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Computer Analysis of Energy Requirements in Single-Family Residences: A Limited Case Study of the Effects of Envelope Design

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ABSTRACT

A number of design variations of a typical one-story single-family residence were analyzed to determine annual heating and cooling energy requirements. The National Bureau of Standards Load Determination computer program, NBSLD, was used to accomplish the analysis. Design details for each of the residence variations are described in detail. Annual heating and cooling energy requirement calculations are presented and discussed. The results show only a small dependence on the thermal mass of the building envelope for the two climates studied (Washington, D.C. and Orlando, Florida). The thermal properties of the windows had greater effect. Concluding the report are technical generalizations based on the present study, and recommendations for further work in order to produce a definitive study of the effect of selected building design parameters on energy consumption.

Key Words: Building energy consumption analysis; computerized building energy analysis; cooling load calculation; energy conservation; heating load calculation ; NBSLD analysis of residences; residential energy conservation; thermal mass effect in buildings.

FOREWORD

The work detailed in this report was initiated as an ad hoc task for the Department of Housing and Urban Development several years ago, and was presented to the sponsor in preliminary form for their immediate use. It is reported here as useful background for current work at the National Bureau of Standards and the Department of Housing and Urban Development, and the data cited are still correct, but it does not represent the present state of the art with regard to the effect of thermal mass on building energy performance.

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COMPUTER ANALYSIS OF ENERGY REQUIREMENTS IN SINGLE-FAMILY RESIDENCES: A LIMITED CASE STUDY OF THE EFFECTS OF ENVELOPE DESIGN

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1. INTRODUCTION

As part of the overall national energy policy, the identification and development of practices and techniques which conserve energy in residences will play a significant role. Methods for widespread implementation of such techniques would be used to accomplish national energy conservation goals. For example, energy conservation practices and techniques would be incorporated in federally developed model building codes for energy performance.

At the specific request of the Office of Policy Development and Research of the Department of Housing and Urban Development (HUD), the National Bureau of Standards was asked to examine the effect of variations of certain building design parameters, particularly envelope construction, on the energy performance of typical single-family residences. The purpose of the task was to provide HUD with sufficiently accurate information on the energy performance of such a residence that they could determine the reasonableness of insulation requirements which were proposed as revisions of the FHA Minimum Property Standards for single-family housing. The NBS response constituted an ad hoc task, aimed at accomplishing limited goals which would satisfy HUD needs for information in a responsive time interval.

To meet HUD needs, it was decided to use the NBS load determination computer program, NBSLD, to calculate monthly and annual space heating and cooling loads for several variations of a typical single-family residence. While the basic geometry and orientation of the one-story structure were kept constant, limited variations were made of certain parameters, namely the relative area and U-values* of the windows, the U-values and mass of the walls (roughly corresponding to wood-frame and masonry construction), and the weather data used. The report is thus not intended to be either a definitive or a systematic study of all building design parameters which could affect the energy performance of a residence. Subsequent sections of the report describe in detail the analysis methodology, define the house models analyzed, and present the results which were obtained and their significance. Concluding the

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* The U factor of a wall component is the overall conductance from interior air to exterior air. It includes the conductance of the solid part of the component and also accounts for the effect of air film heat transfer on the inside surface.

report are technical generalizations based on the present study, and recommendations for further work which would be necessary to produce a definitive, systematic study of selected parameters which affect energy consumption.

2. RESIDENCE MODELS

2.1 BASIC DESIGN

All analyses were accomplished using variations on a one-story, rectangular house model (see Figure 1). The model typifies the "rambler" or ranch-house design common in the residential construction industry. The basic design included a peaked roof with a naturally ventilated attic and unheated basement. Windows were located in all four walls. Since the house interior was modeled as a single thermal zone, details of the interior structural design of the house were not needed and were, therefore, not developed. Interior heat sources such as the heat released from lights, appliances, and occupants were considered. Overall floor area was approximately 110 m^2 (more precise values are given subsequently).

A complete, detailed description of all parameters used in the various models can be conveniently divided into two broad categories: those parameters which remained fixed throughout all analyses, and those which were changed. Table 1 lists the parameters that fall into each of these categories. The subsequent sections of this report and supporting tables contain details of the values for each of these parameters.

It is important to point out that due to input limitations of the thermal loads analysis computer program NBSLD (or any other program, for that matter), it is sometimes necessary to make appropriate assumptions to convert a particular physical design to that set of inputs which will correctly represent the thermal model for that design. When done properly, the conceptual model will "behave" during the computer analysis just as the actual structure would in real life, subject to the same environmental conditions. In this particular effort, such assumptions had to be made to model the roof, the attic, and the unheated basement. Although the subsequent descriptions of those components of the design might appear to be physically different, they are modeled so that they would behave thermally as would the actual physical design.

In all cases, the values of parameters were chosen to be typical of those encountered for actual materials and designs for this type of house. Many of the final choices were based on constraints placed by the sponsor. Where possible, recognized sources such as ASHRAE published data were used. No attempt was made, however, to define or quantify the nature of the typicality concept, or the normal range of variation of parameters encountered in actual construction of this type.

It should be noted that not all aspects of the design of the residences used in this study are optimal, with regard to energy consumption. The

