PASSIVE SOLAR DESIGN FOR THE NORTHERN UNITED STATES

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ABSTRACT

This paper reports on research approaches to passive building design in the northern United States, which is characterized by temperate and cool climate zones. Regional mapping approaches to climatic design are reviewed. While regional definitions do indicate the generalized nature of local climate, important variations in microclimatic and building system variables are not properly represented by regional mapping approaches. The climate-based parameters defined by Givoni's Building Bioclimatic Chart (Figure 11) provide a basis by which to characterize climate data, and by which it can be illustrated that passive heating and cooling strategies can provide comfort in all U.S. climates. A computer-based parametric analysis is presented comparing the relative effectiveness of passive building elements in a severe winter week in 20 U.S. locations and year-round conditions in 4 cities representative of U.S. climates. System variables of passive design elements are shown to be more important than climatic variables in northern U.S. locations, which are predominantly underheated. Some climate-design elements, such as south-facing windows or insulation, may increase cooling loads. Others, such as thermal mass and underground coupling, reduce both heating and cooling loads and are therefore of interest in underheated climatic zones that also have cooling requirements.

In the concluding section of this paper, various passive systems are discussed with reference to temperate climate applications, where both heating and cooling loads and requirements can be met by appropriate climatic design.

NORTHERN UNITED STATES: OVERVIEW OF CLIMATIC DESIGN MAPPING CHARACTERIZATIONS

The northern United States experiences predominantly underheated conditions and was characterized by Olgyay and Olgyay (1963) as "temperate" and "cool" bioclimatic zones (Figure 1). The passive design techniques that are appropriate in temperate and cool conditions differ from one another in degree but not in kind (whereas different kinds of techniques are used in hot-wet and hot-arid climatic zones). In cool zones of the United States, insulation strategies, passive solar heating, and underground or earth-sheltered design are effective. In temperate zones, the same techniques are useful, differing from cool climate applications only in sizing and application details.

This point is reinforced by examination of regional mapping of individual climatic elements, such as recommended insulation standards for the northern United States (Figure 2). These follow directly from heating degree-day variations and recommended zones for underground building (Figure 3), which account for differences between below-ground and above-ground temperatures as well as dew-point temperatures. Regional variations for solar heating have also been mapped, to indicate both the amount of available sunshine (Figure 4) and the solar heating advantage, which combines solar insolation with heating degree-days (Figure 5).

A regional climate design map of the United States, in which both heating and cooling degree-days are included, was developed for the recent Federal effort to establish Building Energy Performance Standards (Figure 6). In this characterization, designed to assist in determining relative energy requirements for conventional buildings and those in which passive solar energy techniques are used, west to east variations in humidity levels or day-night temperature variations are not included. Just as humidity may determine whether underground building is appropriate, day-night temperature swings typical of a region may determine whether capacity insulation or time-lag effects (in contrast to resistance insulation strategies) can be exploited. This results in a distinction between western and eastern regions of the United States as mapped in Figure 7. These and other factors were included in mapping

