last several years, including the oil embargo of 1973-74 and subsequent skyrocketing energy costs, the United States has become increasingly concerned with the conservation of energy in all sectors of national activity. The residential sector has long been recognized as both a major user of energy - presently comprising about 20 percent of the total national energy use, and a less than efficient user of energy - significant reductions in residential energy use have been deemed plausible in several studies.

This summary report on residential energy use in eleven U.S. cities is part of a continuing program devoted to the analysis of the reduction of residential energy use in the United States. In initiating this research program in 1971, the U.S. Department of Housing and Urban Development (HUD) gave to the contractor, Hittman Associates, Inc., (HAI) the task of *"... identifying means for obtaining greater efficiencies in the utilization of energy in residences, in order to obtain lower per capita consumption without modification of existing life-styles."* The reports published as a result of this work dealt with the consumption and efficient use of energy in Baltimore/Washington area residences.*

Many researchers and decision makers had the need to apply the results of these reports to other regions of the country. In such applications, consideration had to be given to several geographically-variant factors such as climate, basic structural design, construction materials, and available fuels. Thus the need for a detailed geographical analysis of residential building construction and energy use was realized.

**See "Residential Energy Conservation (A Summary Report)," HUD-HAI-8, July 1974, and seven technical reports cited therein.*

In 1975, HAI was retained by HUD to perform such a detailed geographical analysis "... *to extend the previous results obtained for the Baltimore/Washington area to ten geographical locations in the United States.*"* The locations selected for this analysis were:

- Atlanta, Georgia
- Boston, Massachusetts
- Chicago, Illinois
- Denver, Colorado
- Houston, Texas
- Los Angeles, California
- Miami, Florida
- Minneapolis, Minnesota
- San Francisco, California
- St. Louis, Missouri

These locations represent diversified climates and include variations in other factors such as design practices, energy prices, local income levels, and ethnic backgrounds; all influencing local building construction and therefore heating and cooling energy use. Four of the locations studied; Boston, Chicago, Denver, and Minneapolis; are representative of cold regions with 5000 or more heating degree days. Four other locations; Atlanta, Baltimore, San Francisco, and St. Louis; are mild regions with 3000 to 5000 heating degree days. The remaining three locations; Los Angeles, Houston, and Miami; represent regions with dominant cooling seasons. Weather parameters such as heating and cooling degree days, average wind velocity, and available solar radiation for the eleven locations are presented in Table I.

The boundaries for each geographical area were defined in accordance with the Federal Government's definition of standard metropolitan statistical areas (SMSA's). For each of these locations, it was sought: to identify and quantify the total heating and cooling energy requirements in typical single-family detached, single-family attached (townhouse), low-rise multifamily, and high-rise multifamily dwellings; and to evaluate the use of various technical innovations capable of reducing energy use in the typical dwellings.

In conducting each of these city-specific studies, the following multi-step approach was taken.

- Identify the current trends in construction and design and the resulting energy use patterns of residences in each area.

**See "Regional Residential Energy Consumption," HIT-650-1 through 10, 1976.*

TABLE I. SUMMARY OF ANNUAL WEATHER DATA

	ATLANTA	BALTIMORE	BOSTON	CHICAGO	DENVER	HOUSTON	LOS ANGELES	MIAMI	MINNEAPOLIS	SAN FRANCISCO	ST. LOUIS
Average Heating Degree Days	3095	4200	5621	6127	6016	1434	1245	206	8159	3042	4750
Average Cooling Degree Days	1589	1245	661	925	630	2889	1185	4038	585	108	1475
Total Available Solar Radiation (Ly/Day)	394	355	311	273	416	442	447	453	348	446	380
Cooling Degree Days*	2131	1455	888	1175	602	3254	1066	4370	923	218	1793
Average Wind Velocity (MPH)	9.1	9.5	12.7	10.3	9.0	7.4	6.2	9.1	10.6	10.5	9.5
Weather Year	1955	1954	1961	1951	1961	1959	1951	1960	1957	1951	1949

*Based on 60°F discomfort cooling index.

- Define characteristic single-family, townhouse, low-rise, and high-rise structures representing typical new buildings in each area.

- Calculate the hourly, monthly, and annual energy requirements for heating and cooling each characteristic structure for a typical weather year (the selected weather year for each region is given in Table I).

- Define improved single-family, townhouse, low-rise, and high-rise structures incorporating a package of several energy conserving modifications.

- Calculate the hourly, monthly, and annual energy requirements for heating and cooling the improved residences for the chosen weather year, and compare the results with those of the (unmodified) characteristic residences.

The following chapters describe the characteristic buildings, present their heating and cooling loads and the resulting energy use, and discuss the potential energy savings associated with a set of improvements made to each building. All the information included in this summary report has been documented in the twelve city-specific reports referenced at the back of this report.

II. SUMMARY AND CONCLUSIONS

Building trends and practices were identified for the eleven cities through an extensive survey of builders and architects. Four building classes were studied, including single-family, townhouse, low-rise, and high-rise residences. A brief synopsis of the building trends and practices identified follows.

- Single-family houses have declined in popularity in recent years but are still the most prevelant form of housing, followed in turn by townhouses, low-rise apartments, and high-rise apartments.

- The typical single-family houses defined in this study had floor areas that varied from 1139 to 1852 square feet and about 200 square feet of glass. All the single-family buildings had moderate roof insulation and all but the Miami house had wall insulation. The most common HVAC system was a gas-fired, forced air heating system used in conjunction with a central air conditioning system.

- Typical townhouses tended to be about 25 percent smaller than the single-family houses, ranging in size from 1150 to 1672 square feet and having an average of 130 square feet of glass. The townhouses each had ceiling and wall insulation levels comparable to the single-family houses, except the Baltimore and Miami townhouses, which had no wall insulation. The most common HVAC system was a gas-fired, forced air heating system and a central air conditioning system. The most common living unit arrangement was eight two story living units side by side in each townhouse building.

- The low-rise apartments were typically between 525 and 1140 square feet and had an average of 90 square feet of glass. The low-rises followed the same insulation pattern as the townhouses, with the Baltimore, Miami, and St. Louis buildings having no wall insulation. The most common HVAC system was a gas-fired or electric forced air system and either central or window air conditioning. The typical living unit arrangement was 24 living units in a two or three story building.

- The high-rise apartments had floor areas varying from 550 to 1326* square feet with an average of 80 square feet of glass. The high-rise buildings were not well insulated; many having only an air gap for wall and ceiling insulation. The most common heating distribution systems were two-pipe fan coil and baseboard radiation, the cooling was central in the two-pipe fan coil buildings and window units in those heated by baseboard radiation. The arrangement of living units was 149 to 224 units in a ten or fifteen story building.

Energy use patterns of these buildings were quantified using the computerized Hittman Associates, Inc., Building Energy Analysis Model (BEAM). These patterns are outlined below.

- Single-family residences required the most energy for heating and cooling, followed in turn by townhouses, high-rises, and low-rises. This trend was mainly the result of changes in exterior surface area, air infiltration, and internal load density.

- The inefficiencies associated with electricity generation made the choice of heating energy the most important factor in determining a building's primary energy use. These inefficiencies also tended to make the residences in regions with large cooling requirements the most energy intensive.

- Climatic environment dominated in-structure energy use in the single-family residences and did so to a lesser degree in townhouses, high-rises, and low-rises, respectively.

- A high correlation was found between a building's exterior surface area and its infiltration load. The high-rise buildings had unusually large infiltration loads resulting from large stack effects and required hall and stairway ventilation.

- Building construction proved to be the most variable factor in determining in-structure energy use and is therefore the most important consideration in residential energy conservation.

**The unusually large 1326 square foot living unit was a three bedroom condominium in Houston, Texas.*

- The Thermal Load Factor* (TLF) was a good measure of the heating thermal integrity in the single-family, townhouse, and low-rise buildings.

The energy use of the characteristic buildings was analyzed to determine where energy reductions could be made. A set of improvements for each building was formulated and the energy required by the improved buildings was calculated in a manner similar to that used for the characteristic residences. An analysis of the resulting energy savings follows.

- Reductions in total heating and cooling energy use were typically between 30 and 60 percent (see Figure 1). These savings were the result of technically feasible modifications to houses of standard design and construction.

- The most important modifications analyzed included a reduction in glass area; use of double glazing or reflective glass; installation of weather-stripping and caulking; increased wall, floor, and ceiling insulation; and utilization of more efficient HVAC systems.

- The TLF's of the characteristic buildings proved to be a good measure of the potential heating energy savings in all but the high-rise apartment buildings.

Three major conclusions can be drawn from the results of this study.

- Current building practices are not in the best interests of energy conservation and can be significantly improved - typically resulting in about 50 percent reductions in energy use - by several structural and HVAC improvements. See Figure 1 for a summary of potential energy savings.

- Although fuel choice dominates primary energy use and climatic environment dominates in-structure energy use, the fact that a building's thermal integrity is the most readily improvable energy use factor makes it very important from an energy conservation standpoint.