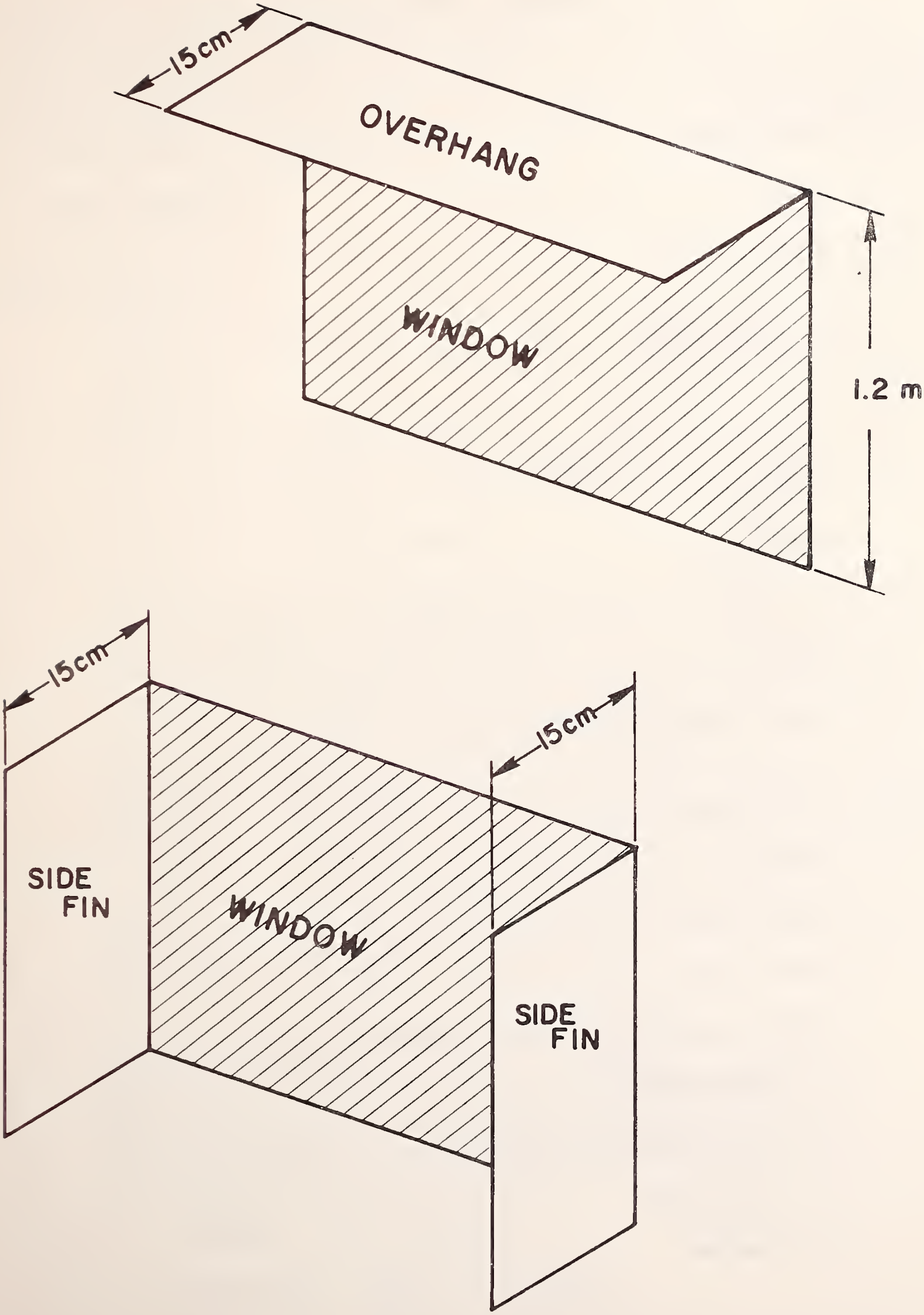

Figure 1. Basic house design used for energy analysis.

Table 1. Parameter Summary List

Fixed Parameters

1. Orientation

2. Interior Air Design Conditions

3. Interior Loads

   a. Lighting
   b. Appliances
   c. Occupants

4. Attic/Roof Design

5. Thermophysical Properties

   a. Roof
   b. Ceiling
   c. Floor
   d. Door

6. Basement

7. Window Shading Devices

Variable Parameters

1. Weather

2. Aspect Ratio

3. Window Area

4. Window Type/Thermophysical Properties

5. Air Infiltration

6. Wall Thermophysical Properties

   a. Wood Frame
   b. Masonry
   c. Massless

house orientation, assumptions regarding internal loads, thermostat settings, and infiltration rates, and some other aspects of the design could probably have used better assumptions or design choices. In all instances where this might be the case, the values used in this study were those requested by the sponsor, in order to guarantee comparability of these results with other studies.

2.2 FIXED PARAMETERS

Detailed descriptions of the fixed parameters are presented in the order shown in Table 1.

1. Envelope Orientation: Long axis parallel to north-south direction.

2. Interior Air Design Conditions:

   Winter (October-March): 70°F, 20% rh mininum;

   Summer (April-September): 75°F, 60% rh maximum;

   Except for two test cases, NBSLD computed the load each hour that was required to maintain the interior air temperature at exactly the value specified above. Thus, there could be instances in the winter where an abnormally high outdoor air temperature, combined with interior heat generation, could cause a net cooling load. Analogously, heating loads could occur during the summer season. The relative humidity was allowed to float above the minimum limit in the winter, and below the maximum limit in the summer. A lower energy requirement would have resulted if the interior room temperature had been constrained to a band within the range of 70°F to 75°F, with heating or cooling required only to satisfy those constraints. Also, no attempt was made to provide ventilation air to reduce cooling loads during those hours when the outside air temperature would have made it possible.

3. Interior Loads: Three types of interior energy sources, all of which were heat-producing, were considered in the analysis. They are listed below, along with corresponding minimum and maximum values. Additionally, the values for each of these interior loads changed between the stated limits hourly according to the schedules shown in Table 2.

   Lighting: 0 to .079 W/m^2

   Appliances: .0056 to .0557 W/m^2

   Occupants: 1.5 to 5 persons. Each person contributes 132 W to the sensible heat gain in the space, and 132 W to the latent heat gain.

Table 2. Hourly Schedules for Interior Load Sources

Hour	Lighting W/m^2	Lighting (w/ft^2)	Appliances W/m^2	Appliances w/ft^2	Occupancy (# persons)
1	0		.0056	(.06)	5
2	0		.0056	(.06)	5
3	0		.0056	(.06)	5
4	0		.0056	(.06)	5
5	0		.0056	(.06)	5
6	0		.0056	(.06)	5
7	.03161	(.34)	.0167	(.18)	5
8	.0474	(.51)	.0223	(.24)	5
9	.0316	(.34)	.0223	(.24)	4
10	.0158	(.17)	.0223	(.24)	3
11	0		.0223	(.24)	2.5
12	0		.0223	(.24)	1.5
13	0		.0223	(.24)	1.5
14	0		.0446	(.48)	1.5
15	0		.0446	(.48)	1.5
16	.0158	(.17)	.0446	(.48)	1.5
17	.0474	(.51)	.0446	(.48)	2.5
18	.0632	(.68)	.0557	(.6)	5
19	.0790	(.85)	.0557	(.6)	5
20	.0790	(.85)	.0557	(.6)	5
21	.0790	(.85)	.0557	(.6)	5
22	.0632	(.68)	.0111	(.12)	5
23	.0316	(.34)	.011	(.12)	5
24	.0316	(.34)	.0056	(.06)	5

4. Attic/Roof Design

The house was designed with a peaked roof (peak parallel to length) approximately 2 m high with 30 cm overhangs on the east and west sides. The attic thus enclosed was naturally vented. Two air changes per hour were assumed. Although the areas were correctly modeled, NBSLD does not account for the changed sun angles on a peaked roof, but rather assumes roofs are flat.

5. Thermophysical Properties: The roof and floor were assigned a fixed set of thermophysical properties based on their layered construction. For each layer, the thermal conductivity, density, specific heat, and thickness were specified. These values are shown in Table 3. The ceiling was assumed to be simply a thermal transfer medium with no thermal mass and a conductance of .28 $W/m^2{\cdot}K$ (.05 $Btu/hr{\cdot}ft^2{\cdot}°F$). Similarly, the single door located in the east wall was assumed to have an area of 1.67 m^2 (18 ft^2), a U value of 3.12 $W/m^2{\cdot}K$ (.55 $Btu/hr{\cdot}ft^2{\cdot}°F$) and no thermal mass.