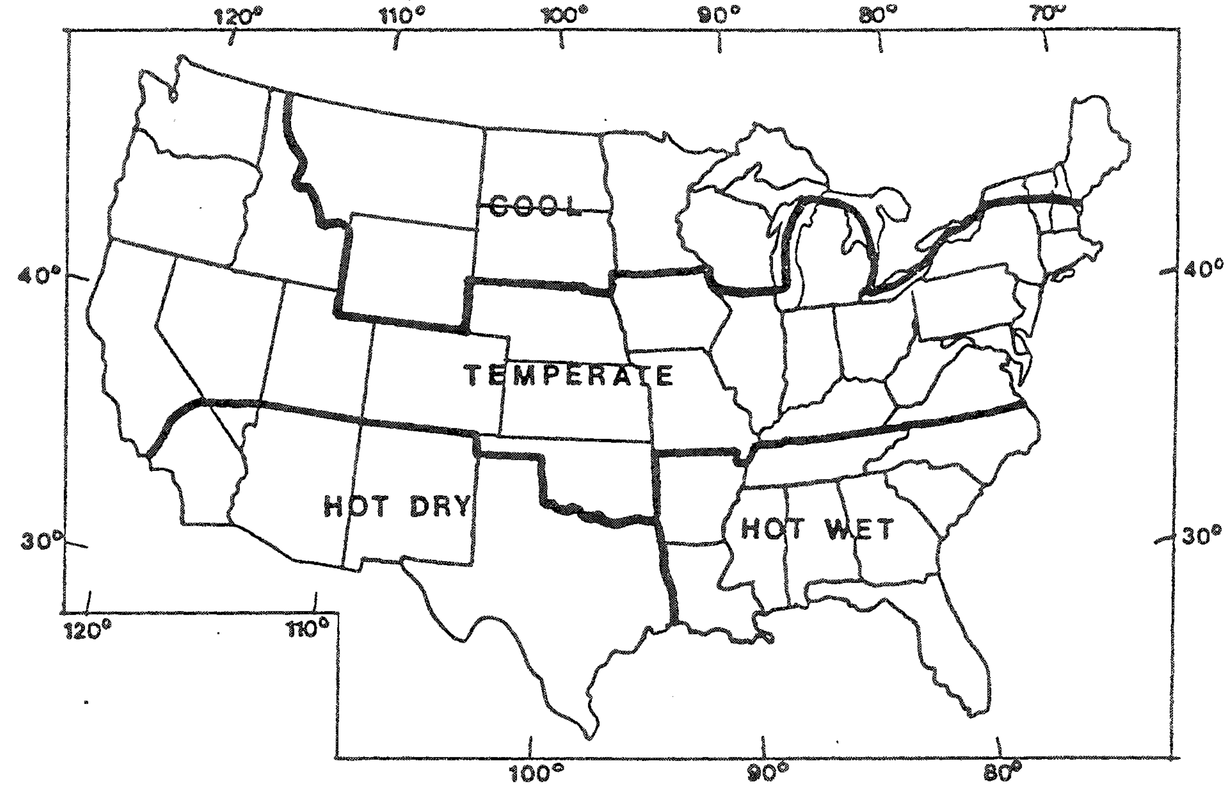
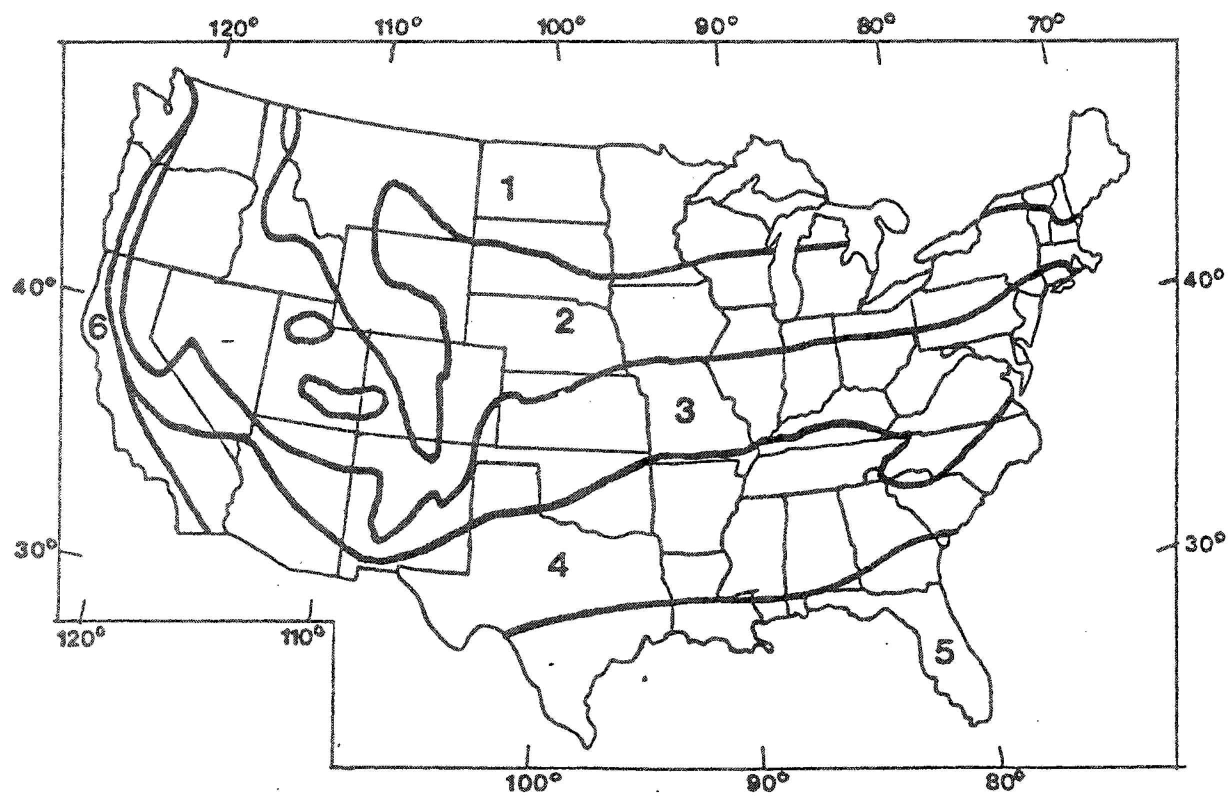