**The Thermal Load Factor is a building floor area and climate normalized building energy requirement.*

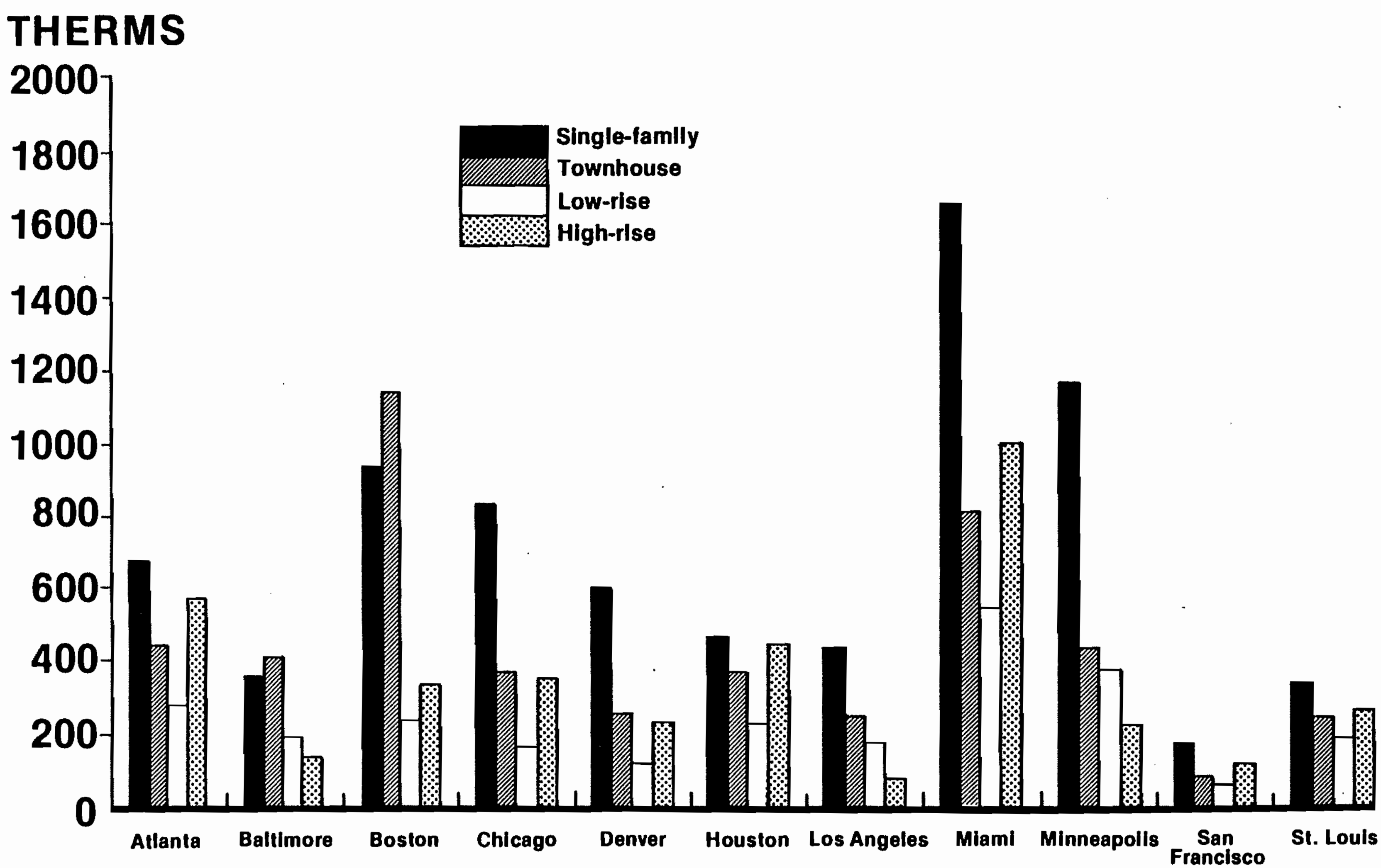

Figure 1. Reductions in Total Primary Energy Use For Improved Buildings

- The TLF is a good measure of a building's thermal integrity for heating and could therefore be used as the basis of a construction standard, but more research is required to develop an equivalent measure for building cooling thermal integrity.

III. IDENTIFICATION OF CHARACTERISTIC RESIDENTIAL STRUCTURES

Typical, or characteristic, residences representative of the current design and energy use patterns in single-family residences, townhouses, and low-rise and high-rise apartments, were defined for the eleven selected metropolitan areas. This identification was based on a large data base developed from information gathered from national and municipal agencies, trade and industrial sources, and utility companies. Performing an informal sampling, compatible sets of building parameters were synthesized to represent complete residential structures typical of current building design practices in each area.

The design and structural features considered important in defining these residences included:

- structural parameters such as contruction details, dimensions, and materials used, and

- energy use parameters such as heating and cooling equipment, types of fuel and energy used, and appliances and their energy use levels.

Whereas specific life-styles were not prescribed for the residents of the characteristic residences, a certain number of life-style parameters were imposed, by necessity, for the analyses. Examples of life-style parameters that were identified include:

- thermostat set points,

- relative humidity set points,

- type and number of appliances,

- daily profiles of appliance and lighting usages, and

- use of ventilation fans.

Most of these parameters were defined for average conditions; no attempt was made to modify the parameters to allow for variations caused by weekends or holidays, vacations, entertaining of large groups, difference in age or affluence of the residents, etc. Occupancy loads were, however, adjusted for weekends. The only component of internal load that varied significantly from building to building was lighting, which was defined as a linear function of floorspace, and thus varied geographically as did floorspace. In consideration of the sites and quality of the characteristic residences and of the appliances used in these residences, it was assumed that the residences would be occupied by individuals or families in the middle income group. It should be recognized that the life-style of any given resident in a real case could vary greatly from the average conditions defined for these analyses, and that variations in occupant life-style will affect a building's energy use in a non-negligible way.

With respect to ventilation air, the single-family, townhouse, and low-rise apartment structures were defined as having no mechanical ventilation equipment, whereas the high-rise apartment structures had ventilation air supplied to the halls. The normal rate of air infiltration through the structures, augmented by kitchen and bathroom fans, was more than sufficient to meet the physiological and aesthetic requirements of both the townhouse and low-rise units. The windows of the respective characteristic residences were defined as remaining closed during periods of heating and cooling. However, allowances were made for daily opening of entrance doors in accordance with each residence's population.

A. Single-Family Residences

The detached single-family residence is still the most prevalent form of housing in the U.S. In 1973, some 64 percent of the existing stock of year-round dwelling units nationwide were in single-family buildings. However, recent demographic trends, combined with costs of building materials, land, and financing, have begun to diminish the domination which the single-family home has held. In 1973, only 55 percent of the dwelling units started nationwide were in single-family residences.

Quantitative data for design and structural features of single-family residences was obtained from a national builder practices survey and was augmented by previous field observations in the Baltimore/Washington area. The survey included over 1600 builders nationwide, who were responsible for the construction of approximately 84,000 single-family houses in 1973. Information was gathered on construction details, building materials, heating and cooling equipment, and household appliances.

Other sources from which single-family housing data was obtained included a recent study of the potential for solar heating and cooling of buildings, which specified typical residential structures in various U.S. regions. Some building parameters such as window area, for which published regional data was not available, were specified by recourse to HAI's statistical analyses of Baltimore/Washington area construction and standard civil engineering and construction handbooks. Compatibility among building elements was carefully preserved. Typical appliance mixes and electricity consumption levels were based on the data acquired for the characteristic single-family house in the Baltimore/ Washington area.

On the basis of the data collected, characteristic single-family detached residences were defined for all eleven locations. Table II summarizes the major characteristics specified for the single-family residences in each location.

The rancher house was the most predominant style, followed in turn by two story and split level styles. With the exception of the Miami house, the buildings were of wood frame construction with a pitched and shingled roof. Typical wall construction included an exterior siding of wood or masonry material and batt insulation, with an overall R value between 10 and 13 hr ft^2 °F/Btu. The Miami house was of solid masonry construction with a built-up roof and no wall insulation. The ceiling and roof R values for the eleven characteristic houses ranged from 14 to 21. The living areas varied from 1139 sq ft in St. Louis to 1852 sq ft in Denver. Floor area figures only include space that was heated and cooled, not unconditioned basements or garages. All windows were single glazed, and some buildings had storm windows. All the HVAC systems were central forced air using gas for heating and electricity for cooling, except in Miami where electricity was used for both heating and cooling. The five single-family houses located in areas with more than 4000 heating degree days had full basements (Baltimore, Boston, Chicago, Minneapolis, and St. Louis).

B. Townhouse Residences

General trends in the housing market over the last several years, especially in large metropolitan areas, indicate that the construction of single-family detached housing units is declining rapidly. In the nation, the portion of private housing starts which were single-family detached residences has decreased steadily, from 79.5 percent in 1960, to 65.4 percent in 1965, to 56.8 percent in 1970, to 55.4 percent in 1973. These trends indicate that in the future, townhouse and multi-family residences will dominate the construction scene in large urban areas.

TABLE II. SUMMARY OF ENERGY USE PARAMETERS IN CHARACTERISTIC SINGLE-FAMILY BUILDINGS

	ATLANTA	BALTIMORE	BOSTON	CHICAGO	DENVER	HOUSTON	LOS ANGELES	MIAMI	MINNEAPOLIS	SAN FRANCISCO	ST. LOUIS
Basic Design											
Building Type	2 Story	2 Story	Split Level	2 Story	Split Level	Rancher	Rancher	Rancher	Rancher	Rancher	Rancher
Frame	Wood	Wood	Wood	Wood	Wood	Wood	Wood	Block Construction	Wood	Wood	Wood
Basement	Slab-On-Grade	Full	Full	Full	Part	Slab-On-Grade	Slab-On-Grade	Slab-On-Grade	Full	Slab-On-Grade	Full
Living Area (Sq Ft)	1700	1695	1200	1700	1852	1705	1705	1705	1457	1457	1139
Window Area (Sq Ft)	215	230	145	215	230	210	230	190	185	185	145
Glazing Type	Single	Single	Single, Storm	Single, Storm	Single	Single	Single	Single	Single, Storm	Single	Single
Exterior Siding	Brick Veneer	Wood Shiplap	Wood Shingle	Brick Veneer	Brick Veneer	Brick Veneer	Stucco	Stucco	Hardboard	Stucco	Brick Veneer
Wall Insulation	3-1/2" Batt	2-1/4" Batt	2-1/2" Batt	3-1/2" Batt	3-1/2" Batt	3-1/2" Batt	3-1/2" Batt	None	3-1/2" Batt	3-1/2" Batt	3-1/2" Batt
Wall R Value[1]	13	12	10	13	13	13	12	3	13	12	13
Roofing Material	Asphalt Shingle	Asphalt Shingle	Asphalt Shingle	Asphalt Shingle	Asphalt Shingle	Wood Shingle	Asphalt Shingle	Built-up	Asphalt Shingle	Wood Shingle	Asphalt Shingle
Ceiling Insulation	6" Fill	5" Fill	4" Fill	6" Fill	4" Fill	6" Fill	3-1/2" Batt	4" Fill	6" Fill	4" Fill	6" Fill
Roof R Value[1]	21	16	14	21	14	21	14	15	21	14	21
Heating System	Forced Air	Forced Air	Forced Air	Forced Air	Forced Air	Forced Air	Forced Air	Forced Air	Forced Air	Forced Air	Forced Air
Heating Energy	Gas	Gas	Gas	Gas	Gas	Gas	Gas	Electricity	Gas	Gas	Gas
Cooling System	Central	Central	Central	Central	Central	Central	Central	Central	Central	Central	Central

[1] Hr Ft^2°F/Btu

The primary source of data for the townhouse residences was the same as for the single-family residences, a national builder practices survey. Of the housing units constructed nationally by the surveyed builders, 19 percent, or approximately 16,000 units, were townhouses.

In addition to the builder practices survey, the earlier data collection done for the Washington/Baltimore area was used for reference. Similar sources and methodologies used for the single-family residences were also utilized for the townhouse structures.

Table III summarizes the major characteristics for each townhouse building. The buildings were all two stories containing eight living units. Construction methods, materials, insulation levels, and HVAC systems were similar in the townhouse and single-family residences, with two major exceptions including living space floor areas and presence of basements. The townhouses were typically about 25 percent smaller than the single-family houses, with floor areas ranging from 1150 sq ft in Minneapolis to 1672 sq ft in Atlanta and Houston, and only three townhouses had full basements (Boston, Minneapolis, and St. Louis).