6. Basement: Although the actual basement design was assumed to be an unheated space under the whole house, this cannot be input directly into NBSLD. The substitute thermal model chosen was therefore a special form of a slab-on-grade structure directly beneath the floor construction. The floor construction consisted of layers of carpet, felt, 1.6 cm (5/8-inch) plywood, 1.9 cm (3/4-inch) subfloor, and R7 insulation. Below that was a layer of insulation ($R=00.176Km^2/W$) and finally a 15 cm (6-inch) layer of sand and gravel. Experience with NBSLD has shown this type of model to given reasonable results for the heat transfer through the floor.

7. Window Shading Devices: Awning-like devices were assumed to shade each of the window areas. NBSLD accepts geometrical input based on the design shown in Figure 2. Actual dimensions for the geometry are also shown in the figure. No allowance was made for the possibility of different shading in the summer and winter.

2.3 VARIABLE PARAMETERS

1. Weather: Actual hourly weather data for a one-year period and for two specific locations were used in this analysis. The respective locations and calendar years used were Washington, D.C., 1954, and Orlando, Florida, 1957.* Hourly data required

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*Neither of these years are ASHRAE selected test reference years. It is also not known how typical or representative those weather years are, since no analysis of weather data characteristics was made.

Table 3. Thermophysical Properties of Fixed House Envelope Components

Component/ Sublayer	Thickness cm	(in)	Thermal Conductivity $W/m \cdot K$	$(Btu/hr \cdot ft \cdot °F)$	Density kg/m^3	(lb/ft^3)	Specific Heat $J/kg \cdot K$	$(Btu/lb \cdot °F)$
Roof:								
Asphalt Shingles	.64	(1/4)	.38	(.22)	801	(50)	1256	(.30)
Plywood	1.27	(1/2)	.16	(.09)	545	(34)	1591	(.38)
Floor:								
Carpet	.64	(1/4)	.12	(.07)	320	(20)	879	(.21)
Felt = thermal resistance = .02 $m^2 \cdot K/W$ (.06 $ft^2 \cdot °F \cdot hr/Btu$)								
Plywood	1.59	(5/8)	.16	(.09)	545	(34)	1591	(.38)
Subfloor	1.91	(3/4)	.16	(.09)	545	(34)	1591	(.38)
R-7 insulation	6.13	(2/4)	.052	(.03)	80	(5)	1256	(.3)
Airspace = thermal resistance = .18 $m^2 \cdot K/W$ (1 $ft^2 \cdot °F \cdot hr/Btu$)								
Sand/Gravel	15.2	(6)	.35	(.2)	1602	(100)	1675	(.4)

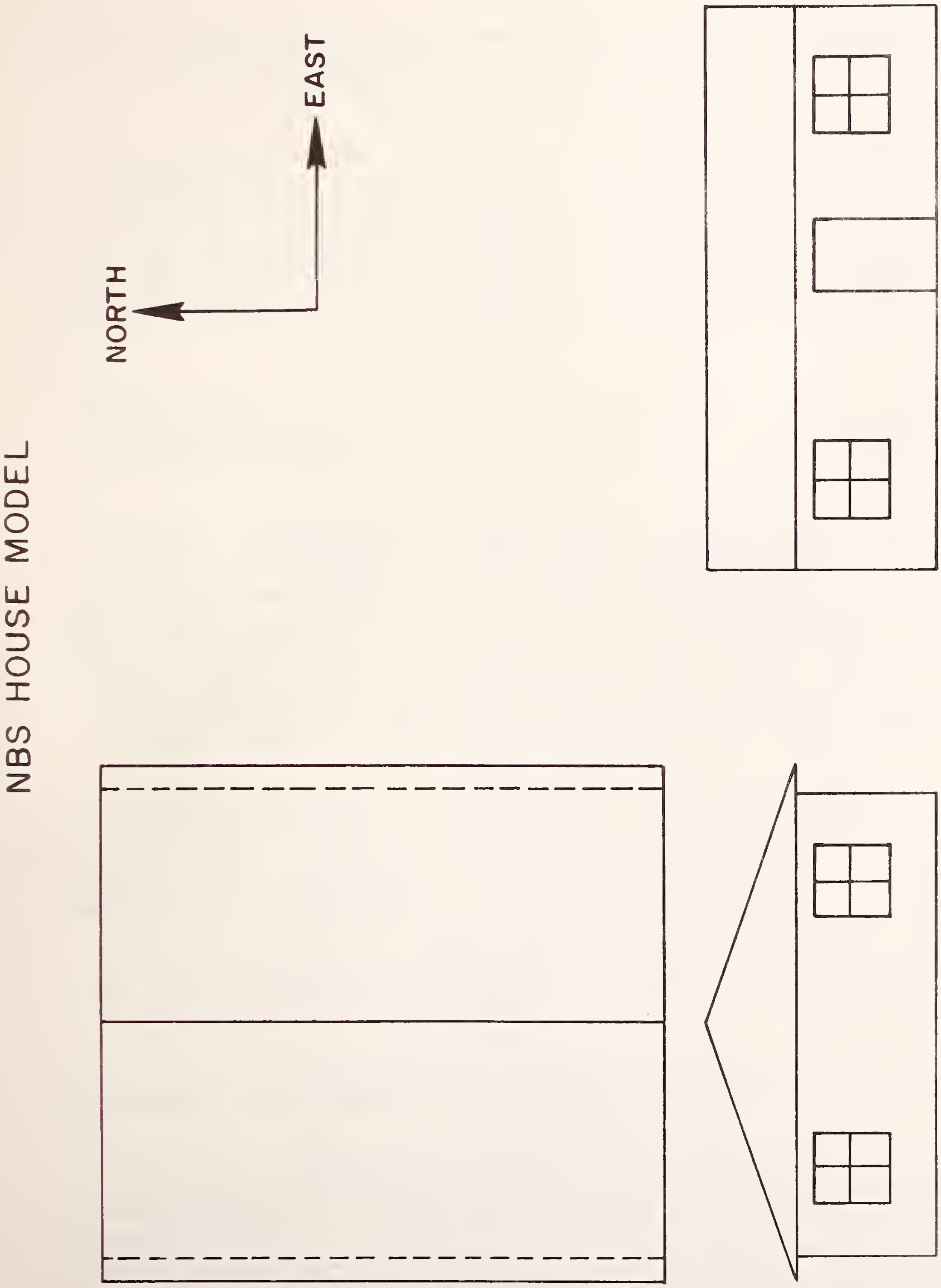

Figure 2. Geometry and dimensions of window-shading devices used in this report.

by NBSLD for an analysis include dry-bulb temperature, wet-bulb temperature, dewpoint temperature, wind speed, barometric pressure, cloud-cover index, and type of cloud cover.

