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DENVER RESIDENTIAL ENERGY CONSUMPTION

Final Report
September 1976

Department of Housing and Urban Development

Office of the Assistant Secretary for Policy Development and Research

ENERGY CONSERVATION

DENVER RESIDENTIAL ENERGY CONSUMPTION

HIT-650-4
FINAL REPORT

September 1976

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for
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Harvey M. Bernstein
Taghi Alereza

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I. INTRODUCTION

This report on residential energy consumption in Denver, Colorado, is part of a continuing program devoted to the analysis of residential energy consumption 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."* Subsequent reports were published which dealt with the consumption and efficient use of energy in Baltimore/Washington area residences.*

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

Atlanta, Georgia

Boston, Massachusetts

Chicago, Illinois

Denver, Colorado

Houston, Texas

Los Angeles, California

Miami, Florida

Minneapolis, Minnesota

San Francisco, California

St. Louis, Missouri

The boundaries for each geographical area were defined in accordance with the Federal Government's definition of standard metropolitan statistical areas (SMSA's). An SMSA

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

includes one central city and one or more contiguous counties that are metropolitan in character, as determined by the percentage of the labor force that is nonagricultural and by the amount of commuting between the county and the city. For each of these locations, it was sought (1) to identify and quantify the total heating and cooling energy requirements in typical single-family detached, single-family attached, low-rise multifamily, and high-rise multifamily dwellings; and (2) to evaluate the use of various technical innovations potentially capable of minimizing energy consumption in 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 energy consumption patterns of residences in the area.

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

Calculate the hourly, monthly, and annual energy requirements for heating and cooling each characteristic structure for the chosen weather year (a year selected after careful scrutiny to be typical for the location).

Define improved single-family, townhouse, low-rise, and high-rise structures incorporating 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 corresponding (unmodified) characteristic residences.

This report on energy consumption in Denver is the fourth of ten city-specific reports to be issued in the detailed geographical analysis series. In addition to the summary and statement of conclusions to follow, the report includes chapters on the characterization of typical Denver residences, on the computation of heating and cooling energy requirements in the typical residences, and on the energy consumption of thermally "improved" Denver residences.

The most basic location-specific factor in determining heating and cooling energy consumption is climate. Denver enjoys the mild, sunny, semi-arid climate that prevails over much of the central Rocky Mountain region, without the extremely cold mornings of the high elevations and restricted mountain valleys during the cold part of the year, or the hot afternoons of summer at lower altitudes. Wind is lessened by the promixity of the mountains. Extremely warm or cold weather is usually of short duration. Airmasses from at least four different sources influence Denver's weather: polar air from Canada and the far northwest; moist air from the Gulf of Mexico; warm dry air from Mexico and the southwest; and Pacific air modified by its passage overland.

The Denver weather year is characterized by 6016 heating degree days (base 65°F) and 630 cooling degree days (base 65°F). The yearly mean wind velocity is 9.0 mph, with a fastest recorded wind velocity of 51 mph, in July 1965. There are normally 115 clear days, 133 partly cloudy days, and 117 cloudy days per year in Denver (Ref. 1). Residential construction trends, discussed in Chapter III, have been influenced historically by the structural and thermal demands imposed by this climatic environment. Other factors, such as fuel and electricity prices, local income levels, and the ethnic backgrounds represented in Denver's population have also influenced construction practices, and, therefore, heating and cooling energy consumption.

II. SUMMARY AND CONCLUSIONS

Heating and cooling energy requirements were determined by a time-response, multizone computer program for characteristic single-family, townhouse, low-rise, and high-rise residences in Denver. Based on national weather records kept since 1935, 1961 was picked as being a typical weather year for the Denver area. Heating and cooling energy requirements were determined similarly for modified versions of these Denver characteristic residences, incorporating various structural and systems improvements.

To identify the current trends in housing in the Denver area, a large data base was developed from information obtained from national and municipal government agencies and local builders. Using these data, parameters were identified for the design, construction, internal loads, and comfort control systems for the following characteristic structures:

Single-family: A three bedroom split-level house.

Townhouse: A two-story structure containing eight three bedroom apartments in a row.

Low-Rise: A three-story building with 12 one bedroom, and 12 two bedroom units.

High-Rise: A 15-story building with 89 one bedroom and 90 two bedroom units.

In defining these parameters, good quality materials, components, and workmanship were assumed consistent with current practice and standards. The residences are typical of those occupied by middle-income residents, and, therefore, the kinds and use-rate of appliances and life-style patterns were assumed accordingly. The "modified" residences of each type were defined to incorporate structural and HVAC system improvements practical from a builder's or architect's viewpoint. That is, no radical changes were made; e.g., flue gas heat recovery units were added to gas furnaces and only commercially available insulation material was added to the structure.

The energy requirements for the Denver residences were calculated for the 1961 weather year using a two-step process. In the first step, the hourly heating and cooling loads were calculated for each dwelling unit. Calculations were made using a computer program whose inputs included design and materials of the structure, building surroundings, internal thermal loads (lights, appliances, and occupants), hourly weather data, and pertinent astronomy of the sun. Included in this program was the calculation of heating and cooling loads (both sensible and latent) due to the infiltration of outside air. In the second step, the monthly and annual energy required to meet the heating and cooling loads were calculated using specific heating, cooling, and ventilation systems. The inputs to these calculations included the heating and cooling load data, equipment performance and energy requirements at full and partial loads, and the type of energy required. The computer model used was the existing Buildings Energy Analysis Model (BEAM) developed at Hittman Associates, Inc.

Hourly load calculations were performed for both heating and cooling, in each space-conditioned "zone" of the four types of residences, over each day of the 1961 Denver weather year. This approach to the development of annual loads and primary energy consumption produced data for Denver residences equivalent to some 54,000 different one-day, one-zone load profiles.

A summary of the calculated average annual heating and cooling loads, and primary energy consumption for dwelling units of each type considered, are shown in Table I. Heating loads were much greater than cooling loads in every residence except the low-rise, which had similar heating and cooling loads. This was due to lack of ventilation and a large amount of internal heat generation in the low-rise building.

The energy conserving modifications made for the single-family, townhouse, low-rise, and high-rise structures are summarized in Table II. Both structural and comfort control system modifications were made. The following paragraphs discuss the energy savings realized in each type of residence.

The improved Denver single-family residence required only 30 percent as much in-structure energy as the characteristic residence. This was by far the largest improvement of any residence for in-structure energy consumption. Primary energy consumption was reduced 68 percent, implying only 32 percent as much was required, again the biggest improvement of any residence. The main reason for the large improvements in the single-family structure's energy consumption was the fact that the characteristic residence was grossly inefficient, requiring nearly three times as much primary energy as any other residence, and over six times as much as the characteristic low-rise residence. Structural modifications significantly reducing both the heating and cooling loads accounted for the bulk of the improvement, with a more efficient comfort control system making up the rest. The improved single-family's floor area-normalized primary energy requirement was 0.48 therm/sq ft.

The improved townhouse required 44 percent as much primary energy as the characteristic residence. Part of the reduction was due to a more efficient comfort control system, but the bulk was due to structural modifications lowering the heating load by over 50 percent. The townhouse had a low floor area normalized primary energy requirement of 0.35 therm/sq ft.

The improved low-rise required 48 percent of the primary energy that the characteristic residence consumed, nearly the smallest percent reduction of any residence studied. The obvious reason for this was that the characteristic residence was by far the most efficient building, requiring less than half as much energy as any other residence. The improved floor area-normalized primary energy requirement was 0.30 therm/sq ft, the lowest of any improved residence.

The improved high-rise required 56 percent of the primary energy consumed by the characteristic residence, the smallest improvement encountered. Two factors limit the improvement possible in a high-rise building: (1) the large load created by required mechanical ventilation and (2) the large amounts of non-apartment floor space, such as halls and lobbies, that must be heated and cooled. Due to these two constraints, the improved high-rise had a floor area normalized primary energy requirement of 0.54 therm/sq ft, the largest of any residence in Denver.

TABLE I. SUMMARY OF ANNUAL HEATING AND COOLING LOADS AND PRIMARY ENERGY REQUIREMENTS FOR THE DENVER CHARACTERISTIC AND IMPROVED RESIDENCES

	Single-Family		Townhouse		Low-Rise		High-Rise	
	Characteristic	Improved	Characteristic	Improved	Characteristic	Improved	Characteristic	Improved
Heating load per average unit, therms	1478.1	494.8	479.3	221.9	180.7	79.7	421.6	184.2
Cooling load per average unit, therms	361.3	244.3	185.8	171.4	122.6	135.5	132.9	133.4
Primary energy consumption per average unit, therms*	2778.0	885.2 (68)	1030.0	458.3 (56)	457.6	218.0 (52)	955.5	536.9 (44)
Primary energy consumption per sq ft of floor area,** therms	1.50	0.48	0.78	0.35	0.64	0.30	0.96	0.54

*Percent reduction in primary energy consumption per average dwelling unit is given in parentheses. Number in parentheses for each residence type is found with the relationship:

$$\text{Percent reduction} = \frac{\text{(Energy consumption, characteristic)} - \text{(energy consumption, modified)}}{\text{Energy consumption, characteristic}} \times 100.$$

**Floor area includes halls, lobbies, and stairwells in high-rise buildings.

TABLE II. ENERGY CONSERVATION MODIFICATIONS FOR CHARACTERISTIC DENVER RESIDENCES

	Glass[1] Reduction in North Face (%)	Glass[1] Reduction in South Face (%)	Addition of Weather-Stripping	Addition of Storm Windows or Double Glazing	Revised Wall Insulation R Value	Revised Ceiling Insulation R Value	Revised Floor U Value	Improved Gas/Oil Furnace Efficiency	Use of Heat Recovery System	Improved Cooling System C.O.P.
Single-family	50	5	*	*	17	27	0.8	*	*	*
Town-house	50	9	*	Exists	17	27	0.8 Exists	*	*	*
Low-Rise	See Note 1		*	*	17	27	0.1 Exists	*	*	*
High-Rise	See Note 1		*	*	12	17	0.1	*	*	*

[1]*Total glass reduction for all buildings equals 25 percent.*

**Change made in Characteristic Residence.*

III. CHARACTERIZATION OF TYPICAL RESIDENTIAL STRUCTURES IN DENVER

Typical, or characteristic, new residential buildings for the Denver area were synthesized following the methodology of previous HAI Residential Energy Consumption studies for the U.S. Department of Housing and Urban Development. Four such typical residences were developed, including a single-family (detached) house, a townhouse, a low-rise apartment building, and a high-rise apartment building.