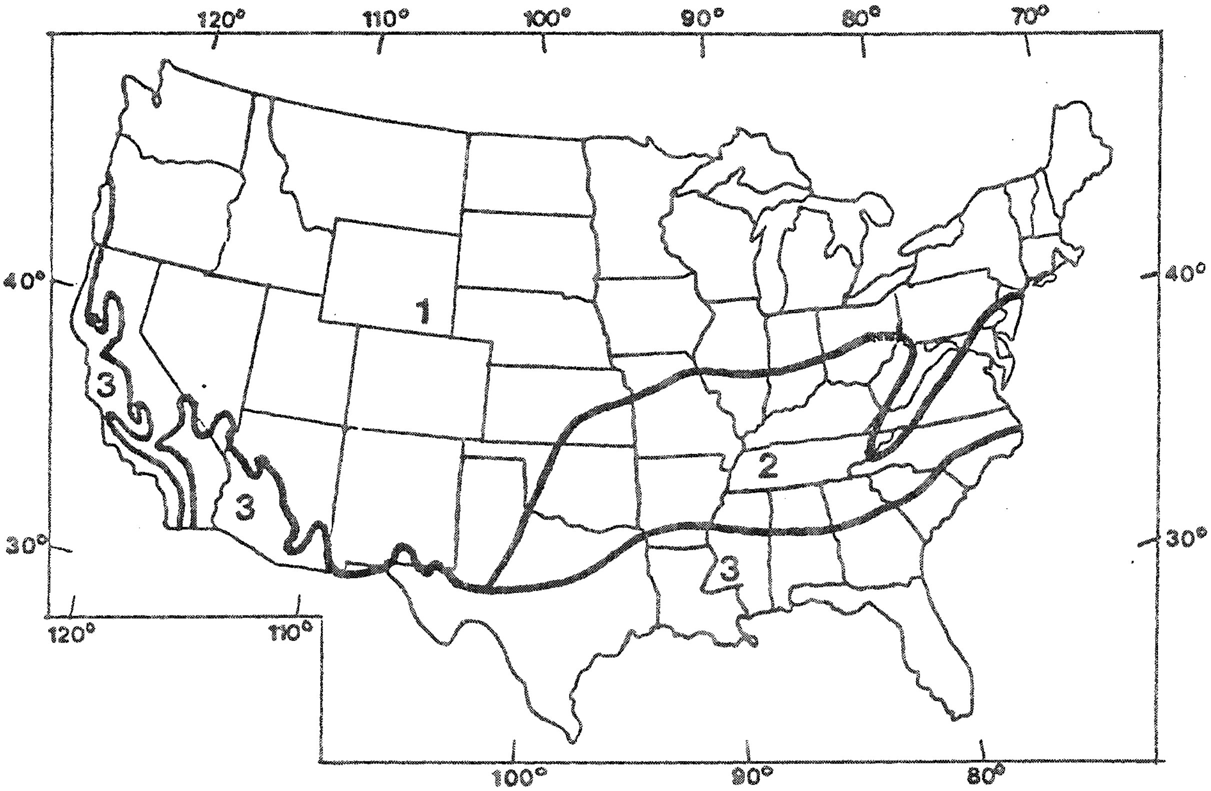