2. Aspect Ratio/Wall Geometry: All walls were 2.44 m (8 ft) in height. Two different geometries were used in the various analyses performed. One assumed a house width of 8.54 m (28 ft) and length of 13.41 m (44 ft), giving an enclosed floor area of 114.6 m^2 (1232 ft^2) and an aspect ratio (width/length) of .64. The other assumed a width of 10.58 m (34.7 ft) and a length of 11.98 m (39.3 ft), giving an area of 126.8 m^2 (1364 ft^2) and an aspect ratio of .88.

3. Window Area: The total window area was, in all cases, approximately 19.7 m^2 (212 ft^2). The actual distribution on each wall varied slightly in some cases, and is described in detail in Table 4.

4. Window Type: Two types of windows were considered. Single-glazed windows were assumed to have a maximum U value of about 6.2 $Wm^{2} \cdot K$ (1.10 $Btu/hr \cdot ft^{2} \cdot {}^{\circ}F$). Storm windows were assumed to have a maximum U value of 3.7 $W/m^{2} \cdot K$ (0.65 $Btu/hr \cdot ft^{2} \cdot {}^{\circ}F$). The maximum in each assumed an exterior surface air film heat transfer coefficient based on a 6.7 m/s (15 mph) wind speed. For a particular hour, the U value varied based on the actual wind speed at that time. The value was computed by NBSLD using actual weather data for wind speed.

5. Air Infiltration: The air infiltration rate is calculated by NBSLD on an hourly basis. The value is dependent on the wind speed at the particular time, and is scaled from a maximum value specified as input to the program. In this effort, the maximum value was assumed to be dependent only on the type of window used in a particular model configuration. Maximum values assumed in this study were 1.5 air changes/hour associated with single glazing and 1.3 air changes/hour associated with storm windows.

   Additionally, there was assumed to be no mechanical ventilation for any of the cases studied.

6. Thermophysical Properties - Walls: Three general types of wall construction were considered in this study. The first two were layered constructions which were intended to be typical of wood-frame and masonry designs found in current residential construction. The details of the thermophysical properties of these constructions are presented in Table 5. Note that the variation in overall U value for these constructions was due only to a variation in the thickness of the insulating layer for each

Table 4. Varying Aspect Ratio and Window Distribution Comparison

	North (South) Walls	East Wall	West Wall	Total House
Case I				
Window	5.1 (55) [20%]+	3.7 (40) [18.5%]*	5.8 (62) [20%]	19.7 (212) [19.5%]*
Wall	20.4 (220)	23.8 (256)	23.4 (252)	60.2 (948)
Door	0 (0)	1.7 (18)	0 (0)	1.7 (18)
Total	25.5 (275)	29.2 (314)	29.2 (14)	109.4 (1178)
Case II				
Window	5.1 (55) [24.5%]	3.7 (40 [15.6%]*	5.8 (62) [17.6%]	19.7 (212) [20%]*
Wall	15.7 (169)	27.3 (294)	26.9 (290)	85.7 (922)
Door	0 (0)	1.7 (18)	0 (0)	1.7 (18)
Total	20.8 (224)	32.7 (352)	32.7 (352)	107.0 (1152)
Case III				
Window	4.2 (44.8) [20%]	4.9 (52.4) [20%)*	6.5 (70.4) [20%]	19.7 (212.4) [20%]*
Wall	16.6 (179.2)	26.2 (281.6)	26.2 (281.6)	85.6 (921.6)
Door	0 (0)	1.7 (18)	0 (0)	1.7 (18)
Total	20.8 (224)	32.7 (352)	32.7 (352)	107.0 (1152)

+ Numbers in brackets are percentage ratios of window area to total wall area.

* Door area included.

Table 5. Thermophysical Properties of Wall Components

Component/ Sublayer	Thickness		Thermal Conductivity		Density		Specific Heat	
	cm	(in)	W/m·K	(Btu/hr·ft·°F)	kg/m^3	(lb/ft^3)	J/kg·K	(Btu/lb·°F)
Wood-frame wall:								
Shiplap siding	2.54	(1)	.12	(.07)	641	(40)	2512	(.6)
Sheathing	1.27	(1/2)	.05	(.03)	288	(18)	1298	(.31)
Insulation	variable		.043	(.025)	9.6	(.6)	754	(.18)
Gypsum board	1.27	(1/2)	.17	(.1)	801	(50)	837	(.2)
Masonry wall:								
Concrete block (aircore)	20.3	(8)	.66	(.38)	961	(60)	754	(.18)
Insulation	variable		.05	(.03)	80	(5)	1256	(.3)
Gypsum board	1.27	(1/2)	.73	(.42)	801	(50)	837	(.2)

construction type. All other parameters and properties were held constant. Table 6 summarizes the calculated U value as a function of insulation thickness for wood-frame and masonry wall types.

The third type of wall was a hypothetical heat-transfer medium represented by only a thermal conductance or U factor and having no thermal mass effect.

Summarizing this section, Table 7 shows how all the variable parameters described above were combined to form the actual test configurations analyzed in this study. A total of 22 different variations were analyzed. Results of the analyses performed on each of the combinations are discussed in detail in Section 4 of this report.

3. ANALYSIS METHODOLOGY

In order to evaluate the relative performance of the various test cases, a single indicator of energy performance was chosen. That indicator was the net hourly interior space thermal load for heating and cooling. The hourly loads were summed for each month and for the year to obtain cumulative heating and cooling requirements for those periods. Heating and cooling systems were not modeled, and subsequently actual energy consumption required to satisfy the computed cumulative load by real equipment was not obtained. For the purpose of this effort, i.e., determining the relative performance of various residential envelope designs, the cumulative heating and cooling loads are a sufficient performance indicator.

3.1 LOAD CALCULATIONS

Net hourly heating or cooling loads were computed using ASHRAE-recommended response-factor load calculation methodology [1]* by means of the National Bureau of Standards Load Determination Program, NBSLD [2]. NBSLD computes the dynamic thermal behavior of a building due to external weather and solar insolation data, and also based on hourly summations of internal heat gains due to lighting, appliances, occupants, etc. Hourly loads are calculated based on all of these factors and a specification of the interior temperature and humidity conditions of the room. These specifications may be either fixed single values or a range of allowable values. For this effort, all except two test cases were analyzed using a single fixed value of temperature and an allowable range of humidity. The values were different for winter and summer periods, as described in the previous section. The two exceptions assumed an acceptable interior temperature band from 21°C to 23.9°C (70°F to 75°F).

The program also includes a routine which can calculate the actual interior temperature as it floats from hour to hour in the case that no heating and/or cooling (or a limited amount) is supplied to satisfy the net load. This option was not used in the present study.

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* Numbers in brackets refer to references in Section 6 of this report.