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

Structural parameters such as construction details, dimensions, and materials used.

Energy consumption parameters such as heating and cooling equipment, types of fuels and energy used, and appliances and their energy consumption 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 profile of appliance usage

Usage 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. In consideration of the sizes and quality of the characteristic residences, and of the appliances included in these residences, it can be assumed that the residences would be occupied by individuals or families in the middle income group. It should also 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 can affect the buildings' energy consumption 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 structure had ventilation air supplied to, and only 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 esthetic 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.

Current trends in Denver area housing were identified by contacting a large number of area builders and acquiring data for a large number of residential buildings constructed in that area. Based on this informal sampling, and data provided by the Department of Housing and Urban Development, compatible sets of building parameters were synthesized to represent complete residential structures typical of the Denver area. This chapter describes relevant structural and energy parameters, and their selected values for the four typical residential structures thus characterized.

A. Single-Family Residences

The single-family (detached) 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 (Ref. 2). Recent demographic trends, combined with costs of building materials, land, and financing, however, 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.

In the Denver SMSA, this trend is even more pronounced. In 1970, the total stock of housing units in Denver was comprised of 68.2 percent single-family buildings. In 1973, according to the number of building permits issued, only 43.9 of the housing starts were in one-unit buildings.

In this context, the term "single-family residence" refers to the completely detached single-family house. Approximately 12,400 such houses were built in the Denver metropolitan area in 1973 (based on building permits issued).

Quantitative data for design and structural features of single-family residences was obtained from the National Survey of Builder Practices (Ref. 3). This survey included over 1600 builders nationwide, who were responsible for the construction of approximately 84,000 single-family homes in 1973. Information was gathered on construction details, building materials used, heating and cooling equipment, and appliances used. The Denver area builders were responsible for the construction of 1097 homes in the area during 1975.

Other sources from which single-family housing data were obtained included a recent study of the potential for solar heating and cooling of buildings (Refs. 4, 5), 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 (Refs. 6, 7, and 8). Compatibility among building elements was carefully preserved. Typical appliance mixes and electricity consumption levels were taken from the previous work by HAI for single-family housing in the Baltimore/Washington area.

On the basis of the data obtained for single-family residences in the Denver area, structural and energy consumption parameters for a typical single-family residence were defined as in Table III. Figure 1 shows the floor plan for the typical Denver single-family residence. This internal floor plan was not itself critical to the energy analyses performed, since the single-family house was treated as a unit shell in heat transfer calculations.

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 for 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, construction of townhouse and multifamily residences will dominate in large urban areas.

TABLE III. STRUCTURAL AND ENERGY CONSUMPTION PARAMETERS FOR TYPICAL SINGLE-FAMILY RESIDENCE IN THE DENVER AREA

STRUCTURAL PARAMETERS:	
Basic House Design	3-Bedroom Split Level, 9 ft stories
Foundation	Partial Basement
Garage/carport	2-Car Garage
Floor area, ft^2	1852 Square Ft
Construction	Wood Frame, 2x4 Studs 16" on ctr.
Exterior walls:	
Outside surface	Brick veneer
Sheathing	1/2" Insulation Board
Insulation	3 1/2" Fiberglass Batts
Inside surface	1/2" Gypsumboard
Ceiling insulation	Asphalt Shingles, 1/2" Plywood Sheathing, Air Space, 4" Fiberglass Loose-Fill Insulation, 1/2" Gypsumboard
Roof	Gable
Windows:	
Type	Aluminium Sliders
Glazing	Single
Area, ft^2	190 Sq Ft
Exterior doors:	
Type	Wood
Number	Two
Total area, ft^2	40 Sq Ft
Patio door(s):	
Type	Aluminum Sliders
Glazing	Single
Area, ft^2	40 Sq Ft
Orientation	South

ENERGY CONSUMPTION PARAMETERS:*	
Energy consuming equipment:	
Heating system	Gas, Forced Air
Cooling system	Electric, Forced Air
Hot water heater	Gas (270 Therms/Year)
Cooking range/oven	Electric (2340 Kw-hr/Year)
Clothes dryer	Gas, (90 Therms/Year)
Refrigerator/freezer	Electric (1830 Kw-hr/Year)
Lights	Electric/Incandescent (2200 Kw-hr/Year)
Color TV	Electric (500 Kw-hr/Year)
Furnace fan	Electric (394 Kw-hr/Year)
Dishwasher	Electric (363 Kw-hr/Year)
Clothes washer	Electric (103 Kw-hr/Year)
Iron	Electric (144 Kw-hr/Year)
Coffee maker	Electric (106 Kw-hr/Year)
Miscellaneous	Electric (1200 Kw-hr/Year)
HEATING/COOLING LOAD PARAMETERS:	
Dwelling facing	East
People per unit	Two Adults, Two Children
Weather year	1961

* Figures shown in parentheses represent energy input to structure for each appliance (based on data in Reference 10).

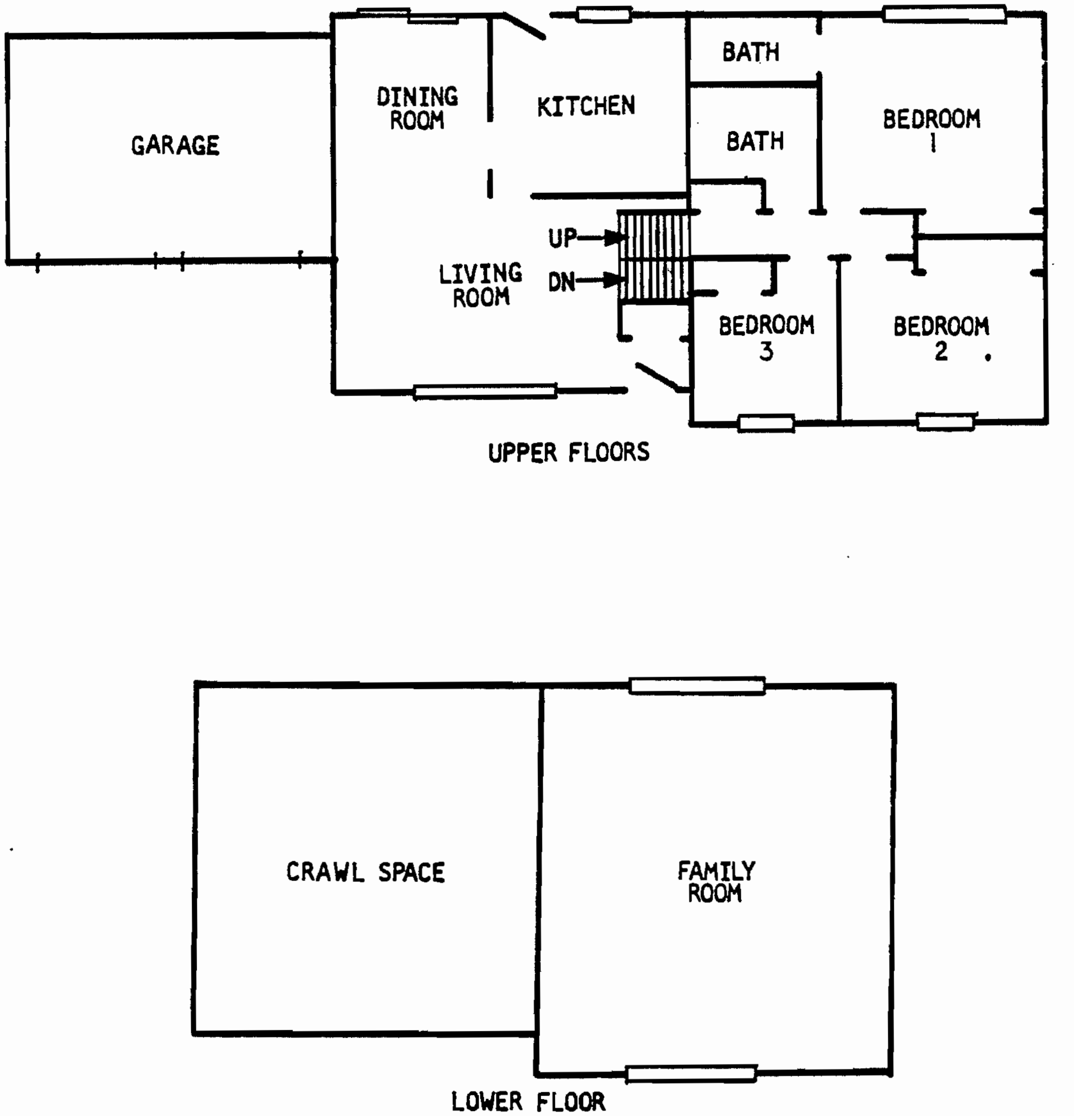

Figure 1. Floor Plan for the Characteristic Single-Family House in Denver

For the townhouse residences, the primary source of data was the same as for the single-family residences; the National Survey of Builder Practices (Ref. 3). Of the 84,000 housing units constructed nationally by surveyed builders, 19 percent, or approximately 16,000 units, were townhouses, The Denver area sub-sample included four contractors who together were responsible for the construction of 840 townhouse units in 1973.