C. Low-Rise Residences

Generally speaking, the low-rise multifamily residence is one which does not require mechanical elevation. The low-rise building may contain either for-rent or for-sale dwelling units, although the for-rent variety is most common. In the United States, there were approximately 256,000 low-rise dwelling units constructed in 1974.

The primary source of data used for the specification of low-rise building components (except Baltimore, for which data was acquired previously) was a very recent nationwide survey of builders who had built single-family, townhouse, and low-rise residences in the past year. This survey was performed from May 1975 to September 1975, and covered only dwelling units built during 1974. The survey was responded to by about 9000 builders, who had built approximately 200,000 dwelling units in 1974. Based on the government figure of approximately 1,300,000 dwelling units built in 1974, this represents a composite nationwide sampling rate of approximately 14 percent. The city-specific response rates for low-rise buildings for the cities represented in this study varied considerably, from five percent in Los Angeles to 48 percent in Miami. Eight of the ten cities had response rates

TABLE III. SUMMARY OF ENERGY USE PARAMETERS IN CHARACTERISTIC TOWNHOUSE BUILDINGS

	ATLANTA	BALTIMORE	BOSTON	CHICAGO	DENVER	HOUSTON	LOS ANGELES	MIAMI	MINNEAPOLIS	SAN FRANCISCO	ST. LOUIS
Basic Design											
Number of Stories	2	2	2	2	2	2	2	2	2	2	2
Frame	Wood	Wood	Wood	Wood	Wood	Wood	Wood	Block Construction	Wood	Wood	Wood
Basement	Slab-On-Grade	Slab-On-Grade	Full	Slab-On-Grade	Crawl Space	Slab-On-Grade	Slab-On-Grade	Slab-On-Grade	Full	Slab-On-Grade	Full
Number of Units in Structure	8	8	8	8	8	8	8	8	8	8	8
Living Area (Sq Ft)	1672	1300	1320	1320	1320	1672	1320	1320	1150	1320	1320
Window Area (Sq Ft)											
Interior Units	162	118	101	77	117	162	169	169	110	117	117
End Units	197	144	125	101	141	197	193	193	134	141	141
Glazing Type	Single	Single	Single, Storm	Double	Single	Single	Single	Single	Single, Storm	Single	Single
Exterior Siding	Brick Veneer	Brick Veneer	Wood Shingle	Brick Veneer	Brick Veneer	Brick Veneer	Stucco	Stucco	Plywood	Wood	Brick Veneer
Wall Insulation	3-1/2" Batt	None	3-1/2" Batt	3-1/2" Batt	3-1/2" Batt	3-1/2" Batt	3-1/2" Batt	None	3-1/2" Batt	3-1/2" Batt	2-1/4" Batt
Wall R Value[1]	13	11	14	13	13	13	12	3	14	14	10
Roofing Material	Asphalt Shingle	Asphalt Shingle	Asphalt Shingle	Asphalt Shingle	Wood Shingle	Asphalt Shingle	Asphalt Shingle	Asphalt Shingle	Asphalt Shingle	Wood Shingle	Wood Shingle
Ceiling Insulation	6" Fill	5" Fill	6" Batt	6" Fill	5" Fill	6" Fill	3-1/2" Batt	6" Fill	6" Fill	3-1/2" Batt	6" Fill
Roof R Value[1]	21	22	22	21	21	21	14	20	21	14	21
Heating System	Forced Air	Forced Air	Baseboard	Forced Air	Forced Air	Forced Air	Forced Air	Forced Air	Forced Air	Forced Air	Forced Air
Heating Energy	Gas	Gas	Electricity	Gas	Gas	Gas	Gas	Electricity	Gas	Gas	Gas
Cooling System	Central	Central	Window Units	Central	Central	Central	Central	Central	Central	Central	Central

[1] Hr Ft²°F/Btu

of at least 14 percent for low-rise buildings. Table IV presents the summary of major characteristics for the synthesized low-rise structures.

The characteristic low-rise buildings were two or three story structures of wood frame (and batt insulation) or solid masonry (and no insulation) construction. The unit floor areas varied from 525 to 800 sq ft in one bedroom units and from 625 to 1140 sq ft in two bedroom units, indicating that the low rise units were considerably smaller than the townhouses. Except for Minneapolis with storm windows and Boston and Chicago with double glazing, all windows were single glazed. Wall insulation was used in moderate quantities in every low-rise except for those in Baltimore and Miami, which had none. Roof insulation was used in every low-rise, with R values ranging from 6 hr ft^2°F/Btu in Miami to 32 in Minneapolis. Although gas was the most predominant heating fuel, electricity was used for heating in Houston, Miami, and Minneapolis.

D. High-Rise Residences

High-rise residences are defined as residential structures having more than four stories, and typically have mechanical elevation. High-rise buildings have traditionally been renter-occupied, but recent years have shown an increasing tendency towards owner-occupied, or condominium, units in many cities.

The data acquisition for high-rise buildings was accomplished entirely by telephone communication with builders, architects, and engineering consultants in each city studied, except Baltimore, for which data was previously acquired. It was concluded, especially for high-cost rental and condominium units, that the variety in appearance but not construction detail was attributable to the marketing needs of the developer. The potential high-rise occupant's purchase decision criteria, while bounded broadly by cost considerations, seemed more related to considerations of building status, uniqueness, etc. Table V presents the summary of major construction and energy use characteristics for the synthesized high-rise structures in each of the eleven cities.

These buildings were basically of either concrete or steel construction, and contained an average of 189 living units. All units were made up of one and two bedroom apartments except those in Houston, which included three bedroom units as well. The floor areas varied from 550 to 850 sq ft in the one bedroom and 800 to 1178 sq ft in the two bedroom units. The general trend showed larger units and larger percentages of glass used in the Southern regions. Except

TABLE IV. SUMMARY OF ENERGY USE PARAMETERS IN CHARACTERISTIC LOW-RISE BUILDINGS

	ATLANTA	BALTIMORE	BOSTON	CHICAGO	DENVER	HOUSTON	LOS ANGELES	MIAMI	MINNEAPOLIS	SAN FRANCISCO	ST. LOUIS
Basic Design											
Number of Stories	2	2	3	3	3	2	2	3	2	3	2
Frame	Wood	Block Construction	Wood	Wood	Wood	Wood	Wood	Block Construction	Wood	Wood	Block Construction
Basement	Slab-on-Grade	Slab-on-Grade	Slab-on-Grade	Slab-on-Grade	Slab-on-Grade	Slab-on-Grade	Slab-On-Grade	Slab-On-Grade	Slab-On-Grade	Slab-On-Grade	Slab-On-Grade
Number of Units in Structure	24	24	24	24	24	24	24	32	24	24	24
Living Area (Sq Ft)											
1 BDRM Unit	--	--	--	700	600	--	750	800	--	525	--
2 BDRM Unit	1120	1140	1120	986	820	864	900	980	864	625	980
Window Area (Sq Ft)											
1 BDRM Unit	--	--	--	40	72	--	85	92	--	67	--
2 BDRM Unit	110	117	98	56	83	96	94	108	45	72	89
Glazing Type	Single	Single	Double	Double	Single	Single	Single	Single	Single, Storm	Single	Single
Exterior Siding	Brick Veneer	Brick Veneer	Brick Veneer	Brick Veneer	Brick Veneer	Brick Veneer	Stucco	Stucco	Brick Veneer	Plywood	Stucco
Wall Insulation	3-1/2" Batt	None	3-1/2" Batt	3-1/2" Batt	3-1/2" Batt	3-1/2" Batt	2-1/4" Batt	None	3-1/2" Batt	3-1/2" Batt	None
Wall R Value[1]	13	11	13	13	13	13	9	3	13	12	3
Roofing Material	Asphalt Shingle	Asphalt Shingle	Asphalt Shingle	Built-up	Asphalt Shingle	Asphalt Shingle	Asphalt Shingle	Built-up	Asphalt Shingle	Asphalt Shingle	Asphalt Shingle
Ceiling Insulation	6" Fill	5" Fill	6" Fill	6" Fill	6" Fill	6" Batt	3-1/2" Batt	1-1/2" Rigid	10" Fill	6" Fill	6" Fill
Roof R Value[1]	21	22	22	21	14	22	14	6	32	21	21
Heating System	Forced Air	Forced Air	Baseboard	Forced Air	Forced Air	Forced Air	Forced Air	Forced Air	Baseboard	Forced Air	Forced Air
Heating Energy	Gas	Gas	Oil	Gas	Gas	Electricity	Gas	Electricity	Electricity	Gas	Gas
Cooling System	Individual Forced Air	Individual Forced Air	Window Units	Individual Forced Air	Individual Forced Air	Individual Forced Air	Individual Forced Air	Individual Forced Air	Window Units	Individual Forced Air	Window Units