Table 6. Calculated U for Different Wall Types

Wall Type	Insulation Thickness		U Value	
	cm	(in)	$W/m^2 \cdot K$	$(Btu/hr \cdot ft^2 \cdot °f)$
Masonry	2.54	(1)	1.05	(.185)
"	3.70	(1.458)	.082	(.150)
"	6.35	(2.5)	.596	(.105)
Wood Frame	5.59	(2.2)	.573	(.101)
" "	6.30	(2.48)	.522	(.092)
" "	8.89	(3.5)	.369	(.065)
"Hypothetical"	-	-	.568	(.100)

Table 7. Parametric Configurations

Weather	Geometry Dimensions	Case *	Window Type	Type	U, $W/m^2 \cdot K$	$(Btu/hr \cdot ft^2 \cdot °F)$
Washington, D.C. '54	10.6m x 12m	I	Single	Masonry	1.05	(.185)
" "	" "	I	Storm	"	1.05	(.185)
" "	" "	I	Storm	"	.852	(.150)
" "	" "	I	Single	"	.596	(.105)
" "	" "	I	Storm	"	.596	(.105)
" "	" "	I	Single	"	.574	(.101)
" "	" "	I	Storm	"	.574	(.101)
" "	" "	I	Storm	"	.574	(.101)
" "	" "	I	Storm	Frame	.574	(.101)
" "	" "	I	Single	"	.522	(.092)
" "	" "	I	Storm	"	.522	(.092)
" "	" "	I	Single	"	.369	(.065)
" "	" "	I	Storm	"	.369	(.065)
" "	" "	I	Single	Zero-Mass	.568	(.100)
" "	" "	I	Storm	"	.568	(.100)
" "	8.5m x 13.4m	II	Single	"	.568	(.100)
" "	" "	III	Single	"	.568	(.100)
Orlando, Florida '57	10.6m x 12m	I	Single	Masonry	.852	(.150)
" "	" "	I	Single	"	.574	(.101)
" "	" "	I	Storm	"	.574	(.101)
" "	" "	I	Single	Frame	.522	(.092)
" "	" "	I	Storm	"	.522	(.092)

* See Table 4.

4. ANALYSIS RESULTS

4.1 SUMMARY OF TEST CASES

A total of twenty-two test cases were analyzed, based on the parameters described in Section 2 of this report. These test cases are itemized in Table 7. Seventeen tests were performed using Washington, D.C. weather, and five Orlando, Florida weather, respectively. The test cases for Washington were about equally divided between envelope design of masonry, wood-frame and zero thermal mass. For Orlando, tests involved masonry and wood-frame cases only. U values for the walls ranged from 3.7 to 10.5 $W/m^2 \cdot K$ (.65 to 1.85 $Btu/hr \cdot ft^2 \cdot °F$). The number of tests involving single glazing and storm windows was about equal. Except for two of the zero-mass wall cases, the house geometry and distribution of window areas did not change throughout the effort. The same assumptions regarding schedules for all sources of internal loads were used in all analyses.

A complete summary of analysis results for all test cases is given in Table 8. For each case, data are presented for the cumulative annual heating and cooling requirements (AHR, ACR, respectively). Total values, and values normalized per unit floor area of the model, are both presented. The following two sections separate discussion of the results according to the weather data used for the analyses.

4.2 RESULTS USING WASHINGTON, D.C. WEATHER

The first seventeen test case results shown in Table 8 represent total and area-normalized AHR's and ACR's for Washington, D.C. weather. For all test cases, the maximum normalized ACR is about 1.8 times as large as the minimum, while the maximum normalized AHR is about 1.6 times as large as the corresponding minimum. The maximum for each occurred for the same test case (#1) which had the highest solid wall U-value and single glazing. The minimum AHR and ACR did not occur with the same model. The minimum AHR occurred for test case #13, which represents a combination of the lowest U-value studied and storm windows. The minimum ACR occurred for test case #7, a masonry constructed model and the only test case (with complete annual results) that allowed a variable temperature band instead of maintaining a constant interior temperature.

The particular test case will be discussed in greater detail in the following section of this report. Neglecting consideration of the variable temperature analysis of test case #7, then test case #8 (the same model using a fixed-temperature analysis) and test case #13 (having the lowest AHR) had the two lowest ACR's and were almost exactly the same value (0.2% difference).

The effect of envelope heat transfer performance on annual energy requirements is shown in Figure 3, which shows plots of normalized AHR's and ACR's as a function of the U-value of the solid portion of the wall. The points divide into two groups, both of which approximate straight

Table 8. Annual Heating and Cooling Requirements, Total and Normalized

Test #	Heating				Cooling			
	Total		Normalized		Total		Normalized	
	GJ	(MBtu)	MJ/m^2	$(kBtu/ft^2)$	GJ	(MBtu)	MJ/m^2	$(kBtu/ft^2)$
1	49.31	(46.74)	389.2	(34.27)	31.67	(30.02)	250.0	(22.01)
2	36.56	(34.65)	288.6	(25.41)	30.83	(29.22)	243.4	(21.43)
3	33.64	(31.88)	265.5	(23.38)	30.51	(28.92)	240.9	(21.21)
4	42.75	(40.52)	337.4	(29.71)	30.88	(29.27)	243.7	(12.46)
5	29.90	(28.34)	236.0	(20.78)	30.14	(28.57)	237.9	(20.95)
6								
7	33.54	(31.79)	264.7	(23.31)	19.74	(18.71)	155.8	(13.72)
8	29.59	(28.05	233.7	(20.58)	30.08	(28.51)	237.5	(20.91)
9	29.88	(28.32)	235.9	(20.77)	30.51	(28.92)	240.9	(21.21)
10	42.00	(39.81)	331.5	(29.19)	31.22	(29.59)	246.4	(21.70)
11	29.17	(27.65)	230.3	(20.28)	30.43	(28.84)	240.2	(21.15)
12	40.14	(38.05)	316.8	(27.90)	30.98	(29.36)	244.5	(21.53)
13	27.33	(25.90)	215.7	(18.99)	30.16	(28.59)	238.0	(20.96)
14	42.68	(40.45)	336.8	(29.66)	31.44	(29.80)	248.1	(21.85)
15	29.92	(28.36)	236.2	(20.80)	30.64	(29.04)	241.8	(21.29)
16	41.71	(39.53)	329.2	(28.99)	30.75	(29.15)	242.8	(21.38)
17	41.83	(39.65)	330.2	(29.08)	31.13	(29.51)	245.8	(21.64)
18	1.78	(1.69)	14.08	(1.24)	90.76	(86.02)	716.4	(63.08)
19	1.56	(1.48)	12.38	(1.09)	89.32	(84.66)	705.0	(62.08)
20	0.70	(0.66)	5.45	(0.48)	84.04	(79.65)	663.3	(58.41)
21	1.61	(1.53)	12.72	(1.12)	89.29	(84.63)	704.8	(62.06)
22	0.73	(0.69)	5.79	(0.51)	83.94	(79.56)	662.5	(58.34)