In addition to the builder practices survey, the earlier data collection and townhouse specification done by HAI, under contract to HUD (Ref. 10) for the Baltimore/Washington area, was used for reference. Other sources included standard engineering and construction handbooks (Refs. 6, 7). Compatibility among building elements was carefully preserved.

The structural and energy consumption parameters for the typical Denver area townhouse residence are presented in Table IV. The floor plan for the typical Denver townhouse is presented in Figure 2.

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, though the for-rent variety is most common. In the United States, there were approximately 256,000 low-rise dwelling units constructed in 1974 (Ref. 11). In the Denver area, approximately 9000 multifamily dwelling units were constructed in 1974, and of these, approximately 8550 units were contained in low-rise buildings (Ref. 11). While historical data on the growth of low-rise housing was not specifically obtained, the historic growth patterns of multifamily housing in the Denver area are applicable.

The primary source of data used for the specification of low-rise building components was a very recent nationwide survey (Ref. 12) of builders who had built single-family, townhouse, and lowrise 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 government figures of approximately 1,300,000 dwelling units built in 1974, this represents a composite sampling rate of approximately 14 percent nationwide. The city-specific response rates for low-rise buildings for

TABLE IV. STRUCTURAL AND ENERGY CONSUMPTION PARAMETERS FOR TYPICAL TOWNHOUSE RESIDENCE IN THE DENVER AREA

GENERAL PARAMETERS:		
Arrangement	Rectangular Structure, Eight Town House Units in a Row	
Basic design	2-Story, 3 Bedroom	
Foundation	Crawl Space, Poured Concrete	
DIMENSIONAL PARAMETERS:		
(Areas are per townhouse unit, not per floor level)	Intermediate Units	End Units
Floor area, ft^2	1320	1320
Interior wall area, ft^2	603	1174
Window glass area, ft^2	77	101
Patio door, ft^2	40	40
Exterior door(s), ft^2	20	20
Roof area, per unit, ft^2	660	660
Story height, ft	9	9
CONSTRUCTION PARAMETERS:		
Construction type	Wood Frame, 2x4 Studs 16" on ctr	
Exterior walls:		
Siding	Brick Veneer	
Sheathing	1/2" Insulation Board	
Insulation	3 1/2" Fiberglass Batt Insulation	
Inside surface	1/2" Gypsumboard	
Interior walls:	1/2" Gypsumboard, 2x4 Studs 16" on ctr, 1/2" Gypsumboard	
Roof:	Gable	
Exterior door:	Wood Frame	
Windows: Glazing	Double	
Frames	Single Hung, Aluminum	
Patio door:		
Glazing	Double	
Frames	Aluminum Sliding	

Roof composition	Wood Shakes, 1/2" Plywood Air Space, 6" Loose Fill Fiberglass Insulation, 1/2" Gypsumboard
ENERGY CONSUMPTION PARAMETERS:*	
Heating system	Forced Air, Gas
Cooling system	Forced Air, Electric
Hot water heater	Gas (270 Therms/year)
Cooking range	Electric (2340 Kw-hr/year)
Clothes dryer	Gas (90 Therms/year)
Refrigerator/freezer	Electric (1830 Kw-hr/year)
Lights	Electric-incandescent (1570 Kw-hr/year)
Color TV	Electric (500 Kw-hr/year)
Furnace fan	Electric (394 Kw-hr/year)
Dishwasher	Electric (363 Kw-hr/year)
Clothes washer	Electric (103 Kw-hr/year)
Iron	Electric (144 Kw-hr/year)
Coffee maker	Electric (106 Kw-hr/year)
Miscellaneous	Electric (1200 Kw-hr/year)
HEATING/COOLING LOAD PARAMETERS:	
Dwelling facing	East
People per unit	Two Adults, Two Children
Typical weather year	1961
Patio Door Facing:	West

* Figures shown in parentheses represent energy input to structure for each appliance (based on data in Reference 10).

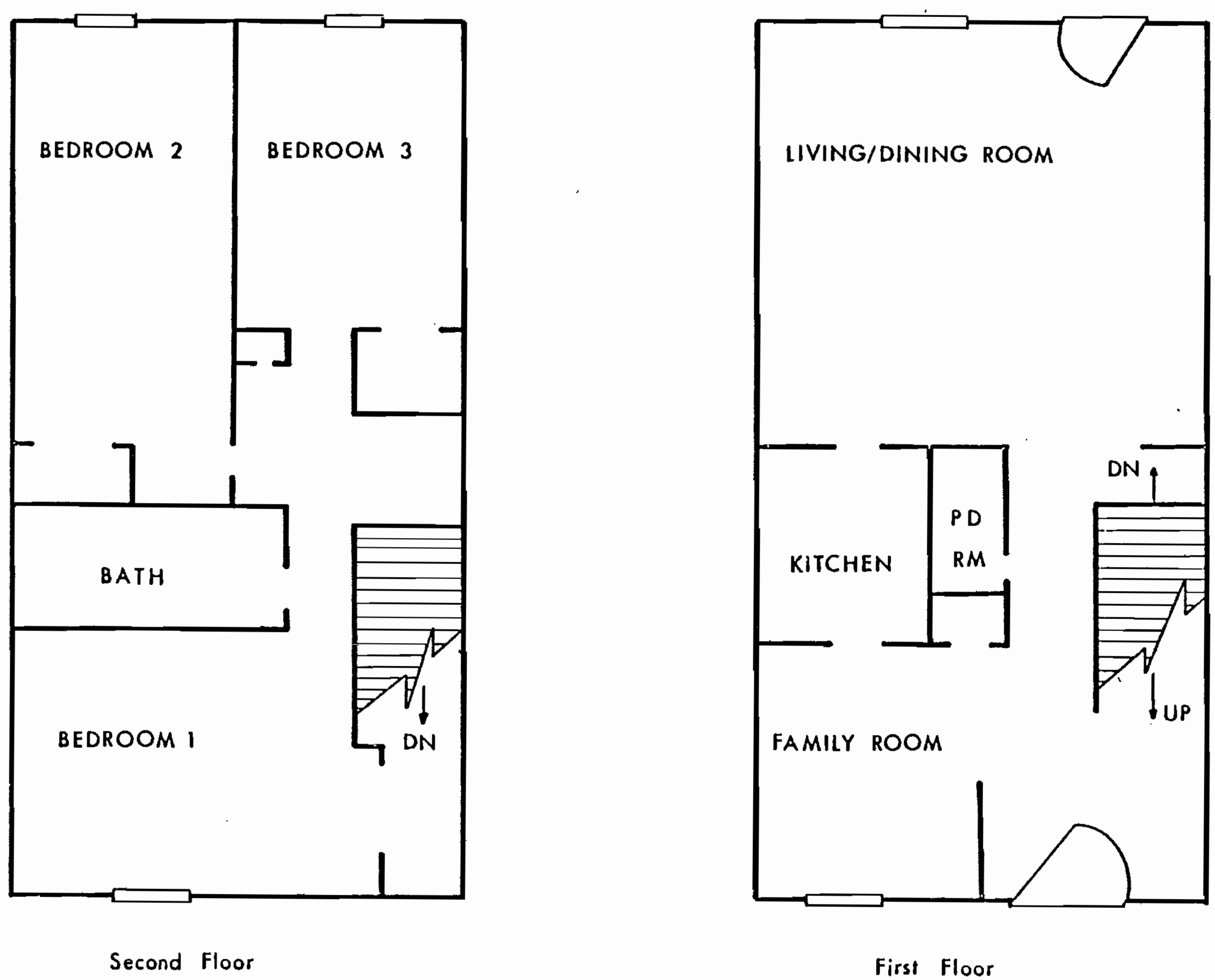

Figure 2. Floor Plan for Characteristic Townhouse

the ten cities represented in this study vary considerably, from five percent in Los Angeles to 48 percent in Miami. Eight of the ten cities had response rates of at least 14 percent for low-rise buildings.

In the Denver metropolitan area, approximately 8550 low-rise units were built in 1974. Builders responding to this survey were responsible for 1384 of those units, giving a 16 percent sampling rate. In addition to this survey, HAI's previous low-rise data acquisition work for HUD (Ref. 13), wherein a similar specification was done for the Baltimore/ Washington area, was consulted as a reference. Judgements based on previous experience were made where necessary to ensure compatibility among building elements.

The structural and energy use characteristics for the low-rise residence are presented in Table V. Figure 3 shows the arrangement and floor plan of the units within the building.