[1] Hr Ft^2 °F/Btu

TABLE V. SUMMARY OF ENERGY USE PARAMETERS IN CHARACTERISTIC HIGH-RISE BUILDINGS

	ATLANTA	BALTIMORE	BOSTON	CHICAGO	DENVER	HOUSTON	LOS ANGELES	MIAMI	MINNEAPOLIS	SAN FRANCISCO	ST. LOUIS
Basic Design											
Number of Stories	15	10	15	15	15	15	15	10	15	10	15
Frame	Reinforced Concrete	Reinforced Concrete	Reinforced Concrete	Reinforced Concrete	Reinforced Concrete	Reinforced Concrete	Reinforced Concrete	Concrete Block	Reinforced Concrete	Reinforced Concrete	Steel
Floors and Roof Deck	Reinforced Concrete	Reinforced Concrete	Reinforced Concrete	Concrete Deck	Concrete Deck	Concrete Slab	Concrete Deck	Concrete Deck	Concrete Deck	Concrete Deck	Concrete Deck
Basement	None	None	None	Underground Garage	Underground Garage	None	None	None	None	Underground Garage	None
Number of Units in Structure	179	196	209	210	179	149	179	208	193	149	224
Living Area (Sq Ft)											
Interior Apartments	753 (1-br) 899 (2-br)	850 (1-br)	600 (1-br)	812 (1-br) 957 (2-br)	725 (1-br) 899 (2-br)	1053 (2-br) 1302 (3-br)	696 (1-br) 899 (2-br)	700 (1-br) 1155 (2-br)	594 (1-br)	899 (2-br)	550 (1-br)
End Apartments	884 (2-br)	950 (2-br)	589 (1-br)	960 (2-br)	896 (2-br)	1326 (3-br)	896 (2-br)	1178 (2-br)	600 (1-br)	896 (2-br)	300 (2-br)
Window Area (Sq Ft)											
Interior Apartments	168 (1-br) 208 (2-br)	17 (1-br)	96 (1-br)	105 (1-br) 105 (2-br)	30 (1-br) 70 (2-br)	110 (2-br) 155 (3-br)	45 (1-br) 75 (2-br)	42 (1-br) 100 (2-br)	45 (1-br)	99 (2-br)	88 (1-br)
End Apartments	244 (1-br)	48 (2-br)	176 (1-br)	150 (1-br)	130 (1-br)	170 (3-br)	120 (2-br)	244 (2-br)	72 (1-br)	159 (2-br)	180 (2-br)
Glazing Type	Single	Single	Double	Double	Single	Single	Single	Single	Double	Single	Single
Exterior Siding	5" Precast Concrete	4" Brick Veneer	4" Brick Veneer	4" Concrete	6" Precast Concrete	8" Precast Concrete	4" Precast Concrete	5/8" Stucco	4" Brick Veneer	6" Precast Concrete	Metal Panel
Wall Insulation	1" Rigid	Air Gap	3-1/2" Fiberglass	1" Rigid	1" Syrofoam	1/2" Rigid	3-1/2" Batt	Air Gap	1" Rigid	Air Gap	1" Rigid & Air Gap
Wall R Value[1]	6	5	13	6	6	4	13	4	6	3	6
Roofing Material	Built-up	Built-up	Built-up	Built-up	Built-up	Built-up	Built-up	Built-up	Built-up	Built-up	Built-up
Ceiling Insulation	1-1/2" Rigid	Air Gap	3" Rigid	1-1/2" Rigid	1-1/2" Rigid	1-1/2" Rigid	2" Rigid	1" Rigid	2" Rigid	3" Rigid	2" Rigid
Roof R Value[1]	8	3	12	7	7	8	9	6	9	7	9
Heating System	Baseboard	2-Pipe Fan Coil	Baseboard	2-Pipe Fan Coil	2-Pipe Fan Coil	Baseboard	2-Pipe Fan Coil	Heat Pump	Baseboard	2-Pipe Fan Coil	Baseboard
Heating Energy	Electricity	Gas	Electricity	Gas	Gas	Electricity	Gas	Electricity	Gas	Gas	Electricity
Cooling System	Central	Central	Window Units	Central	Central	Central	Central	Heat Pump	Window Units	Central	Central

[1] $Hr\ Ft^2\ {}^\circ F/Btu$

for Boston and Los Angeles, there was little or no insulation in the walls and the roof R values ranged from 3 hr ft^2°F/ Btu in Baltimore to 12 in Boston. Gas and electricity were used almost equally for heating and electricity was used for all cooling.

IV. COMPUTATION OF HEATING AND COOLING ENERGY REQUIREMENTS

Annual heating and cooling loads and the resulting energy requirements were calculated for each of the 44 characteristic residences defined in Chapter III. To determine the heating and cooling loads or heat delivery/removal requirements for each residence, a time-response computer program was used. This computer program included subroutines for computing hourly loads throughout the year due to conduction, convection, air infiltration, radiation, and internal heat gain. Annual HVAC energy requirements were calculated from the monthly heating and cooling loads by applying the appropriate system and auxiliary component efficiencies and coefficients of performance determined for each characteristic residence. The computer program computation procedures, and the results of these computations, are discussed in the following sections.

A. Description of the Computer Program Used for Load Calculations

The computer program used in determining the heating and cooling loads for the typical residential structures was a sub-program of the Hittman Building Energy Analysis Model (BEAM) called the Load Calculation Sub-program (LCSP). The BEAM program is a revised version of the original U.S. Postal Service Program. The program has undergone considerable modification and its capabilities have been expanded, the resulting program being an efficient and flexible computer model.

The Load Calculation Sub-program is a complex of heat transfer, climatic, and geometric subroutines which compute both heating and cooling loads imposed on building HVAC systems by each of as many as 21 thermal zones on an hourly basis. The input to the LCSP includes building architecture and surroundings, local weather, and the orientation of incident solar radiation. Building loads are computed on the basis of actual recorded weather data for a selected year, accurate evaluation of heat gain due to solar radiation, and simulation of transient heat transfer in the building's structure. The output consists of hourly weather and psychrometric data, total sensible and latent loads, and the infiltration loads for each conditioned space.

B. Calculation of Heating and Cooling Loads and Energy Requirements

In calculating the heating and cooling loads for each characteristic residence, the detailed structural and design inputs were based on data which is summarized in Tables II through V. Profiles of internal loads resulting from lights, appliances, and occupants were also specified. These profiles varied for weekdays and weekends throughout the year. A constant thermostat set point of 72°F was defined for both the heating and cooling seasons. In calculating the loads, it was assumed that all windows in the residences remained closed.

For this analysis, each single-family house was represented as a single thermal control zone, and the living units within the multifamily residences; townhouses, low-rises, and high-rises; were each identified as separate zones. Many of the units had the same combinations and orientation of exposed walls, roofs, floors, windows, and doors. These units were considered as being thermally equivalent, thus allowing a simplicication of the energy analysis model. The simplest example of this technique is the analysis of a townhouse building. Each townhouse structure is comprised of eight units with six thermally equivalent intermediate units and two unique end units. Thus, using the equivalence technique reduces the number of units analyzed from eight to three. Care was exercised in utilizing this technique to maintain a high degree of accuracy. The resulting annual heating and cooling loads are summarized in Tables VI through IX. These loads are dependent on a multitude of variables, including overall climatic conditions and general building configuration.

When examining the components of the heating and cooling loads for each class of building, some interesting correlations were found. One of these was the very close correspondence between building surface areas and infiltration loads for the single-family, townhouse, and low-rise buildings. Due to large amounts of required ventilation and a significant stack effect, this correlation did not extend to the high-rise buildings. In fact, in some cases the high-rise heating loads were almost exclusively due to infiltration.* Table X presents the infiltration loads on a square foot basis for each building studied.

**In high-rises, the internal heat generation is typically large enough to balance the bulk of the conduction losses through the exterior walls.*

TABLE VI. SUMMARY OF ANNUAL HEATING AND COOLING LOADS AND ENERGY USE IN CHARACTERISTIC SINGLE-FAMILY BUILDINGS

	ATLANTA	BALTIMORE	BOSTON	CHICAGO	DENVER	HOUSTON	LOS ANGELES	MIAMI	MINNEAPOLIS	SAN FRANCISCO	ST. LOUIS
HEATING LOAD PER UNIT (THERMS)	352	710	915	998	1478	253	255	86	1411	454	689
COOLING LOAD PER UNIT (THERMS)	574	282	90	178	361	835	360	1326	91	70	219
IN-STRUCTURE HEATING ENERGY USE PER UNIT (THERMS)	490	1010	1285	1403	2065	356	345	90	1996	608	975
IN-STRUCTURE COOLING ENERGY USE PER UNIT (THERMS)	325	125	48	96	200	467	185	774	53	30	117
TOTAL IN-STRUCTURE ENERGY PER SQUARE FOOT (THERMS/SQ FT)	0.48	0.76	1.11	0.88	1.22	0.48	0.31	0.51	1.40	0.44	0.96
PRIMARY HEATING ENERGY PER UNIT (THERMS)	506	1044	1328	1447	2130	367	355	295	2054	627	1005
PRIMARY COOLING ENERGY PER UNIT (THERMS)	1053	388	152	309	648	1516	606	2492	170	99	384
TOTAL PRIMARY ENERGY PER SQUARE FOOT (THERMS/SQ FT)	0.92	0.96	1.23	1.03	1.50	1.10	0.56	1.63	1.52	0.50	1.22

TABLE VII. SUMMARY OF ANNUAL HEATING AND COOLING LOADS AND ENERGY USE IN CHARACTERISTIC TOWNHOUSE BUILDINGS

	ATLANTA	BALTIMORE	BOSTON	CHICAGO	DENVER	HOUSTON	LOS ANGELES	MIAMI	MINNEAPOLIS	SAN FRANCISCO	ST. LOUIS
HEATING LOAD PER UNIT (THERMS)	259	492	475	393	479	151	72	23	500	146	414
COOLING LOAD PER UNIT (THERMS)	401	343	99	177	186	720	291	794	111	101	224
IN-STRUCTURE HEATING ENERGY USE PER UNIT (THERMS)	285	691	472	554	680	203	96	25	663	192	584
IN-STRUCTURE COOLING ENERGY USE PER UNIT (THERMS)	229	206	62	93	102	402	147	467	61	46	129
TOTAL IN-STRUCTURE ENERGY PER SQUARE FOOT (THERMS/SQ FT)	0.31	0.69	0.40	0.49	0.59	0.36	0.18	0.37	0.63	0.18	0.54
PRIMARY HEATING ENERGY PER UNIT (THERMS)	294	712	1521	571	700	209	99	81	683	197	602
PRIMARY COOLING ENERGY PER UNIT (THERMS)	742	663	200	300	329	1300	476	1508	198	149	417
TOTAL PRIMARY ENERGY PER SQUARE FOOT (THERMS/SQ FT)	0.62	1.06	1.30	0.66	0.78	0.90	0.44	1.20	0.77	0.26	0.77

TABLE VIII. SUMMARY OF ANNUAL HEATING AND COOLING LOADS AND ENERGY USE IN CHARACTERISTIC LOW-RISE BUILDINGS

	ATLANTA	BALTIMORE	BOSTON	CHICAGO	DENVER	HOUSTON	LOS ANGELES	MIAMI	MINNEAPOLIS	SAN FRANCISCO	ST. LOUIS
HEATING LOAD PER UNIT (THERMS)	130	327	218	116	181	72	27	13	178	26	326
COOLING LOAD PER UNIT (THERMS)	293	173	153	145	123	403	222	542	119	124	225
IN-STRUCTURE HEATING ENERGY USE PER UNIT (THERMS)	181	470	310	165	257	53	37	11	177	69	465
IN-STRUCTURE COOLING ENERGY USE PER UNIT (THERMS)	164	105	86	68	59	220	115	318	69	49	115
TOTAL IN-STRUCTURE ENERGY PER SQUARE FOOT (THERMS/SQ FT)	0.30	0.51	0.38	0.27	0.44	0.32	0.20	0.37	0.28	0.21	0.59
PRIMARY HEATING ENERGY PER UNIT (THERMS)	186	484	310	170	265	171	38	36	572	35	479
PRIMARY COOLING ENERGY PER UNIT (THERMS)	494	337	376	218	192	711	373	1028	223	158	374
TOTAL PRIMARY ENERGY PER SQUARE FOOT (THERMS/SQ FT)	0.60	0.73	0.61	0.46	0.64	1.02	0.53	1.19	0.92	0.34	0.87