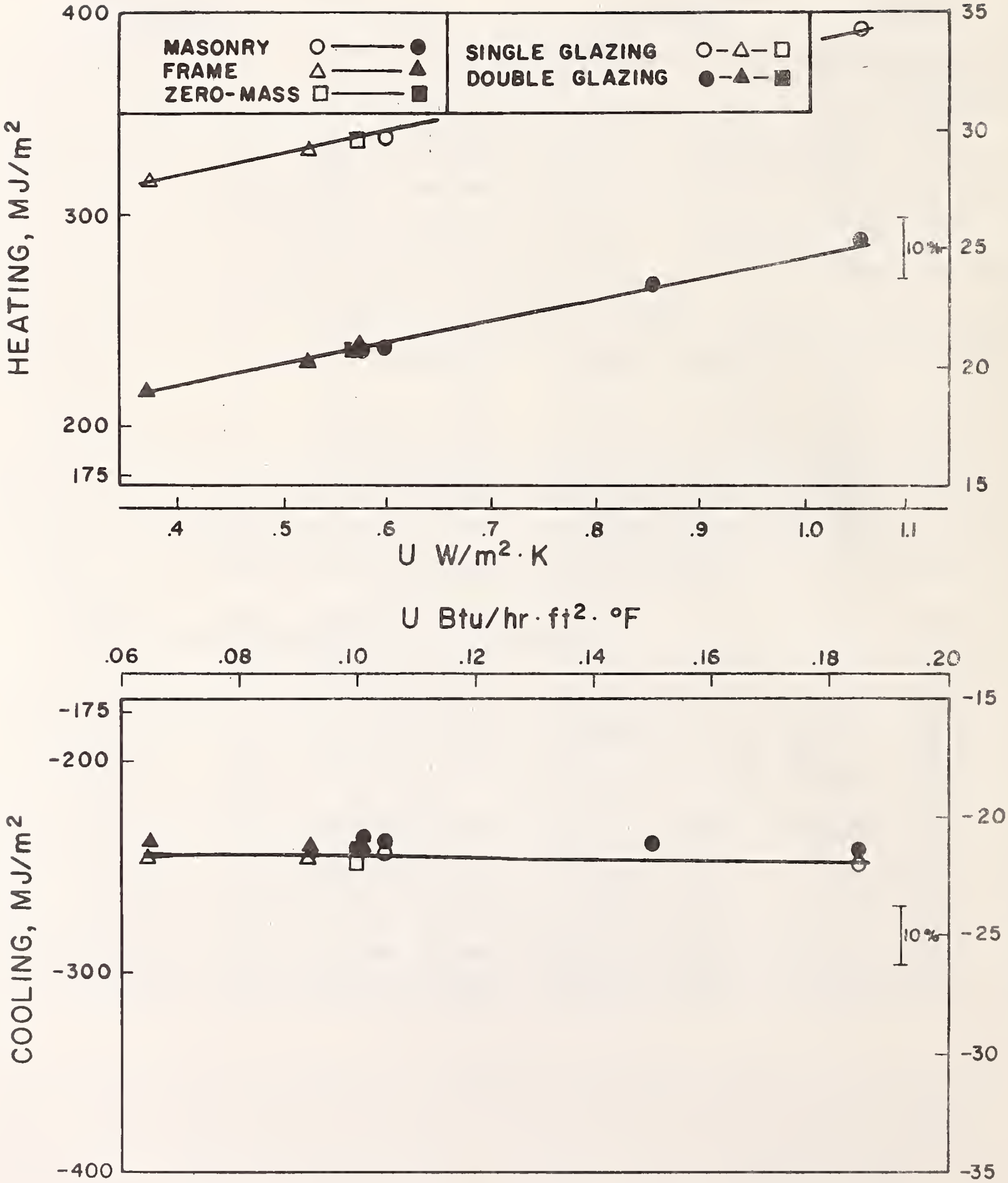

Figure 3. Annual heating and cooling requirements calculated using Washington, D.C. weather data.

lines. The AHR points of the upper group all represent test cases with single glazing, while those of the lower group all represent test cases with storm windows. Similarly, the ACR points divide into two groups based on the type of glazing. While the frame and masonry envelopes generally had different U-values, it is evident that they (and also the zero-mass envelope) all fall approximately on the same straight line. Near the value of .57 $W/m^2 \cdot K$ (.1 $Btu/hr \cdot ft^2 \cdot °F$) for U, where tests can be directly compared for all three envelope types, there is a maximum difference in AHR of about 1% and in ACR of about 1.8% for storm window cases. From this figure, it is seen that the relative effect of window type is greater than that of envelope type, for a given U-value of the solid portion of the wall.

Tests cases #14, #16, and #17 examined the effect of minor variations in geometry and window area distribution for the zero-mass envelope model, as detailed in Section 2 of this report. The maximum variations in normalized AHR and ACR for these cases were about 2.3% and about 2.2%, respectively. It is difficult to make any generalized conclusions of the effect of geometry and window variations based on these data, since neither the parameter variations nor the resultant AHR and ACR values were greatly changed. The largest normalized AHR and ACR occurred for the test case (#14) which had the lowest aspect ratio (was most nearly square), which also had the greatest area of wall exposed to the south. Although it is reasonable to expect that this was a contributing factor, it is not possible to separate the relative importance of this effect from those due to changes in window areas and distributions among the test cases.

The results in Figure 3, which indicate the relative significance of window type, led to an examination of the dependence of AHR and ACR on overall or effective U-values based on an average of the properties of the different parts of the wall (solid portions, windows, doors). Table 9 shows the computed equivalent U-values, U_e, and the data on which the computations were based, for each of the Washington, D.C. test cases. Figure 4 shows a resultant plot of AHR and ACR values versus U_e. Compared to the good fits to straight lines represented by the data in Figure 3, the data shown in Figure 4 show a much wider variation of individual points from the lines shown, which were fitted to the data by a linear regression analysis. The conclusion that results from examination of this figure is that the concept of a simple, linear, generalized heat conduction approach (i.e., $AHR = U_2 \cdot A \cdot "\Delta T"$) based on a generalized representation of average annual temperature difference (e.g., heating degree days) and equivalent average U-values, U_e, does not have a great degree of validity for the data developed in this study.