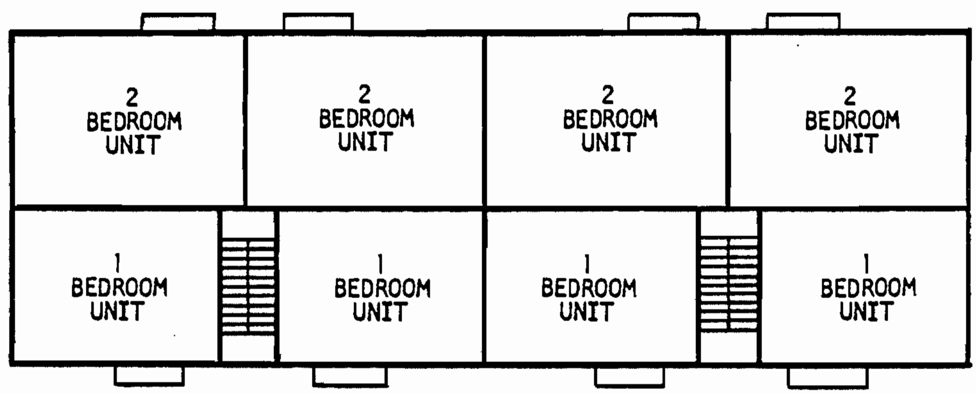

Figure 3. Floor Plan for Characteristic Low-Rise Structure

D. High-Rise Buildings

High-rise residences are defined as residential structures having more than four stories. They 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 of the U.S. central cities.

TABLE V. STRUCTURAL AND ENERGY CONSUMPTION PARAMETERS FOR TYPICAL LOW-RISE RESIDENCE IN THE DENVER AREA

GENERAL PARAMETERS:		
Arrangement	Twelve Units around each enclosed stairwell. Two enclosed stairwells per building.	
Number of stories	Three	
Apartments	12 One-Bedroom, 12 Two-Bedroom	
DIMENSIONAL PARAMETERS:		
	Interior Units	End Units
Floor area, ft^2	600[1], 820[2]	600[1], 820[2]
Exterior wall area, ft^2	350[1], 192[2]	548[1], 435[2]
Window glass, ft^2	32[1], 43[2]	32[1], 43[2]
Door(s), steel, ft^2	20	20
Patio/balcony door(s), aluminum, ft^2	40	40
Roof area, ft^2	600[1], 820[2]	600[1], 820[2]
Story height, ft	9	9
CONSTRUCTION PARAMETERS:		
Construction type	Wood Frame, 2x4 Studs 16" on ctr	
Foundation	Slab-on-grade with perimeter insulation	
Exterior walls:		
Siding	Brick Veneer	
Sheathing	1/2" Insulation Board	
Insulation	3 1/2" Fiberglass Batt Insulation	
Inside surface	1/2" Gypsumboard	
Interior Walls:	1/2" Gypsumboard, 2x3 Studs 16" on ctr, 1/2" Gypsumboard	
Roof	Flat	
Entrance doors, per unit	One, Wood Frame	
Windows and patio doors per unit:		
Glazing	Single	
Frames	Sliding, Aluminum	
Ceiling composition	Built Up Roof, 1/2" Plywood Air Space, 3 1/2" Fiberglass Batt Insulation, 1/2" Gypsumboard	

ENETRY CONSUMPTION PARAMETERS:*	
Electric metering	Individual (per apartment)
Equipment in each structure:	
Central heating system	Individual Forced Air Furnaces, gas
Hot water heater	Individual Unit, Gas
Clothes washers	Electric
Clothes dryers	Gas
Equipment in each apartment:	
Cooling system	Individual Unit, Gas
Cooking range/oven	Electric (2000 Kw-hr/year)
Refrigerator	Electric (1400 Kw-hr/year)
Dishwasher	Electric (280 Kw-hr/year)
Lights	Electric (860[1], 1170[2] Kw-hr/year)
TV	Electric (400 Kw-hr/year)
Misc. appliances**	Electric (1100 Kw-hr/year)
HEATING/COOLING LOAD PARAMETERS:	
Dwelling facing	North
People per unit	Two Adults[1], Two Adults and One Child[2]
Typical weather year	1961

* Figures shown in parentheses represent energy input to structure for each appliance (based

** Includes disposal, iron, coffee maker, etc.

1 one-bedroom apartment

2 two-bedroom apartment

In the Denver area, approximately 9000 multifamily dwelling units were constructed in 1974. Of these, approximately 450 dwelling units were in buildings which were of the high-rise type (Ref. 11). These estimates were not disaggregated by type of occupant (owner or renter).

The data acquisition for high-rise buildings was accomplished entirely by telephone communication with builders, architects, and engineering consultants in each of the ten cities studied. Sources were asked if their opinions on the characteristics of high-rise buildings in their city could be considered representative of the majority of such buildings in their city. Sufficient contacts were made to establish and verify a complete picture of high-rise residential building construction for the area. Compatibility among building components selected for each city was carefully preserved during the analysis.

Three general observations on high-rise residential construction have been made from this informal sampling:

(1) Most cities have both condo (condominium, or owner-occupied) and rental units. Rental units include both private sector and public sector buildings (low-income or elderly housing).

(2) The major differences between high-rise rental and high-rise condo units were in size and utilities. Condo units tended to be larger, both in number of rooms and number of square feet, than rental units. Condo units also tended to have unitary heating and cooling equipment, whereas rental units tended to employ central equipment.

(3) High-rise residential buildings showed marked city-specific homogeneity in construction details, but were heterogeneous in facade, trim, geometry, and other surface features related to appearance.

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, seem actually more related to considerations of status, uniqueness, etc.

In the Denver area, the typical high-rise structure was a 15 story building, comprised of 89 one bedroom and 90 two bed-room rental units. Table VI provides structural and energy consumption parameters for the typical high-rise building in Denver. Figure 4 shows the typical high-rise floor plan.

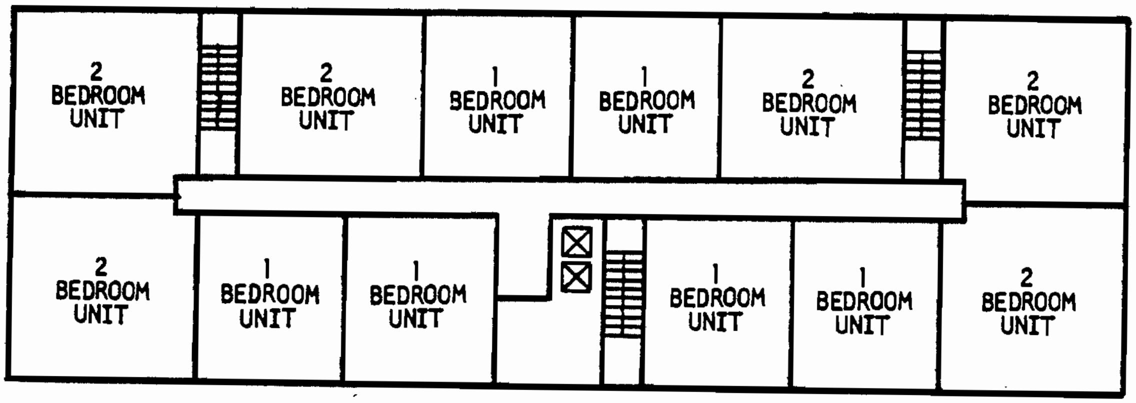

Figure 4. Floor Plan for Characteristic High-Rise Structure

TABLE VI. STRUCTURAL AND ENERGY CONSUMPTION PARAMETERS FOR TYPICAL HIGH-RISE RESIDENCE IN THE DENVER AREA

GENERAL PARAMETERS:

Arrangement	Rectangular Structure, Central Hall on Each Floor, Three Stairwells, Two Elevators
Number of stories	15
Basement	Underground Garage
Apartments	First Floor: 5 one-bedroom apartments; 6 two-bedroom apartments Other Floors: 6 one-bedroom apartments; 6 two-bedroom apartments

DIMENSIONAL PARAMETERS:

	Interior Apartments	End Apartments	Halls & Lobbies	Stairwells & Elevators	Utility Rooms
Floor area, ft^2	725 (1-br) 899 (2-br)	896	1238 (ff)* 1020 (of)**	864	667 (ff)* 160 (of)**
Exterior wall area, ft^2	167 (1-br) 187 (2-br)	417		180 (ff)* 240 (of)**	230 (ff)* 220 (of)**
Roof area, ft^2	725 (1-br) 899 (2-br)	896	1020	864	160
Window glass, ft^2	30 (1-br) 70 (2-br)	130	200 (ff)*		
Entrance doors, ft^2	20	20	20	20	20
Story height, ft	10	10	10	10	10

CONSTRUCTION PARAMETERS:

Frame	Reinforced Concrete
Floors and roof deck	2" concrete deck
Exterior walls:	
Siding	6" Precast Concrete
Sheathing	1" Styrofoam
Insulation	Air Gap
Inside surface	1/2" Gypsumboard
Roof	Built-up roofing; 1 1/2" rigid insulation, 2" concrete deck, air gap, 1/2" gypsumboard
Entrance doors:	
Apartments	One per unit, metal
Lobby	four, steel
Staircases	three, steel
Windows:	
Glazing	single

ENERGY CONSUMPTION PARAMETERS:***

Electric metering	Master (per structure)
Equipment in each structure:	
Central cooling system	Electric
Hot water heater	Gas
Clothes washers	Electric
Clothes dryers	Gas
Elevators	Electric
Lights, signal system, miscellaneous appliances	Electric
Equipment in each apartment:	
Heating system	Hot water, gas
Cooking range	Electric (2000 Kw-hr/year)
Refrigerator	Electric (1400 Kw-hr/year)
Dishwasher	Electric (280 Kw-hr/year)
Lights:	
1-bedroom unit	Electric (1040 Kw-hr/year)
2-bedroom unit	Electric (1290 Kw-hr/year)
TV	Electric (400 Kw-hr/year)
Miscellaneous	Electric (1100 Kw-hr/year)

HEATING/COOLING LOAD PARAMETERS:

Dwelling facing	North
People per apartment:	
1-bedroom	Two Adults
2-bedroom	Two Adults, One Child
Typical weather year	1961

* ff = first floor

** of = other floors

*** Data shown in parentheses represents energy input to structure for each appliance. Data based on Reference 10.

IV. COMPUTATION OF HEATING AND COOLING ENERGY REQUIREMENTS

Annual heating and cooling loads and resultant energy requirements were calculated for each of the four characteristic residences defined in Chapter III for the Denver area. 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 load contributions throughout the year due to conduction, convection, air infiltration, radiation, and internal heat gain. Annual HVAC energy requirements were calculated from monthly heating and cooling loads by applying system and auxiliary component efficiencies and coefficients of performance appropriate for each characteristic residence. The computer program calculation procedures, and the results of these calculations are discussed in the following sections.