TABLE IX. SUMMARY OF ANNUAL HEATING AND COOLING LOADS AND ENERGY USE IN CHARACTERISTIC HIGH-RISE BUILDINGS

	ATLANTA	BALTIMORE	BOSTON	CHICAGO	DENVER	HOUSTON	LOS ANGELES	MIAMI	MINNEAPOLIS	SAN FRANCISCO	ST. LOUIS
HEATING LOAD PER UNIT (THERMS)	214	136	120	296	422	122	40	11	160	227	166
COOLING LOAD PER UNIT (THERMS)	379	174	178	185	133	636	212	752	152	40	235
IN-STRUCTURE HEATING ENERGY USE PER UNIT (THERMS)	217	470	119	421	595	116	47	4	228	324	164
IN-STRUCTURE COOLING ENERGY USE PER UNIT (THERMS)	119	50	109	109	38	411	61	545	90	8	152
TOTAL IN-STRUCTURE ENERGY PER SQUARE FOOT (THERMS/SQ FT)	0.39	0.51	0.35	0.51	0.71	0.41	0.17	0.49	0.46	0.35	0.46
PRIMARY HEATING ENERGY PER UNIT (THERMS)	831	391	434	434	614	393	48	14	236	334	577
PRIMARY COOLING ENERGY PER UNIT (THERMS)	454	367	398	515	341	1400	380	1852	430	183	536
TOTAL PRIMARY ENERGY PER SQUARE FOOT (THERMS/SQ FT)	1.26	0.78	1.13	1.09	0.96	1.32	0.43	1.58	0.86	0.47	1.49

TABLE X. TOTAL ANNUAL INFILTRATION LOADS FOR CHARACTERISTIC BUILDINGS (THERM/SQ FT)

	ATLANTA	BALTIMORE	BOSTON	CHICAGO	DENVER	HOUSTON	LOS ANGELES	MIAMI	MINNEAPOLIS	SAN FRANCISCO	ST. LOUIS
SINGLE-FAMILY											
HEATING	0.11	0.23	0.23	0.25	0.20	0.07	0.06	0.02	0.33	0.14	0.18
COOLING	0.07	0.07	0.02	0.02	0.01	0.16	0.01	0.20	0.02	0.01	0.06
TOWNHOUSE											
HEATING	0.07	0.11	0.15	0.10	0.17	0.06	0.03	0.01	0.15	0.07	0.11
COOLING	0.06	0.03	0.02	0.02	0.01	0.16	0.01	0.13	0.02	0.01	0.05
LOW-RISE											
HEATING	0.05	0.05	0.12	0.08	0.12	0.03	0.02	0.01	0.10	0.03	0.15
COOLING	0.03	0.01	0.01	0.01	0.01	0.09	0.01	0.08	0.01	0.01	0.05
HIGH-RISE											
HEATING	0.08	0.01	0.14	0.16	0.18	0.05	0.04	0.01	0.19	0.10	0.11
COOLING	0.09	0.01	0.01	0.02	0.01	0.17	0.01	0.19	0.01	0.01	0.06

The energy required to heat, cool, and ventilate the characteristic residences was determined using the previously calculated heating and cooling loads. The heating, cooling, and ventilation equipment selected for each residence was the most common equipment for that area. Tables II through V specify the HVAC systems defined for each building. The efficiencies of these systems were based on the findings developed in the system analysis section of the Baltimore/ Washington study. It was assumed that the HVAC systems were operated in only one mode, heating or cooling, during each month, except for the two months when the transition from one conditioning mode to the other occurred. A thirty-one percent electricity conversion/transmission efficiency and three percent gas pipeline losses were assumed for conversion of units of in-structure energy to those of primary energy.

C. Analysis of Characteristic Buildings' Energy Use

The following four part section discusses the results of the energy analysis performed on the characteristic buildings in each of the eleven cities. The first part introduces the Thermal Load Factor (TLF) and describes a general trend observed among the four building classes. The remaining three parts comprise a more in-depth analysis of the building classes and specific noteworthy buildings, emphasising the following aspects:

(1) the dominant role of energy type in determining primary energy use,

(2) the large effect climatic variation has on in-structure energy use, and

(3) the effects building construction has on energy use given a fuel type and climate.

1. A General Energy Use Trend In the Residential Building Classes

Even a casual comparison of the energy use figures presented in Tables VI through IX reveals a general pattern in the energy requirements for the building classes. It is apparent that the single-family houses use the most energy, followed respectively by the townhouses, high-rises, and low-rises. To further quantify this trend, the heating and cooling loads or energy requirements for each building have been normalized with respect to both living unit floor area and climate using the appropriate annual degree days. The resulting value, or Thermal Load Factor (TLF), is a highly descriptive number that reflects a specific building's energy needs. Note that since heating and cooling loads are differently affected by building characteristics, both heating and cooling TLF's have been computed for each building. It is important to realize that the TLF is a climate-normalized figure and therefore should exclusively be a measure of a building's thermal integrity, or more precisely, the lack thereof. Further analysis presented below will establish this fact for the heating TLF but show that several factors reduce the accuracy of the cooling TLF.

The table below presents averages of the heating and cooling TLF's for each building class. In computing these averages, only TLF's of buildings with significant energy requirements were included. To clarify, the warm localities (Miami, Los Angeles, and Houston) were excluded from the average heating TLF calculation since the primary design objective in these areas is to minimize cooling loads. In computing the average cooling TLF for each building class, the cities of Boston, Chicago, Denver, Minneapolis, and San Francisco were excluded for similar reasons.

	Heating	Cooling
Single-Family	11.60	16.9
Townhouse	6.17	16.0
Low-Rise	4.99	18.3
High-Rise	4.53	18.5

The average TLF values display a different trend for heating and cooling. Whereas the heating TLF's monotonically decrease from single-family houses through high-rise buildings, the average cooling TLF is lower in the townhouses than the single-family houses, but then increases for low-rise and high-rise apartment buildings. These opposing trends are explained below.

The decreasing heating TLF trend is the result of three factors, all tending to reduce heating loads for the single-family buildings through the high-rises. These factors include:

(a) a decreasing skin area and associated conduction load for single-family buildings through high-rises,

(b) a progressive reduction in infiltration with the reduction in exterior wall area, and

(c) an increasing internal load density resulting from a similar internal load in each building and a decreasing living unit floor area..

The major consequence of this trend is that the largest heating energy savings are possible in single-family houses. These savings are obtainable through reduced infiltration, increased insulation, and more efficient heating systems.

The trend in cooling is more complicated since it is the net result of several components working in opposition to each other. Whereas infiltration loads decrease for single-family through low-rise buildings, internal loads increase as explained above. Conduction loads are less dominant in cooling than in heating due to a smaller inside-outside temperature differential, thus infiltration and internal heat generation are the major cooling loads. A third load component, solar radiation, decreases with decreasing glass area, and thus also effects the cooling trend. Using these individual cooling load components to explain the net cooling TLF trend, the decrease in TLF from single-family to townhouse buildings reflects the fact that the decreases in infiltration and solar loads outweigh the increases in internal load density. Moving on from the townhouses to the low-rises and high-rises, the internal load density dominates the other components and consequently increases the average TLF's.

Although the trend in cooling values would imply that the largest potential savings exist in the low-rise and high-rise apartment buildings, one must recall that internal loads are mainly responsible for this trend, and that they are fairly invariable, implying a more meaningful analysis of cooling energy savings potential would involve factoring out the effect of internal load density variation on the TLF's. Such a calculation would be very involved, and was not performed since cooling energy saving potentials for each building were quantified through computer simulation.

2. Energy Choice Dominates Primary Energy Use

The most important factor in determining a building's primary energy use is the type of fuel used by that building to meet it's heating and cooling demands. The reason for this lies in the fact that electricity generation, transmission, and distribution are collectively only about 31 percent efficient.

The most convincing example of the dominant role energy type plays in determining heating energy use involves the Boston and Baltimore townhouses. Although the Baltimore building was very poorly built, with no wall insulation and very little ceiling insulation and consequently a larger heating load than Boston, the fact that the Boston building used electricity for heating and the Baltimore building used gas resulted in the Boston townhouse using over twice as much primary energy as the building in Baltimore.

Although almost all residential cooling is done by electric air conditioners, the large primary energy adjustment associated with electricity does impact cooling energy use. One major effect is the amplification of the importance of cooling. Contrary to popular belief, the most energy-intensive residential buildings are not located in the city famous for its cold climate, Minneapolis, or the mile high city, Denver; but in the winter vacation city of Miami. Even though Miami buildings consistantly had the smallest heating loads of any region studied, they had the highest total primary energy use for every building class but townhouses, where Boston's electrically heated building was the largest user.

A more distracting result of this increased weighting of cooling energy use is the confusion of energy conserving building modifications in areas with heating and cooling loads of similar magnitude. As an example, consider the installation of reflective glass in a single-family house located in a region of moderate climate. The reduction of solar energy absorbed by the house will increase the heating load and decrease the cooling load. If the heating load is increased by the same amount that the cooling load is decreased, and gas and electricity are used for heating and cooling respectively, the installation of the glass will reduce primary energy use and increase in-structure energy use. Such a situation forces a value judgement to be made, since electricity is in part generated from replenishable hydro and abundant atomic energy while fossil fuel is both limited and virtually unreplenishable.

3. Climatic Environment Dominates In-structure Energy Use

Given an energy type, a situation which regional politics and economics frequently creates, the most important factor in determining residential energy use is climate. Buildings in cold climates such as Boston, Chicago, Denver, and Minneapolis will require large amounts of energy for heating. Hot climates will result in big cooling energy uses for buildings, such as in Houston and Miami. However, the climatic environment will be of varing impact in different building classes as shown below.

An analysis of the energy use figures in Tables VI through IX results in the conclusion that climate has a decreasing effect on single-family, townhouse, high-rise, and low-rise buildings respectively. The decreased skin area of living units in buildings along with a reduction in window area is the major reason for this decreased climatic effect. An increasing domination of the internal load, a climatic-independent load component, also tends to decrease the effect of the climate on energy use in multi-family buildings. Because of increased infiltration in the high-rise resulting from forced ventilation and a large stack effect, this trend is more pronounced in the low-rise buildings than in the high-rises. In an attempt to quantify this varying climatic dependence, the standard deviation of the heating TLF's for the four building types were computed.

Single-family	Townhouse	Low-rise	High-rise
2.57	1.58	1.49	1.89

These figures show that heating loads vary more in single-family buildings than townhouses, etc. Although these figures in part reflect a more standard construction technique for apartment buildings than for single-family residences, this practice itself is indicative of the decreasing importance of climatic variation in the building classes.