4.3 RESULTS USING ORLANDO WEATHER

Test cases #18 through #22 of Table 8 represent the five analyses accomplished using Orlando weather. The largest area-normalized ACR is about 8% larger than the smallest. The ACR's are so small that comparison is

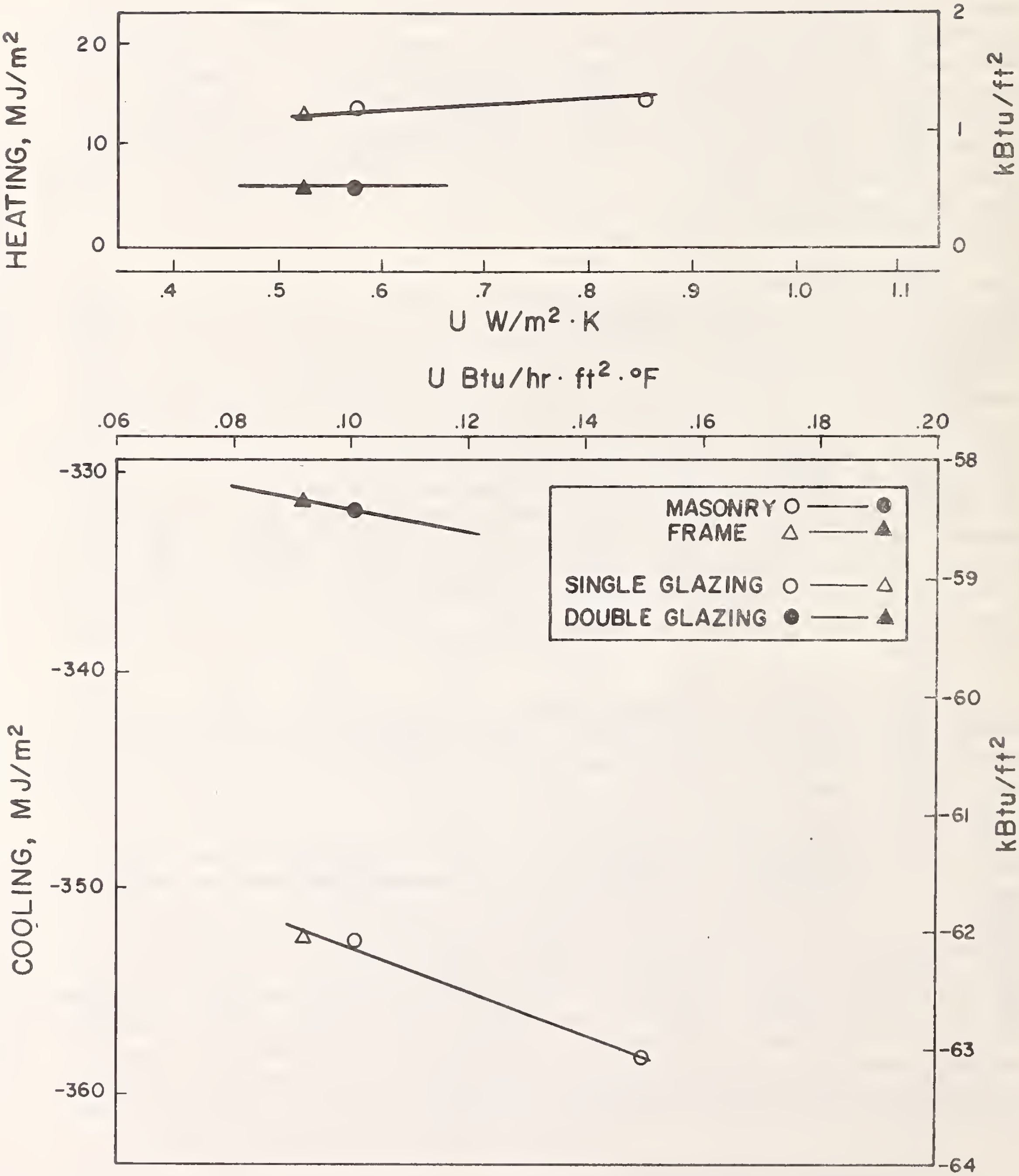

Figure 4. Annual heating and cooling requirements calculated using Orlando, Florida weather data.

Table 9. U_e - Equivalent U-value for Total Walls

Test #	U*	Wall Area (m^2)	U*	Window Area (m^2)	U*	Door Area (m^2)	Total Wall Area (m^2)	Total Wall $W/m^2 \cdot K$	U_e ($Btu/hr \cdot ft^2 \cdot °F$)
1	1.05	60.2	6.02	19.7	3.12	1.7	109.4	1.97	(.348)
2	1.05	"	3.69	"	"	"	"	1.56	(.274)
3	.052	"	3.69	"	"	"	"	1.40	(.246)
4	.596	"	6.02	"	"	"	"	1.61	(.284)
5	.596	"	3.69	"	"	"	"	1.19	(.210)
6	.574	"	6.42	"	"	"	"	1.66	(.293)
7	.574	"	3.69	"	"	"	"	1.18	(.207)
8	.574	"	3.69	"	"	"	"	1.18	(.207)
9	.574	"	3.69	"	"	"	"	1.18	(.207)
10	.522	"	6.02	"	"	"	"	1.55	(.273)
11	.522	"	3.69	"	"	"	"	1.13	(.199)
12	.369	"	6.02	"	"	"	"	1.43	(.251)
13	.369	"	3.69	"	"	"	"	1.01	(.178)
14	.568	"	6.02	"	"	"	"	1.59	(.280)
15	.568	"	3.69	"	"	"	"	1.17	(.206)
16	.568	87.7	6.02	"	"	"	107.0	1.61	(.284)
17	.568	85.6	6.02	"	"	"	107.0	1.61	(2.84)

* $W/m^2 \cdot K$

not meaningful. In a manner similar to Figure 3, Figure 5 shows the AHR and ACR values plotted as a function of the U-value of the solid portion of the wall. As was seen for the earlier data, the Orlando results also closely approximate a straight line dependence on U, with two lines depending on the window type. The agreement of AHR and ACR for masonry and frame envelope types for similar U-values is good. Again, the greatest effect is due to type of window, not the type of envelope. All the data represent constant-temperature analyses. No attempt was made to examine the validity of the generalized, equivalent U (U_e) concept for these data.

For the conditions of the analysis, it is worth while to note that any advantageous effects on ACR due to the thermal mass of masonry walls do not appear to be evident. The ACR value for the frame envelope type differs from the line extrapolated from the two ACR points calculated for masonry walls by less than 0.5%, for the single-glazing test cases.

5. CONCLUSIONS AND RECOMMENDATIONS

Because of the ad hoc nature of this effort, and its attempt to supply a limited amount of data based on specific test cases, the number of conclusions that can be made are limited. To the degree that such conclusions can be made, they are summarized below, and are based on the preceding discussions of analysis results. Following those and concluding the report are some recommendations for a more generalized subsequent study effort. Such an effort would have as its objective the generation of sufficient data to answer questions raised by the present effort (particularly regarding the effect of thermal mass of the envelope on AHR and ACR), but which remain unanswerable based on the present data.

5.1 TEST RESULTS

It is clearly shown in Figures 3 and 5, for the test cases analyzed, that the greatest single effect on AHR and ACR is due to the type of window (single or double pane). This effect is significantly larger than that caused by variation in the U-value of the walls, particularly in the AHR's computed for Orlando where cooling dominated.

The same figures show that, for the conditions of analysis that were used, the effect of wall construction type (and consequently its related thermal mass) on AHR or ACR was not readily discernible for a given U-value. The reasonableness of the constant interior temperature assumption comes into question here, since it is generally held that the full potential of thermal mass cannot be realized unless the interior temperature is allowed to float in a limited band of acceptable values. For the one test case (#7) for which annual AHR and ACR were computed using such an allowable band, comparison with the companion test case, (#8) which used the constant-temperature assumption, shows a lower ACR, but it also indicates a higher AHR. The present results are felt to be too limited to be conclusive.