A. Description of the Computer Program Used for Load Calculations

The Load Calculating Sub-Program (LCSP) of the Buildings Energy Analysis Model (BEAM) was developed at Hittman Associates, Inc., as a revised form of the original U.S. Postal Service program. The Load Calculation Sub-Program is a complex of heat transfer, environmental, and geometric subroutines which compute the heating and cooling loads for each space* at each hour. The input to the LCSP structure is the building surroundings, local weather, and the pertinent astronomy of the sun. The output consists of hourly weather and psychrometric data, sensible loads, latent loads, lighting loads (if applicable), and equipment and lighting power consumption for each space.

The Load Calculation Sub-Program consists of a set of subroutines, small programs (each of which performs an engineering calculation), and a main program which reads the required data, directs the flow of information from one subroutine to another, and writes the output on paper and magnetic tapes. Loads are computed on the basis of actual recorded weather data using the Convolution Principle. Weather data for the selected year is taken from magnetic tapes available from the National Climatic Center.

**Such a space is defined as a room of a group of rooms which are treated as a single load module by the LCSP.*

1. Hourly Weather Data

Weather tapes of past years are available for enough weather stations throughout the United States so that a tape is likely to be available for a station near the site of any building being considered. The Load Sub-Program uses weather tapes to realistically simulate the changing meteorological conditions to which the building is continuously exposed. The data read from the weather tape and a brief summary of the uses to which they are put are listed below:

(a) Dry-bulb temperature (used in computing heat transfer and sensible loads)

(b) Wet-bulb temperature (used in computing humidity ratio and latent loads)

(c) Wind velocity (used in computing outside surface heat transfer film coefficient and infiltration rate)

(d) Wind direction (used in computing infiltration rate)

(e) Barometric pressure (used in computing density of air)

(f) Cloud type and amount (used in computing heat gain and heat loss by radiation between the building and the sky)

2. Hourly Solar Radiation Data

The amount of heat gained by the building through an exterior surface (roof, exterior walls, or windows) depends upon the radiant environment to which the surface is exposed. This radiant environment may be simulated more accurately by a computer than by hand calculations because the computer can evaluate the components of radiant environment on an hourly basis. The program makes hourly calculations of the following components of the radiant environment for each exterior surface:

(a) Angle of incidence of the sun's rays

(b) Direct normal intensity

(c) Brightness of sky and ground

(d) Re-radiation to sky

(e) Shadows cast upon the surface

By combining these data with such constants of the surface as emissivity, shape factor between surface and sky, and shape factor between surface and ground, the program arrives at hourly radiation fluxes.

3. Infiltration Support Program

The mathematical model of this computer program is basically a mass flow balance network. Major components are exterior walls, walls of vertical shafts, floors, leakage areas in the major separations which are lumped together and represented by orifice areas, and ventilation systems.

The value of outside absolute pressure is taken as normal atmospheric pressure. Outside air pressures at other levels depend on the density of outside air and on wind pressure (depending on wind speed and direction). Inside pressures on the floor at various levels are interrelated by the weight of the column of inside air between levels and the pressure drop across the intervening floors. Inside pressures in the shaft at various levels are interrelated only by the weight of the column of shaft air, assuming no frictional pressure drop in the vertical shaft. The flows through the orifices are computed at hourly intervals.

The program is designed to permit variation in the number of floors and shafts, size of orifice areas, and pressurization levels induced by mechanical ventilation.

B. Calculation of Heating and Cooling Loads and Energy Requirements

The annual heating and cooling loads and subsequent energy requirements for the four characteristic residences in the Denver area were calculated for the 1961 Denver weather year. The method used for making the calculations was a two step process. First, hourly heating and cooling loads were calculated for each space in each of the characteristic residences using the LCSP program described previously. Appropriate structural properties and design data for each respective residential building type in the Denver area, as well as daily internal load profiles for lights, appliances, and occupants in the area, were all prepared as input to the LCSP. In the second step, the energy required to meet the heating and cooling loads was calculated. These calculations required the various system capacities, efficiencies and performance characteristics for the type of heating, cooling and ventilation system characterized for each of the four residences.

1. Heating and Cooling Load Calculations

The structural parameters and floor plan configurations defined for each characteristic house in Chapter III were used in formulating inputs to the load calculating computer program. Detailed performance parameters were defined as shown in Tables VII, VIII, IX and X, including total U values for the walls, roof, floors, and doors; material conductivities, densities, specific heats; and R values as appropriate.

Internal load profiles for lights, appliances, and occupants were taken from Reference 12. These profiles were varied for weekdays and weekends throughout the year. A constant thermostat set point of 72°F was established for both the heating and cooling season. All loads tending to decrease the internal temperature were defined as heating loads, and all loads tending to increase the temperature were cooling loads. For example, cold air infiltrating from outside the heating space would contribute as a heating load, whereas an internal load would contribute as a cooling load. In calculating the loads, it was assumed that all windows in the residences remained closed throughout the year.

Monthly and annual heating and cooling loads for the four characteristic structures are shown in Table XI. Annual loads per average dwelling unit for the single-family, town-house, low-rise, and high-rise characteristic structures are also given. It should be noted that, in subsequent calculations of energy requirements, it was assumed that very small loads occurring during some months would not be met by the buildings' HVAC systems.*

The percentage of heating and cooling loads due to the infiltration of outside air through windows, doors, and walls, as well as mechanical ventilation, is shown below for each residential building type. These percentages represent the portion of the total annual loads for the entire building which can be attributed to air infiltration.

**For example, a small cooling load in January, caused by internal heat gain, would not be met by the air-conditioning system, but rather by opening the building's windows.*

TABLE VII. DENVER CHARACTERISTIC SINGLE-FAMILY RESIDENCE STRUCTURAL PARAMETERS

Components	"U" Value (Btu/hr-ft²-°F)	Thickness (ft)	Conductivity (Btu/hr-ft-°F)	Density (lb/ft³)	Specific Heat (Btu/lb-°F)	"R" Value (hr-ft²-°F/Btu)
Upper Walls						
Brick Veneer		0.333	0.757	130	0.22	
Insulation Board	0.076	0.042	0.032	18	0.31	
3 1/2" Batt Insulation		0.292	0.0265	3	0.18	
Gypsumboard		0.042	0.093	50	0.26	
Basement Walls						
Cement Finish		0.02	0.417	116	0.19	
Concrete Block	0.863	0.667	0.60	82	0.20	
Roof						
Asphalt Shingles		0.042	0.096	99	0.26	
Wood Sheathing		0.042	0.065	34	0.29	
Air Space	0.069	--	--	--	--	0.96
Loose Fill Insulation		0.333	0.0274	10	0.18	
Gypsumboard		0.042	0.093	50	0.26	
Door						
Wood Frame	0.67	--	--	--	--	--
Floor (Over Crawl Space)						
Subfloor		0.0625	0.064	34	0.29	
Underlayment	0.416	0.01	0.083	63	0.33	
Carpet/Padding		0.065	0.050	10	0.34	
Floor						
Partial Concrete Basement	0.24					

TABLE VIII. DENVER CHARACTERISTIC TOWN HOUSE RESIDENCE STRUCTURAL PARAMETERS

Components	"U" Value (Btu/hr-ft^2-°F)	Thickness (ft)	Conductivity (Btu/hr-ft-°F)	Density (lb/ft^3)	Specific Heat (Btu/lb-°F)	"R" Value (hr-ft^2-°F/Btu)
Wall						
Brick Veneer		0.333	0.757	130	0.22	
Insulation Board	0.076	0.042	0.032	18	0.31	
3 1/2" Batt Insulation		0.292	0.0265	3	0.18	
Gypsumboard		0.042	0.093	50	0.26	
Roof						
Wood Shakers		0.073	0.065	48	0.31	
Wood Sheathing		0.042	0.065	34	0.29	
Air Space	0.047	--	--	--	--	0.96
Loose Fill Insulation		0.500	0.0274	10	0.18	
Gypsumboard		0.042	0.093	50	0.26	
Door						
Wood Frame	0.67	--	--	--	--	--
Floor (Over Crawl Space)						
3 1/2" Batt Insulation		0.292	0.0265	3	0.18	
Subfloor	0.074	0.0625	0.064	34	0.29	
Underlayment		0.010	0.083	63	0.33	
Carpet/Padding		0.065	0.050	10	0.34	