This trend is very important when considering energy conserving building modifications. Since the low-rise is the least climate-sensitive, structural improvements in that type of building will have the smallest impact on energy use. Another major role climate plays is in determining whether heating or cooling modifications will be the most effective in reducing total energy use. These concepts are explored further in the next chapter.

4. Building Construction is the Most Controllable <u>Factor in Building Energy Use</u>

It is obvious that the climate for a particular region is fixed since no existing technology can significantly modify the weather. As previously stated, the energy for cooling is of one type and frequently the same holds true for heating. Given these facts, building characteristics are the most important factors in determining energy use since they are the most controllable.

Not only are building characteristics the most controllable energy use factor, but designing buildings below reasonable levels of thermal integrity results in extraordinarily large energy requirements, as the following example illustrates. The Baltimore and Minneapolis single-family houses were of similar, acceptable construction. As would be expected, the Minneapolis building used almost twice as much energy for heating as did the one in Baltimore. However, the Baltimore townhouse had no wall insulation and actually used more energy for heating than the Minneapolis townhouse. The Baltimore townhouse also experienced very large cooling loads, with a cooling energy use virtually the same as that of Atlanta's townhouse.

Due to the fact that full basements have a larger surface area in direct contact with the cool subterranean earth than do slab-on-grade foundations, they result in higher heating loads and lower cooling loads than the latter. One might think that this would cause more full basements to be used in the warm climates than the cold ones. However, perhaps due to a lack of understanding of the real response of basements or local construction practices, they are more common in the North than the South.

Comparing the heating TLF's for individual single-family residences, the Boston house with little insulation was the least well built for its climate. The Denver house with no storm windows and only moderate insulation had the next highest heating TLF. The St. Louis house with single glazed windows had the third worst heating TLF. The house in Minneapolis was well insulated and had a moderate glass area with storm windows and thus had a very low TLF compared to the above mentioned residences. This may well be the result of an atypically high energy awareness in Minneapolis stemming from that city's extreme winters.

The townhouse in Baltimore had no wall insulation and single glazed windows; these two short comings combined to give the Baltimore townhouse the worst TLF of any townhouse studied. The next highest TLF computed for a townhouse was for the St. Louis building, with no storm windows and only moderate insulation. The remaining buildings all had the most basic energy conserving features required by their respective climates and thus had similar heating TLF's.

The St. Louis, Baltimore, and Denver low-rise apartment buildings all lacked double-glazing and sufficient insulation and therefore had the highest heating TLF's. However, it should be noted that even the uninsulated Baltimore low-rise building had a better heating TLF than any single-family house. This points out once again that the low-rise living units are much less energy intensive than any other building type. The Chicago low-rise had the best heating TLF of any characteristic building, a very low 2.25 Btu/sq ft degree day. This thermal integrity resulted in a very small heating load of 116×10^5 Btu, less than that of the Atlanta low-rise.

As explained previously, the high-rise buildings were each unique due to a stack effect that varied with building height, different amounts of hall and stairway areas that required heating and cooling, and large amounts of forced ventilation required by building codes. These buildings were very complicated to analyze, requiring up to 21 separate thermal zones. This complexity reflects an extremely intricate thermal loading network. The Denver high-rise, mainly due to a lack of double glazed windows, had the highest TLF of any high-rise, followed by the Atlanta high-rise which had the largest window area. By comparing insulation values in high-rises (very low) with those in the other buildings, and noting that all the high-rises had acceptable TLF's except those without double glazing, one can conclude that the conduction load caused by windows is by far the most dominant heating load in these buildings, exclusive of the fairly constant ventilation load.

Regarding the cooling TLF's, the most prominant fact is that they are larger than the heating TLF's in every building. The reason behind this lies not in the fact that the buildings are all better designed from a heating standpoint but rather because solar radiation and internal loads act to increase cooling loads and decrease heating loads, thus implying an equal number of heating degree days and cooling degree days will result in a cooling load larger than the heating load.

Due to the fact that cooling loads are dominated by factors other than cooling degree days, the normalization of cooling loads with respect to cooling degree days results in a TLF biased toward warm climates. This distortion is large enough so that the cooling TLF for a building does not reflect the thermal integrity of the building but is more an inverse representation of the annual cooling degree days. This lack of a meaningful correlation between the thermal integrity of a building and it's cooling TLF implies further investigation is required to develop a useful metric for evaluating residential buildings with respect to their (cooling) thermal design.

V. ENERGY USE OF IMPROVED BUILDINGS

The previous chapter analyzed the energy use for heating and cooling the 44 characteristic buildings. Thermal Load Factors were calculated for the buildings to measure their thermal integrity in heating, and the TLC's showed significant reductions in energy use were possible. The HVAC systems in the characteristic buildings proved to be less than state-of-the-art with respect to efficiency, implying energy savings were possible in that area as well.

To quantify these potential savings, improvements were defined for each of the characteristic buildings and the resulting loads and energy uses were calculated using the same computer technique as was used for the characteristic buildings. This chapter presents these improvements, discusses the resulting energy savings, and establishes a direct correlation between a building's potential energy savings and its TLF.

A. Discussion of Improvements

As established above, energy savings were deemed possible through improvements to both the building structures and the HVAC systems within the buildings. To fully assess the energy savings possible for each building, both structural modifications and HVAC system improvements were included in the modified buildings. To insure that the results would be of practical application, only currently available and technically feasible improvements were defined for the buildings. Another restriction on the improvements was that they could not effect the life-styles of the occupants. This is a very important point, because significant energy savings are possible in any residential building through changes in the habits of the residents.

In addition to the restrictions on improvements cited above, no basic changes were made in any building design. For example, floor area, building height and orientation, foundation type, and wall material (excluding insulation) were not changed. The most basic design change and the one most noticeable to the building occupants was a reduction of window area by 25 percent in each building. The reason for not modifying the basic designs was not that they were beyond improvement, but rather that the goal of this study was in part to quantify the energy savings possible in buildings of current design and construction.

Tables XI through XIV present the improvements defined for each building. In selecting improvements for each building, a three step process was followed.

- The heating and cooling loads were compared to determine if either one was the dominant factor in the building's total energy use.

- Based on the above comparison the appropriate load was examined in its component parts to determine where improvements would be the most effective in reducing the building's energy requirements.

- Modifications were selected to improve the deficiencies of the characteristic buildings and then checked against the original restrictions to make sure that they were technically feasible, currently available, etc.

The HVAC systems were evaluated independently of the structures and were either modified to increase their performance or replaced entirely with more energy efficient systems. No changes in energy type were made because this action was deemed outside the limits for improvements established at the outset of the study.

B. Calculation of Loads and Energy Use In Improved Buildings

The computational method used to evaluate the improved buildings was the same as that used to calculate the loads and energy uses for the characteristic buildings, i.e., hourly loads and energy use data were calculated for the full weather year using the BEAM computer program. The only changes to the computer inputs were those necessary to include the structural and HVAC system improvements in Tables XI through XIV.

TABLE XI. SUMMARY OF IMPROVEMENTS MADE TO CHARACTERISTIC SINGLE-FAMILY BUILDINGS

MODIFICATIONS STRUCTURAL:	ATLANTA	BALTIMORE	BOSTON	CHICAGO	DENVER	HOUSTON	LOS ANGELES	MIAMI	MINNEAPOLIS	SAN FRANCISCO	ST. LOUIS
Glass Reduction on North Face[1] (%)	25	25	50	44	50	25	25	25	50	25	25
Glass Reduction on South Face[1] (%)	25	25	7	0	5	25	25	25	9	25	25
Addition of Weatherstripping	*		*	*	*	*	*	*	*	*	*
Use of Strom Windows or Double Glazing		*	Existed	Existed	*				Existed		
Use of Reflective Glass						*		*			
Shading Southern Building Face (Seasons Noted)	Summer					All Year		All Year			Summer
Addition of Wall Insulation Up to Indicted R Value	17	11	17	17	17	17	17	11	17	17	17
Addition of Ceiling Insulation Up to Indicated R Value	27	16	27	27	27	27	27	27	27	27	27
Addition of Floor/Perimeter Insulation Up to Indicated R Value	10	4	12.5	12.5	12.5	10 Existed	10 Existed	10	12.5	12.5	12.5
SYSTEM:											
Improved Furnace/Heat Recovery System	*		*	*	*	*	*		*	*	*
Substitution of Heat Pump for Electric Resistant Heating								*			
Use of Improved Cooling System	*			*	*	*	*	*	*	*	*

[1]*Total glass reduction for all buildings equal 25%*

**Change made in characteristic residences*

TABLE XII. SUMMARY OF IMPROVEMENTS MADE TO CHARACTERISTIC TOWNHOUSE BUILDINGS

MODIFICATIONS STRUCTURAL:	ATLANTA	BALTIMORE	BOSTON	CHICAGO	DENVER	HOUSTON	LOS ANGELES	MIAMI	MINNEAPOLIS	SAN FRANCISCO	ST. LOUIS
Glass Reduction on North Face[1] (%)	25	25	50	50	50	25	25	25	50	25	25
Glass Reduction on South Face[1] (%)	25	25	5	9	9	25	25	25	7	25	25
Addition of Weatherstripping	*		*	*	*	*	*	*	*	*	*
Use of Strom Windows or Double Glazing		*	Existed	Existed	Existed				Existed		*
Use of Reflective Glass						*		*			
Shading Southern Building Face (Seasons Noted)	Summer					All Year		All Year			Summer
Addition of Wall Insulation Up to Indicted R Value	17	11	17	17	17	17	17	11	17	17	17
Addition of Ceiling Insulation Up to Indicated R Value	27	22	27	27	27	27	27	27	27	27	27
Addition of Floor/Perimeter Insulation Up to Indicated R Value	10	20	12.5	10 Existed	12.5 Existed	10	10	10	12.5	12.5	10
SYSTEM:											
Improved Furnace/Heat Recovery System	*			*	*	*	*		*	*	*
Substitution of Heat Pump for Electric Resistant Heating			*					*			
Use of Improved Cooling System	*		*	*	*	*	*	*	*	*	*