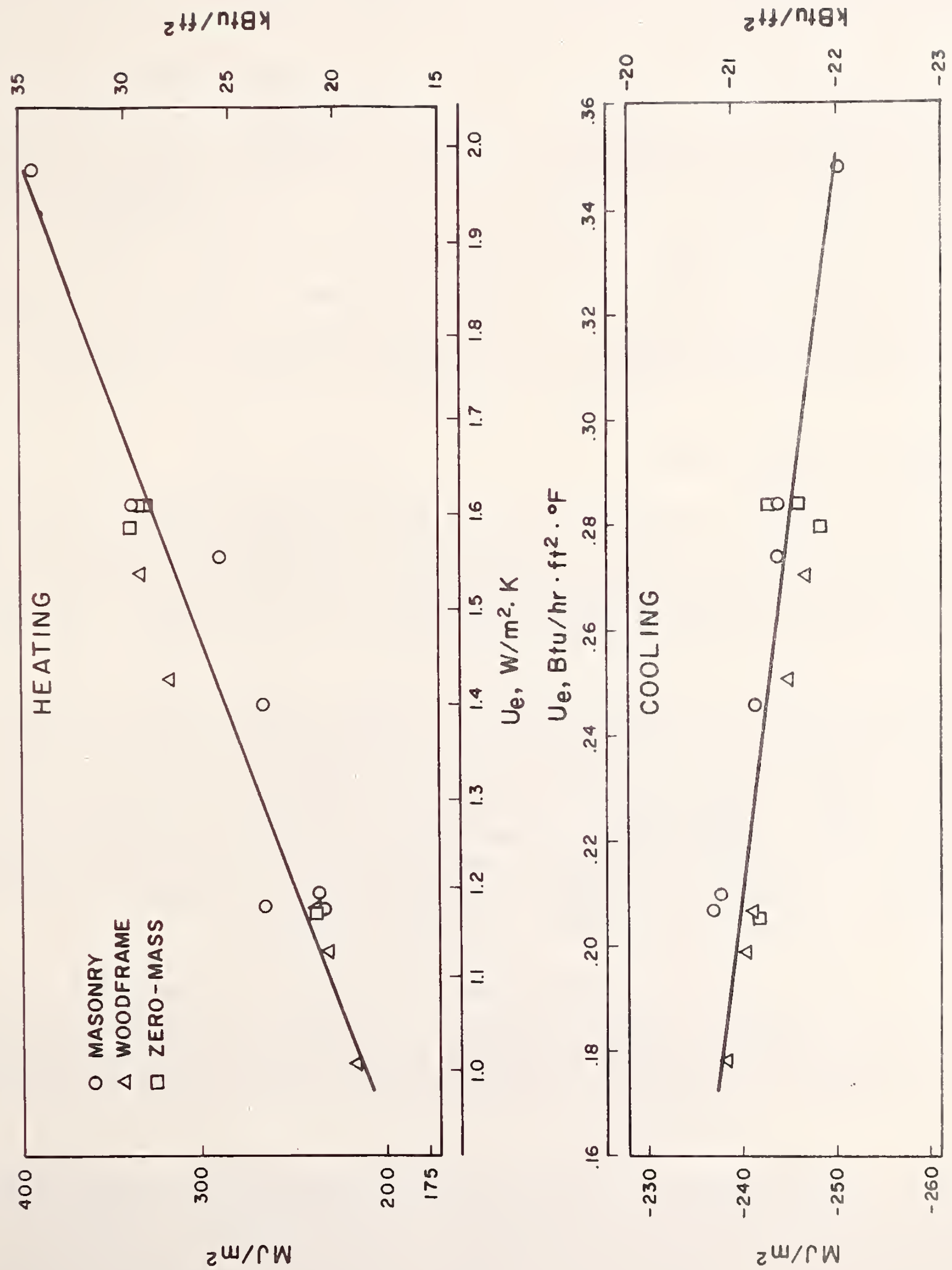

Figure 5. Annual heating and cooling requirements calculated using Washington, D.C. weather data and plotted as a function of equivalent U-value, U_e, for the building envelope.

Small variations in geometry (i.e. aspect ratio) and window area distribution produced only small changes in AHR and ACR. A detailed explanation for the changes and their specific causes cannot be determined from the present limited set of data.

Finally, the concept of a generalized linear transfer equation, based on an average U-value, U_e, computed from the properties and respective areas of the different wall components, is not well supported by the data presented here. There is a relatively large amount of scatter of individual AHR and ACR data points from the line fitted to the points by linear regression. Thus, for approximately the same computed U_e, different test cases showed significantly different AHR and ACR values. The discernible differences are mostly due to the type of window involved, in support of the conclusions stated above. This indicates that the solar contribution to AHR and ACR is the portion of the total that does not obey the generalized linear-heat-transfer concept.

5.2 PARAMETRIC TEST PLAN

The most interesting and significant areas for future study are felt to be on the real effect of thermal mass, and a more detailed study of the effect of geometry and window distribution. In addition, peak heating and cooling loads should be studied as well as AHR and ACR. A wider range of climates should also be considered.

The thermal mass effect should include studies with a wider range of U-values and thermal mass values than the ones presented here. Distribution of thermal mass (i.e. walls, floor, ceiling, interior) should be considered. Most importantly, the analyses should be done using a variable interior temperature assumption, for several allowable temperature ranges. A number of climates representative of different weather regions should be used to determine those regions and other conditions for which the thermal mass effect is most significant.

Additional studies should be performed for different geometries, representing a wider range of aspect ratios. For each of these cases, a range of cases using varying window areas and distributions among the walls should be studied, in order to find the optimum combination of such parameters.

It is also recommended that actual energy consumption be computed by developing a realistic set of assumptions and subsequent simulations for actual heating and cooling equipment. This level of simulation should be done in at least a few cases. If it is found that AHR and ACR correlate well with actual energy use for each component, then the system simulations could be discontinued.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A number of design variations of a typical one-story single-family residence were analyzed to determine annual heating and cooling energy requirements. The National Bureau of Standards Load Determination computer program, NBSLD, was used to accomplish the analysis. Design details for each of the residence variations are described in detail. Annual heating and cooling energy requirement calculations are presented and discussed. The results show only a small dependence on the thermal mass of the building envelope for the two climates studied (Washington, D.C. and Orlando, Florida). The thermal properties of the windows had a greater effect. Concluding the report are technical generalizations based on the present study, and recommendations for further work in order to produce a definitive study of the effect of selected building design parameters on energy consumption.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Building energy consumption analysis; Computerized building energy analysis; Cooling load calculation; Energy conservation; Heating load calculation; NBSLD analysis of residences; Residential energy conservation; thermal mass effect in buildings.

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