TABLE IX. DENVER CHARACTERISTIC LOW-RISE RESIDENCE STRUCTURAL PARAMETERS

Components	"U" Value (Btu/hr-ft^2-°F)	Thickness (ft)	Conductivity (Btu/hr-ft-°F)	Density (lb/ft^3)	Specific Heat (Btu/lb-°F)	"R" Value (hr-ft^2-°F/Btu)
Wall						
Brick Veneer		0.333	0.757	130	0.22	
Insulation Board	0.076	0.042	0.032	18	0.31	
3 1/2" Batt Insulation		0.292	0.0265	3	0.18	
Gypsumboard		0.042	0.093	50	0.26	
Roof						
Built-up Roof		0.031	0.094	70	0.35	
Plywood Sheathing		0.042	0.064	34	0.29	
Air Gap	0.074	--	--	--	--	0.96
3 1/2" Batt Insulation		0.292	0.0265	3	0.18	
Gypsumboard		0.042	0.093	50	0.26	
Door						
Wood Frame	0.67	--	--	--	--	--
Floor						
Concrete Slab	0.10	--	--	--	--	--

TABLE X. DENVER CHARACTERISTIC HIGH-RISE RESIDENCE STRUCTURAL PARAMETERS

Components	"U" Value (Btu/hr-ft²-°F)	Thickness (ft)	Conductivity (Btu/hr-ft-°F)	Density (lb/ft³)	Specific Heat (Btu/lb-°F)	"R" Value (hr-ft²-°F/Btu)
Wall						
Precast Concrete		0.500	0.54	144	0.16	
Rigid Insulation	0.193	0.083	--	--	--	2.78
Air Gap		--	--	--	--	1.01
Gypsumboard		0.042	0.093	50	0.26	
Roof						
Built Up Roof		0.031	0.094	70	0.35	
1 1/2" Rigid Insulation		--	--	--	--	4.17
2" Concrete Deck	0.160	0.167	0.54	144	0.16	
Air Gap		--	--	--	--	0.96
Gypsumboard		0.042	0.093	50	0.26	
Floor						
6" Concrete Deck	0.450	0.500	0.54	144	0.16	
Carpet/Padding		0.065	0.050	10	0.34	

TABLE XI. HEATING AND COOLING LOADS FOR CHARACTERISTIC DENVER RESIDENTIAL STRUCTURES - LOADS ARE GIVEN IN THERMS

Month	Single-Family		Townhouse		Multifamily Low-Rise		Multifamily High-Rise	
	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling
January	246.8	0.0	686.7	0.0	754.6	33.5	12497.5	43.4
February	195.2	0.0	506.1	1.1	593.6	41.6	9759.8	80.6
March	176.3	0.4	443.1	5.0	541.1	59.2	9279.8	88.7
April	117.0	9.8	310.1	48.2	384.3	118.2	6415.3	533.6
May	59.3	30.9	132 3	136.0	177.1	243.1	3090.4	1722.5
June	17.3	76.5	19.3	304.3	24.5	493.0	602.1	4583.9
July	7.5	106.5	5.7	418.2	6.5	678.3	175.3	6792.0
August	4.7	100.3	1.3	416.5	0.4	724.2	53.6	7098.5
September	61.8	28.3	133.7	115.6	122.5	292.4	3016.7	2051.6
October	102.9	8.6	250.6	41.1	261.1	187.3	5117.1	703.1
November	212.2	0.0	568.4	0.4	614.6	44.3	11098.7	66.3
December	277.1	0.0	777.0	0.0	856.1	26.7	14361.9	37.1
Annual Load	1478.1	361.3	3834.3	1486.4	4336.4	2941.8	75468.2	23802.2
Annual Load per Dwelling Unit	1478.1	361.3	479.3	185.8	180.7	122.6	421.6	132.9

PERCENTAGE OF TOTAL ANNUAL HEATING AND COOLING LOADS ATTRIBUTED TO AIR INFILTRATION

	Heating Load	Cooling Load
Single-Family	25	3
Townhouse	47	1
Low-Rise	44	0
High-Rise	43	3

In order to better compare infiltration loads among the four building types, the annual infiltration loads on a per square foot basis are also presented.

TOTAL ANNUAL HEATING AND COOLING INFILTRATION LOADS PER UNIT FLOOR AREA (THERM/SQ FT)

	Heating Load	Cooling Load*
Single-Family	0.20	0.01
Townhouse	0.17	0.00
Low-Rise	0.12	0.00
High-Rise	0.18	0.00

These infiltration loads relate fairly closely to a ratio of building exterior opening area (exterior windows and doors) to building floor area. The single-family structure exhibits the highest exterior opening area to floor area and correspondingly has a high infiltration load per unit floor area. Similarily, the exterior opening area ratio is progressively lower in the townhouse structure and the low-rise structure, with correspondingly decreasing unit floor area infiltration loads. Due to the partial pressurization caused by forced ventilation and higher stack effect, this comparison is not quite valid for the high-rise structure.

2. Calculated Energy Consumption for Heating and Cooling the Characteristic Residences

The energy consumption required to heat, cool, and ventilate the characteristic residences were determined using the previously calculated heating and cooling loads. The heating, cooling, and ventilation equipment used in the residences are described below. For the computation of energy required for cooling, cooling loads were discarded if they occurred in the cold weather period since the simple expediency of opening windows

The infiltration cooling load is small due to fact that, at night, infiltrating cool air balancing the daytime infiltration of warm air; the net effect being no contributed load.

(for entry of cooler outside air) would be a more practical method of meeting these cooling requirements. For both heating and cooling, the thermostat was at 72°F. 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 units of primary energy.

a. Single-Family Detached

Heating - gas fired furnace, forced air system; loads not met between May 20 and September 20; efficiency = 0.7

Cooling - central, electric, forced air system; loads not met between September 20 and May 20; C.O.P. = 1.7

b. Townhouse

Heating - gas fired furnace, forced air system; loads not met between May 20 and September 20; efficiency = 0.7

cooling - central, electric, forced air system; loads not met between September 20 and May 20; C.O.P. = 1.7

c. Low-Rise

Heating - individual gas fired furnaces, forced air system; loads not met between June 10 and September 15; efficiency = 0.7

Cooling - individual electric units; loads not met between September 15 and May 20; C.O.P. = 1.7

d. High-Rise

Heating - central gas fired furnace, hot water system; loads not met between May 20 and September 20; efficiency = 0.7

Cooling - central electric system; loads not met between September 20 and May 20; C.O.P. = 3.2

Detailed analyses of the energy consumed for heating and cooling of the Denver characteristic single-family, townhouse, low-rise, and high-rise residences are shown in Tables XII, XIII, XIV, and XV, respectively. The following data are presented for each residence:

(a) Monthly and annual energy consumption of each major component of the heating, cooling, and ventilation system

(b) Monthly and annual consumption of primary* gas and electric energy used for heating, cooling, and ventilation

(c) Annual average in-structure energy consumption per apartment for each major component of the heating, cooling, and ventilation system

(d) Annual average in-structure energy consumption per square foot of total floor area for each major component of the system

(e) Annual primary energy required per apartment

(f) Annual primary energy required per square foot of total floor area

Annual in-structure and primary energy requirements for the characteristic residences are compared in Table XVI. Comparisons were made for both in-structure and primary energy consumptions based on "per unit," "per square foot of floor area," and "per occupant" consumptions. It should be noted that each basis for comparison normalizes all parameters such as apartment size, number of occupants, and external wall area per unit. When comparing the primary energy consumptions of the residences, the "per unit" consumption for the single-family was the highest, and the low-rise's consumption was the lowest. The ratios of

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**Primary energy is defined as the input energy to generation plants or gas distribution centers; electrical generation was assumed to require 10,910 Btu/Kw-hr consumed within the structure (31 percent thermal efficiency) and gas distribution was assumed to be 97 percent efficient.*

TABLE XII. HEATING AND COOLING ENERGY CONSUMPTION IN THE DENVER CHARACTERISTIC SINGLE-FAMILY RESIDENCE

	Energy Consumption in Therms			Primary Energy in Therms		
Month	Heating	Cooling	Total*	Gas	Electric	Total*
January	352	0	352	363	0	363
February	278	0	278	287	0	287
March	251	0	251	259	0	259
April	167	0	167	172	0	172
May	84	18	102	87	58	145
June	0	45	45	0	145	145
July	0	62	62	0	202	202
August	0	59	59	0	190	190
September	88	16	104	91	53	144
October	147	0	147	151	0	151
November	303	0	303	312	0	312
December	396	0	435	408	0	408
Annual Consumption	2065	200	2265	2130	648	2778
Average Annual Consumption Per Square Foot	1.11	0.10	1.22	0.15	0.35	1.50

Electric energy consumed by furnace fan was negligible compared to total energy consumption so it was not considered.