[1]*Total glass reduction for all buildings equal 25%*

**Change made in characteristic residences*

TABLE XIII. SUMMARY OF IMPROVEMENTS MADE TO CHARACTERISTIC LOW-RISE BUILDINGS

MODIFICATIONS	ATLANTA	BALTIMORE	BOSTON	CHICAGO	DENVER	HOUSTON	LOS ANGELES	MIAMI	MINNEAPOLIS	SAN FRANCISCO	ST. LOUIS
STRUCTURAL:											
Glass Reduction Total Area 25%	*	*	*	*	*	*	*	*	*	*	*
Addition of Weatherstripping	*		*	*	*	*	*	*	*	*	*
Use of Double Glazing		*	Existed	Existed	*				Existed		*
Use of Reflective Glass	*					*	*	*			
Addition of Wall Insulation Up to Indicated R Value	17	11	17	17	17	17	17	11	17	17	17
Addition of Ceiling Insulation Up to Indicated R Value	27	22	27	27	27	27	27	27	27	27	27
Addition of Floor/Perimeter Insulation Up to Indicated R Value	10	20	10	10	10	10	10	10	10	10	10
SYSTEM:											
Improved Furnace/Heat Recovery System	*		*	*	*		*			*	*
Substitution of Heat Pump for Electric Resistant Heating						*			*		
Use of Improved Cooling System	*		*	*	*	*	*	*	*	*	*

*_Change made in characteristic residences_

TABLE XIV. SUMMARY OF IMPROVEMENTS MADE TO CHARACTERISTIC HIGH-RISE BUILDINGS

MODIFICATIONS	ATLANTA	BALTIMORE	BOSTON	CHICAGO	DENVER	HOUSTON	LOS ANGELES	MIAMI	MINNEAPOLIS	SAN FRANCISCO	ST. LOUIS
STRUCTURAL:											
Glass Reduction Total Area 25%	*	*	*	*	*	*	*	*	*	*	*
Addition of Weatherstripping	*		*	*	*	*	*	*	*	*	*
Use of Double Glazing		*	Existed	Existed	*				Existed		*
Use of Reflective Glass	*										
Addition of Wall Insulation Up to Indicated R Value	12	11	12	12	12	12	12	11	12	12	12
Addition of Ceiling Insulation Up to Indicated R Value	17	10	17	17	17	17	17	17	17	17	17
Addition of Floor/Perimeter Insulation up to Indicated R Value	10	20	10	10	10	10	10	10	10	10	10
SYSTEM:											
Improved Furnace/Heat Recovery System				*	*		*		*	*	
Substitution of Heat Pump for Electric Resistant Heating											
Use of Improved Cooling System	*		*	*	*	*	*	*	*	*	*

*Change made in characteristic residences

Figures 2 through 5 show the heating loads, cooling loads, total primary energy per unit, and total primary energy per square foot respectively for each improved building. To simplify the comparison of these values with those for the characteristic buildings, both characteristic and improved values are included in the Figures. The total reductions of primary energy were previously shown in Figure 1. The averages of these reductions by building class are 51, 50, 46 and 41 percent for single-family, townhouse, low-rise, and high-rise buildings respectively. This declining rate of energy savings can be explained by the fact that all structural modifications were performed on the building envelope area, and this decreases from single-family to high-rise buildings, thus decreasing the impact of improvements. An additional factor applied to the high-rise buildings, that being infiltration associated with the large stack effect and required ventilation which could not be compensated for.

The decreasing percent energy savings described above correspond with decreasingly large energy uses in the characteristic buildings, the two trends combining to make single-family houses the largest source of potential energy savings, with decreasing savings potential in the townhouse, low-rise, and high-rise, respectively. The fact that the single-family house is the dominant class of building adds to the magnitude of its potential for energy savings. This is a pleasing result because the owner of a single-family house will typically be the most motivated class of building owner with respect to minimizing energy costs (and therefore use) since he is the least transient and does not experience utility-included rents and other distortions that preclude energy conservation motivation.

C. Thermal Load Factor as a Building Standard

In Chapter IV, the Thermal Load Factor (TLF) was defined as the building load (Btu) divided by the floor space (sq ft) and the appropriate number of degree days. It was established that the heating TLF was a metric of a building's thermal integrity but due to several exogenous factors, the cooling TLF was of little value when approached in a similar manner.

For the heating TLF to be considered as a building design standard, a correlation must be established between the characteristic buildings' TLF's and the percent reductions in their heating loads caused by improving the buildings. For the purpose of investigating the correlation between these two