TABLE XIII. HEATING AND COOLING ENERGY CONSUMPTION IN THE DENVER CHARACTERISTIC TOWNHOUSE

Month	Energy Consumption in Therms			Primary Energy in Therms		
	Heating	Cooling	Total*	Gas	Electric	Total*
January	981	0	981	1011	0	1011
February	723	0	723	745	0	745
March	633	0	633	652	0	652
April	443	0	443	456	0	456
May	189	80	269	195	258	453
June	0	179	179	0	577	577
July	0	246	246	0	793	793
August	0	245	245	0	790	790
September	191	68	259	196	220	416
October	358	0	358	369	0	369
November	812	0	812	837	0	837
December	1110	0	1110	1145	0	1145
Annual Consumption	5440	818	6258	5606	2638	8244
Average Annual Consumption Per Unit	680	102	782	700	329	1030
Average Annual Consumption Per Square Foot	0.51	0.08	0.59	0.53	0.25	0.78

**Electric energy consumed by furnace fan was negligible compared to total energy consumption so it was not considered.*

TABLE XIV. HEATING AND COOLING ENERGY CONSUMPTION IN THE DENVER CHARACTERISTIC LOW-RISE

Month	Energy Consumption in Therms			Primary Energy in Therms		
	Heating	Cooling	Total*	Gas	Electric	Total*
January	1078	0	1078	1111	0	1111
February	848	0	848	874	0	874
March	773	0	773	796	0	796
April	549	0	549	565	0	565
May	253	143	396	260	461	503
June	36	290	326	37	935	972
July	0	399	399	0	1287	1287
August	0	426	426	0	1374	1374
September	175	172	347	180	554	734
October	373	0	373	384	0	384
November	878	0	878	905	0	905
December	1223	0	1223	1260	0	1260
Annual Consumption	6186	1430	7616	6372	4611	10983
Average Annual Consumption Per Unit	257	59	317	265	192	457
Average Annual Consumption Per Square Foot	0.36	0.08	0.44	0.37	0.27	0.64

**Electric energy consumed by furnace fan was negligible compared to total energy consumption so it was not considered.*

TABLE XV. HEATING AND COOLING ENERGY CONSUMPTION IN THE DENVER CHARACTERISTIC HIGH-RISE

Month	Energy Consumption in Therms				Primary Energy in Therms		
	Heating	Cooling	Fans	Total	Gas	Electric	Total
January	17853	0	1161	19014	18405	3745	22151
February	13942	0	1052	14995	14373	3395	17769
March	13256	0	1033	14290	13666	3334	17001
April	9164	0	920	10085	9448	2968	12416
May	4414	538	682	5635	4551	3938	8490
June	0	1432	990	2422	0	7815	7815
July	0	2122	1195	3318	0	10704	10704
August	0	2218	1219	3437	0	11090	11090
September	4309	641	672	5622	4442	4236	8679
October	7310	0	757	8067	7536	2443	9979
November	15855	0	1070	16925	16345	3451	19797
December	20517	0	1235	21752	21151	3984	25135
Annual Consumption	106624	6952	11991	125568	109921	61108	171030
Average Annual Consumption Per Unit	595	38	67	701	614	341	955
Average Annual Consumption Per Square Foot *	0.60	0.04	0.06	0.71	0.62	0.34	0.96

Halls, lobbies, and stairwells included.

TABLE XVI. COMPARISON OF THE ENERGY REQUIREMENTS FOR HEATING AND COOLING THE CHARACTERISTIC DENVER RESIDENCES

Residence Type	In-Structure Energy Consumption in Therms			Primary Energy Consumption in Therms		
	Per Unit	Per Sq Ft of Floor Area	Per Occupant	Per Unit	Per Sq Ft of Floor Area	Per Occupant
Single-Family	2265	1.22	566	2778	1.50	694
Townhouse	782	0.59	196	1030	0.78	257
Low-Rise	311	0.44	124	438	0.62	175
High-Rise	701	0.71	280	955	0.96	382

areas* for individual units in the single-family, townhouse, low-rise, and high-rise were 1.00, 0.71, 0.38, and 0.53, whereas the corresponding ratios for "per unit" primary energy consumption were 1.00, 0.37, 0.16, and 0.34. The dissimilarity of the above two groups of ratios shows that the differences in energy consumption "per unit" cannot be attributed only to differences in floor area.

When comparing the energy consumption of the Denver residences on the basis of floor area, the single-family residence had the highest in-structure and primary energy consumption and the low-rise had the lowest.

When comparing the primary energy consumption of the residences on the basis of number of occupants, the low-rise had the lowest and the single-family had the highest consumption per occupant. The number of occupants for the various residences were defined as four per single-family unit, four per townhouse, two and one-half** per low-rise apartment, and two and one-half per high-rise apartment. The above occupancy density was assumed as reasonable based on the number of bedrooms per residence. Any change in the above occupancy densities could have a marked effect on the relative consumption of energy per occupant.

**In the high-rise residence, the hall, lobby, and stairwell floor areas were assigned in equal portions to each dwelling unit.*

***This figure is an average based on the total number of occupants and dwelling units per building.*

V. ENERGY CONSUMPTION OF IMPROVED DENVER RESIDENCES

Heating and cooling loads and energy consumptions were calculated for improved versions of the single-family detached, townhouse, low-rise, and high-rise structures. The basis for selection of improvements was that they must provide reduction of primary energy consumed for heating, cooling, and ventilation; be currently technically feasible; and not restrict the life-styles of the residents. Improvements considered for inclusion in the improved residences included structural modifications and changes in the comfort control systems.

A. Definition of Improved Residences

The improved residences included changes designed to reduce energy consumption attributed to windows, walls, roofs, floors, infiltration, direct solar radiation, heating systems, cooling systems, and ventilation systems.

1. Structural Modifications

The structural modifications selected for the improved versions of the characteristic single-family, townhouse, low-rise, and high-rise were as follows:

(a) 25 percent reduction of window area

(b) Addition of weatherstripping to reduce infiltration

(c) Increase the thermal resistance ("R" value) of the ground floor, walls, and roof insulation as follows:

	Ground Floor	Walls	Roof
Single-family	11	17	27
Townhouse	11	17	27
Low-Rise	11	17	27
High-Rise	11	12	17

(d) Storm windows or double glazing were added to all residences except the townhouse, which already had them.

All other structural, design, and internal load parameters previously defined for the characteristic residences remained unchanged.

2. System Modifications

The system modifications selected for the improved versions of the characteristic residences were as follows: add a heat recovery device to the furnace and improve heating efficiency and cooling C.O.P. as in the table below:

(a) Improved Single-Family Detached

Heating efficiency = 0.83

Cooling C.O.P. = 2.7

(b) Improved Townhouse

Heating efficiency = 0.83

Cooling C.O.P. = 2.7

(c) Improved Low-Rise

Heating efficiency = 0.83

Cooling C.O.P. = 2.7

(d) Improved High-Rise

Heating efficiency = 0.78

Cooling C.O.P. = 3.2

These improvements were summarized in table form in Table II.

B. Calculation of Loads and Energy Consumption of Improved Residences

The computation methods used for evaluating the modified residences were the same as those used for calculating the loads and energy consumption of the characteristic residences; that is, the hourly loads and energy consumption were calculated for the full weather year using the computer program described in Chapter III, and the only changes in the computations were those required to model the respective modifications.

Monthly and annual heating and cooling loads for the modified single-family, townhouse, low-rise, and high-rise structures are delineated in Table XVII. Annual loads are also given for the average dwelling unit within each type of structure. Detailed analyses of the energy consumed for heating and cooling of the modified Denver structures are shown in Tables XVIII, XIX, XX, and XXI. These analyses included computation of monthly and annual in-structure energy consumption for heating, cooling, and ancillaries; monthly and annual primary energy consumption by type of energy; annual energy consumption per average dwelling unit; and annual average energy consumption per unit floor area.

Annual in-structure and primary energy consumption for the modified residences are compared in Table XXII. Useful comparisons may also be drawn between these results and the analogous results for the Denver characteristic residences, shown previously in Table XVI.

Comparison of the primary energy consumption of the improved Denver residences (Table XXII), shows the following:

(1) In terms of primary energy per dwelling unit, the townhouse units used the least, followed by the low-rise, high-rise, and single-family, in that order.

(2) In terms of primary energy per unit floor area, the low-rise used the least energy, followed by the townhouse then by the single-family, and finally by the high-rise.

(3) In terms of primary energy per occupant, the townhouse (four occupants) again used the least energy, followed by the low-rise (two and one-half occupants), the high-rise (two and one-half occupants) and the single-family (four occupants), in that order. As previously stated, however, this measure is highly dependent on the number of occupants assumed per dwelling unit and is limited in usefulness as a metric for comparison.

TABLE XVII. HEATING AND COOLING LOADS FOR IMPROVED DENVER RESIDENTIAL STRUCTURES - LOADS ARE GIVEN IN THERMS

Month	Single-Family		Townhouse		Multifamily Low-Rise		Multifamily High-Rise	
	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling
January	91.4	0.0	339.6	0.3	338.7	71.6	5,719.0	175.5
February	70.1	0.0	238.0	5.7	283.3	85.0	4,327.5	254.4
March	59.9	0.7	198.2	15.8	249.0	115.5	3,992.2	336.4
April	35.6	7.5	136.1	58.2	169.0	170.8	2,649.3	861.8
May	13.6	22.7	48.4	143.8	69.9	295.2	1,109.2	2,217.1
June	1.7	50.0	3.4	268.2	8.1	480.8	165.3	4,370.8
July	0.3	68.2	0.5	345.3	0.4	615.6	39.8	5,930.5
August	0.0	67.9	0.0	348.3	0.0	659.0	11.9	6,285.4
September	13.7	20.5	44.1	122.3	29.5	349.2	1,109.8	2,003.7
October	27.9	6.8	100.3	56.8	79.1	252.7	1,989.2	1,001.6
November	75.7	0.0	271.8	5.2	270.4	89.6	5,034.4	204.4
December	104.9	0.0	394.9	1.2	416.9	66.9	6,827.4	147.5
Annual Load	494.8	244.3	1775.3	1371.1	1914.3	3251.9	32,975.0	23,889.1
Annual Load per Dwelling Unit	494.8	244.3	221.9	171.4	79.7	135.5	184.2	133.4

TABLE XVIII. HEATING AND COOLING ENERGY CONSUMPTION IN THE DENVER IMPROVED SINGLE-FAMILY RESIDENCE

	Energy Consumption in Therms			Primary Energy in Therms		
Month	Heating	Cooling	Total*	Gas	Electric	Total*
January	110.1	0.0	110.1	113.5	0.0	113.5
February	84.4	0.0	84.4	87.0	0.0	87.0
March	72.1	0.0	72.1	74.3	0.0	74.3
April	42.9	0.0	42.9	44.2	0.0	44.2
May	16.4	8.4	24.8	16.9	27.0	43.9
June	0.0	18.5	18.5	0.0	59.7	59.7
July	0.0	25.2	25.2	0.0	81.3	81.3
August	0.0	25.1	25.1	0.0	80.9	80.9
September	16.5	7.6	24.1	17.0	24.5	41.5
October	33.6	0.0	33.6	34.6	0.0	34.6
November	91.2	0.0	91.2	94.0	0.0	94.0
December	126.4	0.0	126.4	130.3	0.0	130.3
Annual Consumption	593.6	84.8	678.4	611.8	273.4	885.2
Average Annual Consumption Per Square Foot	0.32	0.04	0.36	0.33	0.15	0.48

Electric energy consumed by furnace fan was negligible compared to total energy consumption so it was not considered.