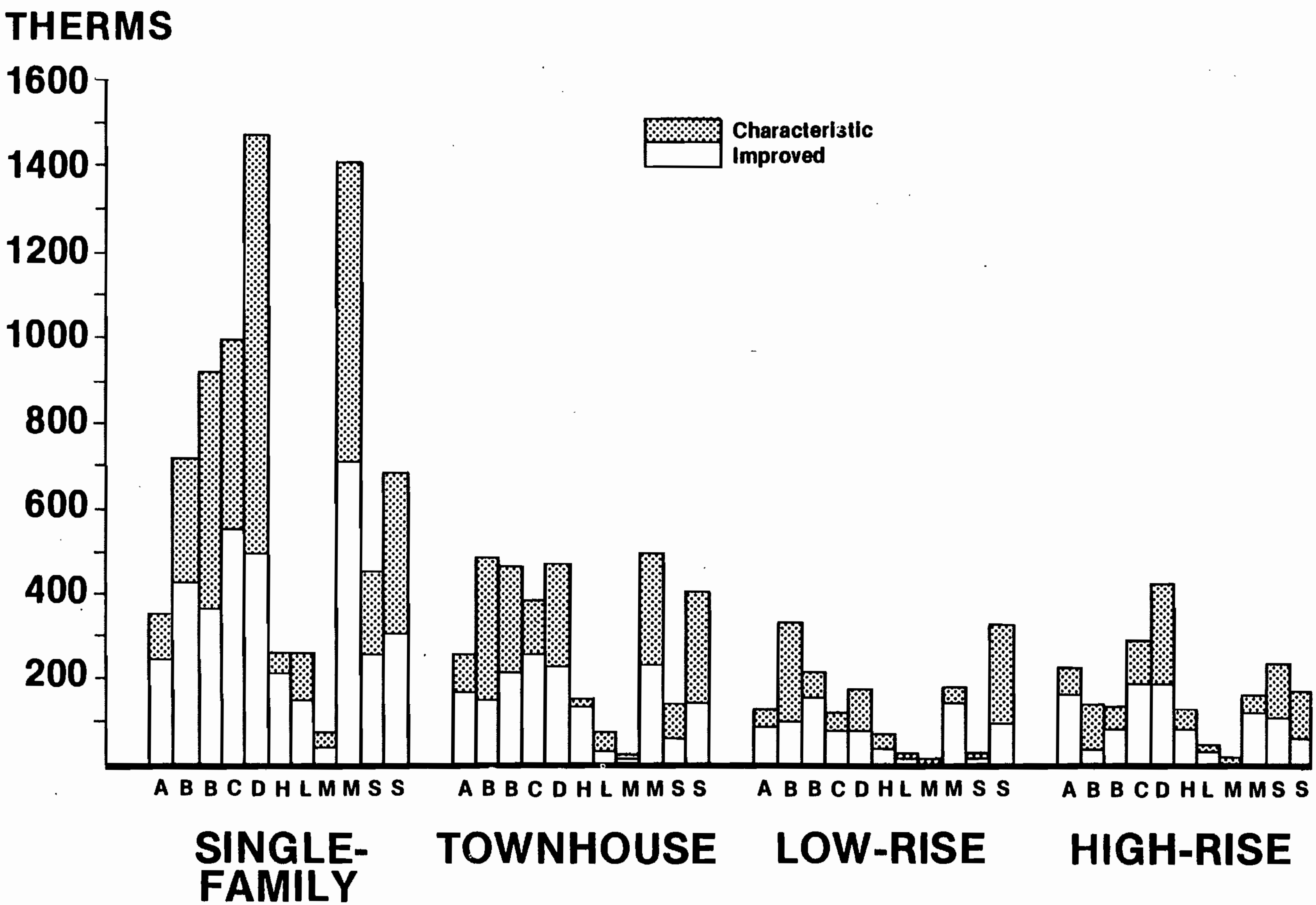

Figure 2. Comparison of Heating Loads In Characteristic and Improved Buildings

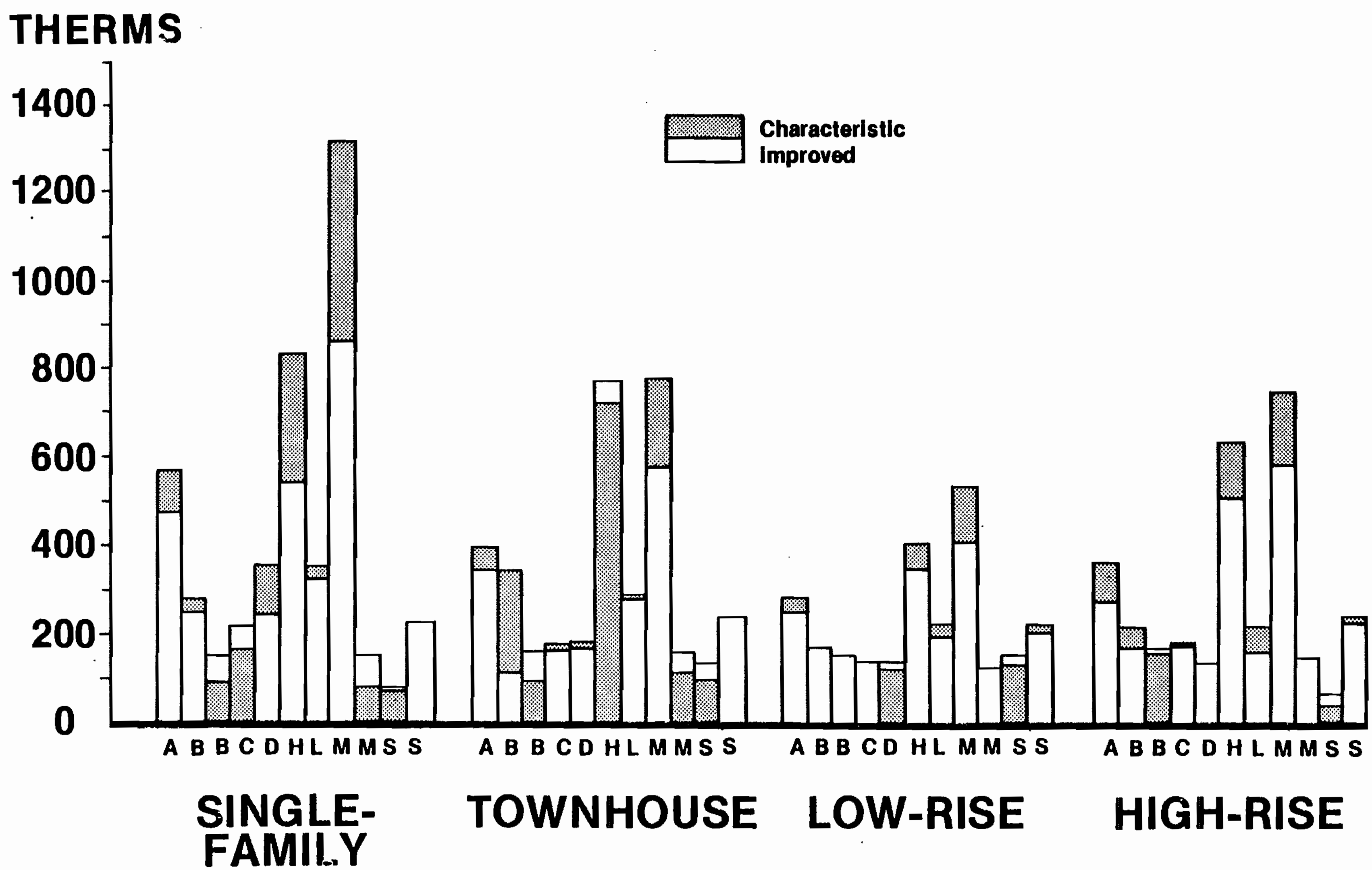

Figure 3. Comparison of Cooling Loads in Characteristic and Improved Buildings

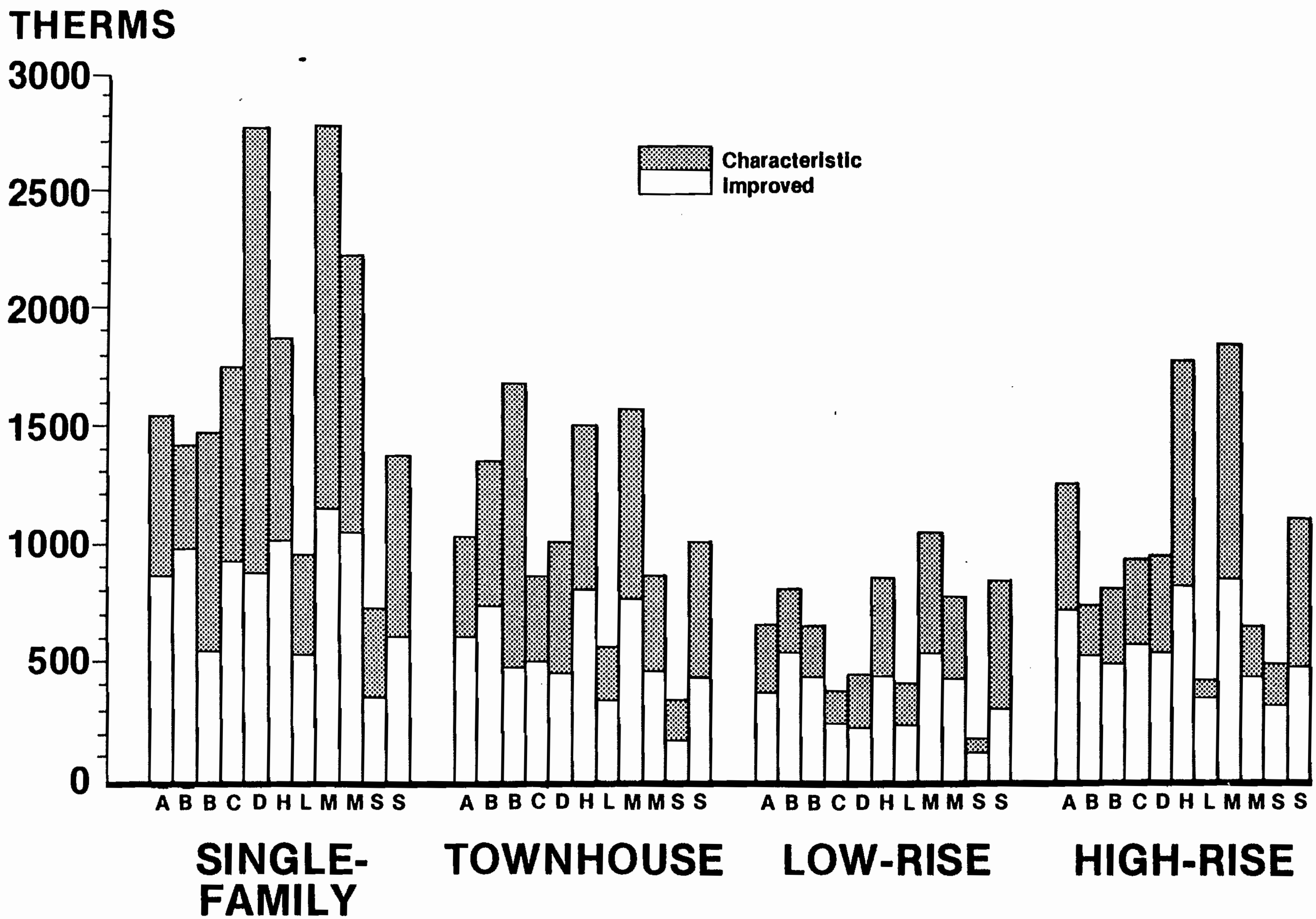

Figure 4. Comparison of Total Primary Energy Per Unit in Characteristic and Improved Buildings

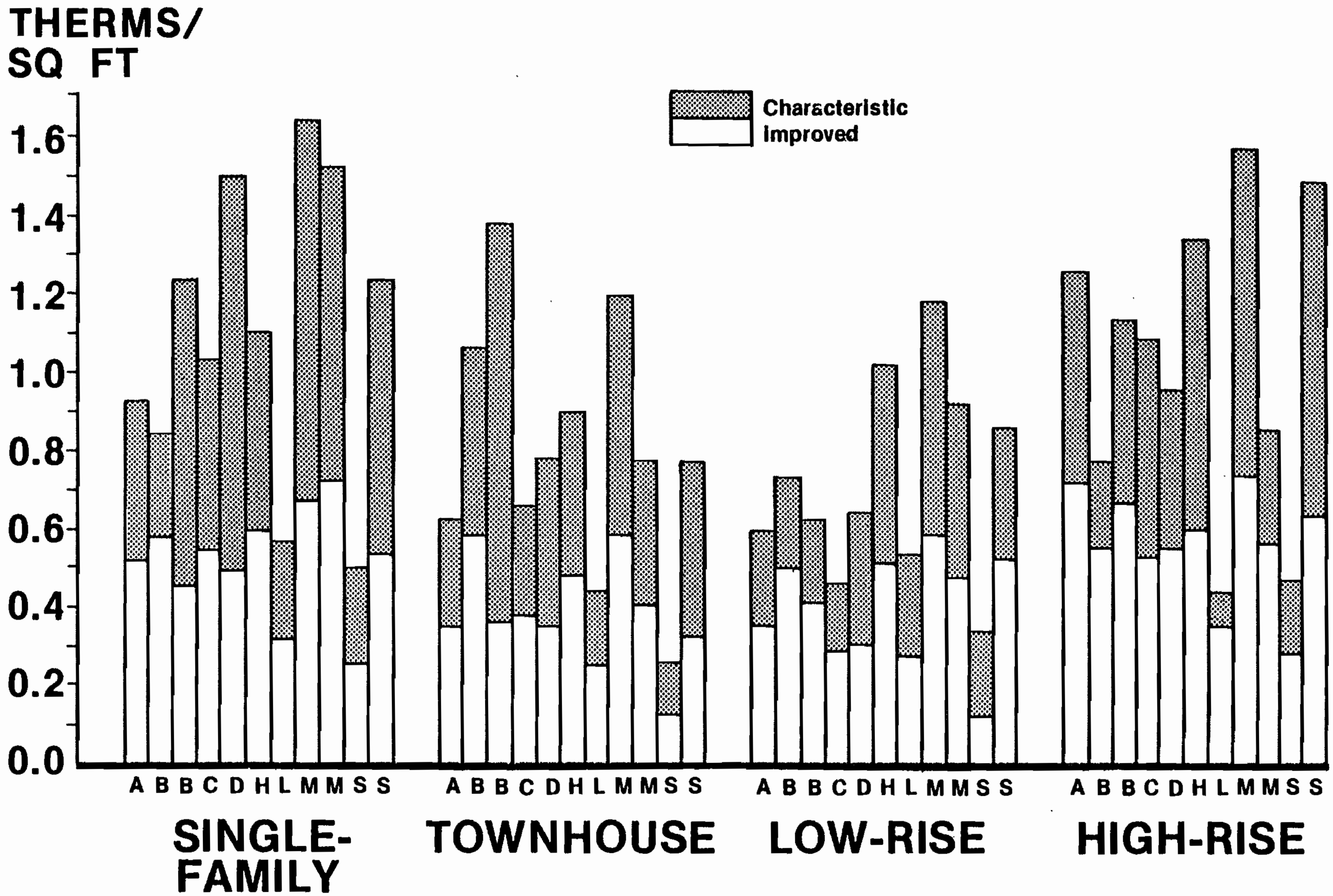

Figure 5. Comparison of Total Primary Energy Per Square Foot in Characteristic and Improved Buildings

values, the percent reductions in heating loads for single-family buildings are compared in the Table below with the characteristic buildings' TLF's for the eight cities in heating climates.

Comparison of Energy Reduction and TLFs

	Heating Load Reduction (%)	Characteristic Heating TLF	Improved Heating TLF
Denver	67	13.3	4.44
Boston	61	14.7	5.77
St. Louis	57	12.6	5.53
Minneapolis	50	11.6	5.99
San Francisco	45	10.1	5.62
Chicago	44	9.6	5.32
Baltimore	40	9.9	5.97
Atlanta	30	6.7	4.68

The percent reductions in heating loads have been ranked in order of decreasing magnitude and it can be seen that the charactistic TLF's follow this ranking very closely. Similar correlation was exhibited by the townhouses and low-rises, but due to various factors previously described, the high-rise buildings showed considerably less meaningful correlation.

A major result of the thermal load component analysis used in selecting improvements for the characteristic buildings was that the heating TLF's for the improved buildings were very similar for each class of building (see table above for example). The average heating TLF's by building class for the eight cities with heating climates were:

Single-Family	5.41 Btu/sq ft DD
Townhouse	2.32 Btu/sq ft DD
Low-Rise	2.04 Btu/sq ft DD
High-Rise	2.49 Btu/sq ft DD

The standard deviation for each class was very small, 0.34, 0.57, 0.91, and 1.38, for single-family through high-rise buildings, respectively.

The average TLF's given above could very well be used as a design standard in any region with a moderate to large number of heating degree days. This method would eliminate the need for detailed load component analysis and only require a rough determination of the heating load for a building to determine if its construction was acceptable for the local climate.

A similar metric for cooling could be developed but it would require more than the simple normalization with respect to floor area and annual degree days used for the heating TLF.

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