TABLE XIX. HEATING AND COOLING ENERGY CONSUMPTION IN THE DENVER IMPROVED TOWNHOUSE

	Energy Consumption in Therms			Primary Energy in Therms		
Month	Heating	Cooling	Total*	Gas	Electric	Total*
January	409.1	0.0	409.1	421.6	0.0	421.6
February	286.7	0.0	286.7	295.5	0.0	295.5
March	238.8	0.0	238.8	246.2	0.0	246.2
April	163.9	0.0	163.9	168.9	0.0	168.9
May	58.3	53.2	111.5	60.1	171.6	231.7
June	0.0	99.3	99.3	0.0	320.3	320.3
July	0.0	127.9	127.9	0.0	412.6	412.6
August	0.0	129.0	129.0	0.0	416.1	416.1
September	53.1	45.3	98.4	54.7	146.1	200.8
October	120.8	0.0	120.8	124.5	0.0	124.5
November	327.4	0.0	327.4	337.5	0.0	337.5
December	475.8	0.0	475.8	490.5	0.0	490.5
Annual Consumption	2133.9	454.7	2588.6	2199.5	1466.7	3666.2
Average Annual Consumption Per Unit	266.7	56.8	274.9	274.9	183.3	458.3
Average Annual Consumption Per Square Foot	0.20	0.04	0.24	0.20	0.14	0.35

**Electric energy consumed by furnace was negligible compared to total energy consumption so it was not considered.*

TABLE XX. HEATING AND COOLING ENERGY CONSUMPTION IN THE DENVER IMPROVED LOW-RISE

Month	Energy Consumption in Therms			Primary Energy in Therms		
	Heating	Cooling	Total*	Gas	Electric	Total*
January	408.0	0.0	408.0	420.6	0.0	420.6
February	341.3	0.0	341.3	351.8	0.0	351.8
March	300.0	0.0	300.0	309.3	0.0	309.3
April	203.6	0.0	203.6	209.9	0.0	209.9
May	84.2	109.3	193.5	86.8	352.6	439.4
June	0.0	178.0	178.0	0.0	574.2	574.2
July	0.0	228.0	228.0	0.0	735.5	735.5
August	0.0	244.0	244.0	0.0	787.0	787.0
September	35.5	129.3	164.8	36.6	417.0	453.6
October	93.5	0.0	95.3	98.2	0.0	98.2
November	325.8	0.0	325.8	335.9	0.0	335.9
December	502.3	0.0	502.3	517.8	0.0	517.8
Annual Consumption	2296.0	888.6	3184.6	2360.9	2866.3	5233.2
Average Annual Consumption Per Unit	95.6	37.9	132.7	98.6	119.4	218.0
Average Annual Consumption Per Square Foot	0.13	0.05	0.18	0.14	0.17	0.30

**Electric energy consumed by furnace fan was negligible compared to total energy consumption so it was not considered.*

TABLE XXI. HEATING AND COOLING ENERGY CONSUMPTION IN THE DENVER IMPROVED HIGH-RISE

Month	Energy Consumption in Therms				Primary Energy in Therms		
	Heating	Cooling	Fans	Total	Gas	Electric	Total
January	7,332.0	0.0	869.3	8,201.3	7,558.7	2,804.2	10,362.9
February	5,548.0	0.0	740.5	6,288.5	5,719.6	2,388.7	8,108.3
March	5,118.2	0.0	807.9	5,926.1	5,276.5	2,606.1	7,882.6
April	3,396.5	0.0	628.2	4,024.7	3,501.5	2,026.4	5,527.9
May	1,422.0	692.8	583.1	2,697.9	1,465.9	4,115.9	5,581.7
June	00.0	1,365.0	974.4	2,340.3	0.0	7,549.3	7,549.3
July	0.0	1,853.3	1,128.6	2,981.9	0.0	9,619.0	1,619.0
August	0.0	1,964.2	1,156.3	3,120.5	0.0	10,066.1	10,066.1
September	1,421.9	626.1	631.7	2,679.7	1,465.9	4,057.4	5,523.3
October	2,550.2	0.0	625.6	3,175.8	2,629.0	2,018.0	4,647.0
November	6,454.3	0.0	817.7	7,272.0	6,653.9	2,637.7	9,291.6
December	8,753.0	0.0	908.7	9,661.7	9,023.7	2,931.3	11,955.0
Annual Consumption	41,996.1	6,502.3	9,872.6	58,371.0	43,294.7	52,820.0	96,114.7
Average Annual Consumption Per Unit	234.6	36.3	55.1	326.0	241.8	295.0	536.9
Average Annual Consumption Per Square Foot*	0.24	0.03	0.05	0.33	0.24	0.30	0.54

*Halls, lobbies and stairwells included.

TABLE XXII. COMPARISON OF THE ENERGY REQUIREMENTS FOR HEATING AND COOLING THE IMPROVED DENVER RESIDENCES

Residence Type	In-Structure Energy Consumption in Therms			Primary Energy Consumption in Therms		
	Per Unit	Per Sq Ft of Floor Area*	Per Occupant	Per Unit	Per Sq Ft of Floor Area*	Per Occupant
Single-Family	678	0.36	170	885	0.48	221
Townhouse	323	0.24	81	183	0.35	46
Low-Rise	133	0.18	53	218	0.30	87
High-Rise	326	0.33	130	537	0.54	215

*Floor area includes halls, stairwells and lobbies in multifamily dwellings.

VI. REFERENCES

1. "Local Climatological Data; Denver, Colorado," National Oceanic and Atmospheric Administration, National Climatic Center, Ashville, NC, 1974.

2. "Annual Survey of Housing," HUD/DOC, 1974.

3. "Builder Practices: A National Survey of Characteristics and Construction Practices for All Types of One-Family Houses," NAHB Research Foundation, Inc., Rockville, MD, prepared for the National Association of Home Builders, Washington, DC, February 1974.

4. "Solar Heating and Cooling of Buildings, Volume II," Westinghouse Electric Corporation, Special Energy Systems, Baltimore, MD, prepared for the National Science Foundation, Washington, DC, May 1974.

5. "Solar Heating and Cooling of Buildings, Volume III," General Electric Corporation, Space Division, Valley Forge, Pennsylvania, prepared for the National Science Foundation, Washington, DC, May 1974.

6. <u>Standard Handbook for Civil Engineers</u>, F.S. Merritt, ed., McGraw-Hill Book Co., New York, NY, 1968.

7. <u>Building Construction Handbook</u>, F.S. Merrit, ed., McGraw-Hill Book Co., New York, NY, 1958.

8. "Residential Energy Consumption - Single-Family Housing Final Report," Report No. HUD-HAI-2, Hittman Associates, Inc., Columbia, MD, prepared for the U.S. Department of Housing and Urban Development, Contract No. H-1654, March 1973.

9. <u>Statistical Abstract of the United States</u>, 1974, U.S. Department of Commerce, Social and Economic Statistics Administration Bureau of the Census, U.S. Government Printing Office, Washington, DC, 1974.

10. "Residential Energy Conservation Summary Report," Report No. HUD-HAI-8, prepared for the Office of Policy Development and Research, U.S. Department of Housing and Urban Development, Contract No. H-1654, by Hittman Associates, Inc., Columbia, MD, July 1974.

11. Private communication, Mr. Donald F. Spear, NAHB Research Foundation, Inc., Rockville, MD, December 3, 1975.

12. Survey of Builder Practices for Single-Family, Townhouse, and Low-Rise Residences (unpublished), by NAHB Research Foundation Inc., Rockville, MD, prepared for Housing Industry Dynamics, Inc., Philadelphia, PA, 1975.

13. "Residential Energy Consumption - Multifamily Housing Data Acquisition," Report No. HUD-HAI-3, Hittman Associates, Inc., Prepared for the U.S. Department of Housing and Urban Development, Contract No. H-1654, October 1972.

14. "Residential Energy Consumption Multifamily Housing - Final Report," Report No. HUD-HAI-4, prepared for the Office of Policy Development and Research, U.S. Department of Housing and Urban Development, Contract No. H-1654, by Hittman Associates, Inc., June 1974.

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