Figure 1 U.S. regional climatic zones (Olgyay and Olgyay 1963).



R values for	1	2	3	4	5	6
—Ceilings	R-38	R-33	R-30	R-26	R-26	R-19
—Walls	R-19	R-19	R-19	R-19	R-13	R-11
—Floor	R-22	R-22	R-19	R-13	R-11	R-11

Figure 2 Currently recommended resistance insulation values (Watson, 1977).



1. Area of greatest advantage. The southwestern end of this zone has less summer benefit because it is drier. Also, yearly temperature extremes are not so great. Northern portions of this zone, with cool summers, would need to use sun's heat to take summertime chill off a sunken living room, but wintertime benefits would be very positive.

2. This area has both summer and winter advantages. But due to high relative humidities, a sunken room in this zone would require some mechanical air-drying to prevent condensation on walls and floors.

3. Area where underground living offers only minor advantages and is not recommended for the following reasons: because climate above ground is pleasant and without great extremes; because the underground temperatures are not different enough to correct the above-ground climate, or because of the complications of extreme humidities. (Source: Dr. Paul Siple, House Beautiful *Climate Control Project, 1949)*

Figure 3 Areas where underground massing is beneficial (Watson, 1977)

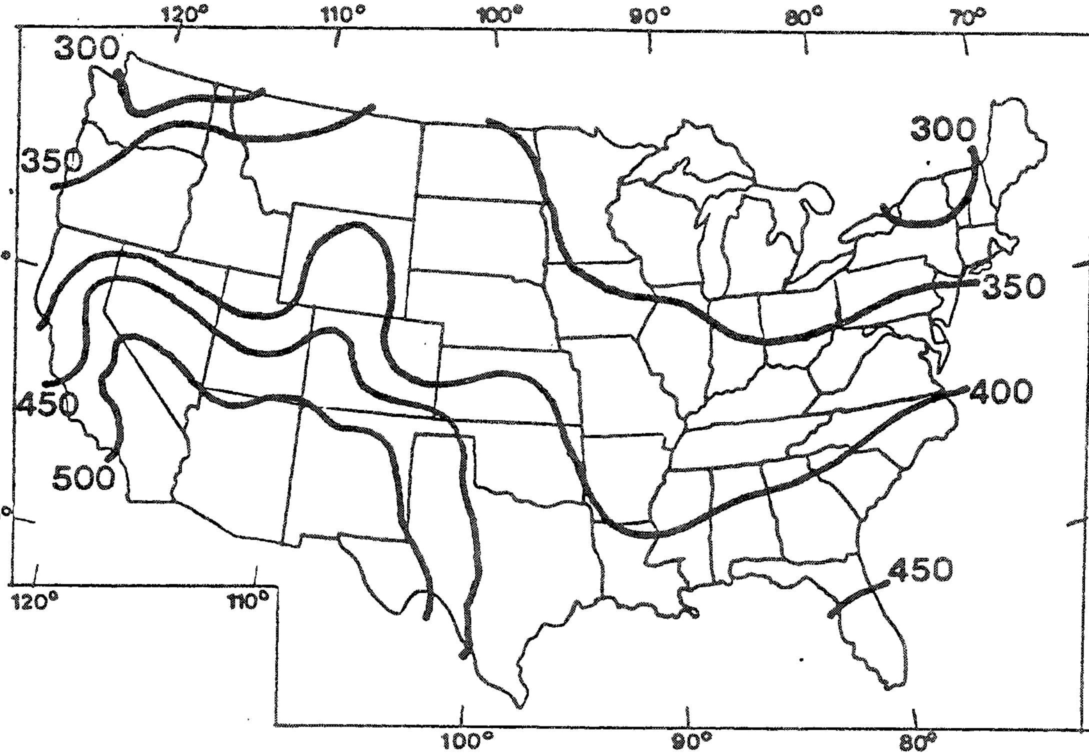
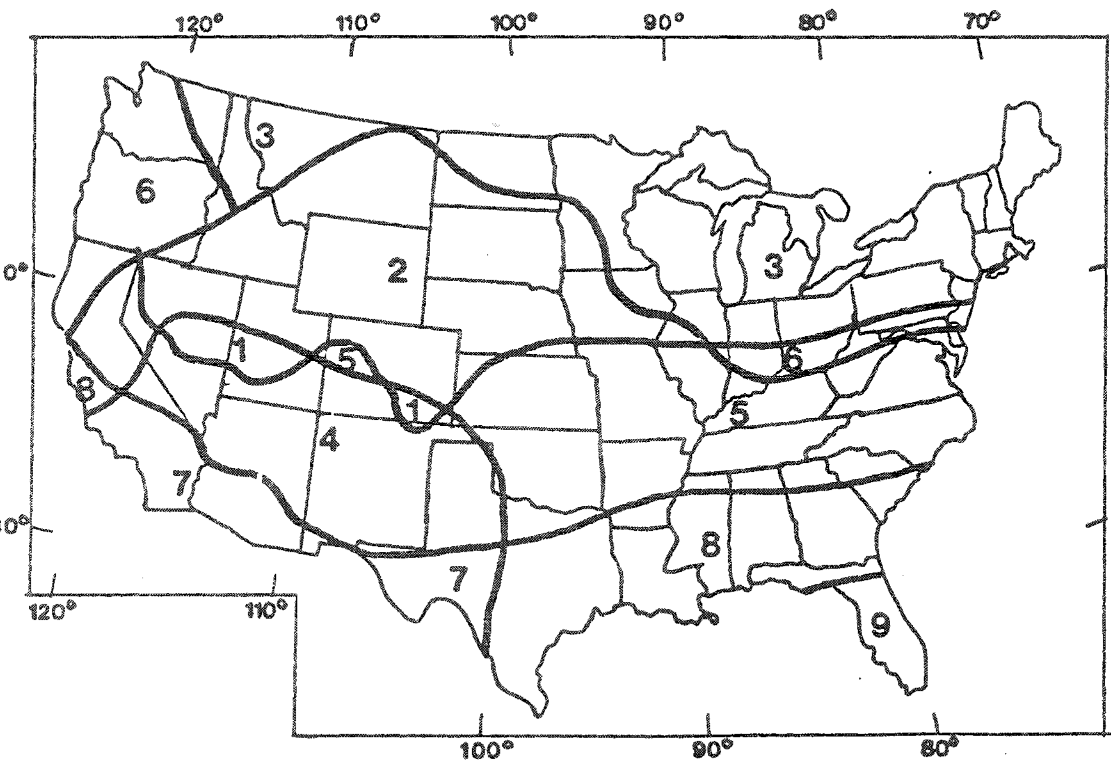


Figure 4 Average annual horizontal radiation in Langleys per day (Watson, 1977)



1. *High Heat Demand—excellent sunshine.*
2. *High Heat Demand—good sunshine*
3. *High Heat Demand—fair sunshine*
4. *Moderate Heat Demand—excellent sunshine*
5. *Moderate Heat Demand—good sunshine*
6. *Moderate Heat Demand—fair sunshine*
7. *Low Heat Demand—excellent sunshine*
8. *Low Heat Demand—good sunshine*
9. *Low Heat Demand—fair sunshine*

Figure 5 Solar Heating Advantage, relative to available solar radiation and winter heating requirement (Watson, 1977).

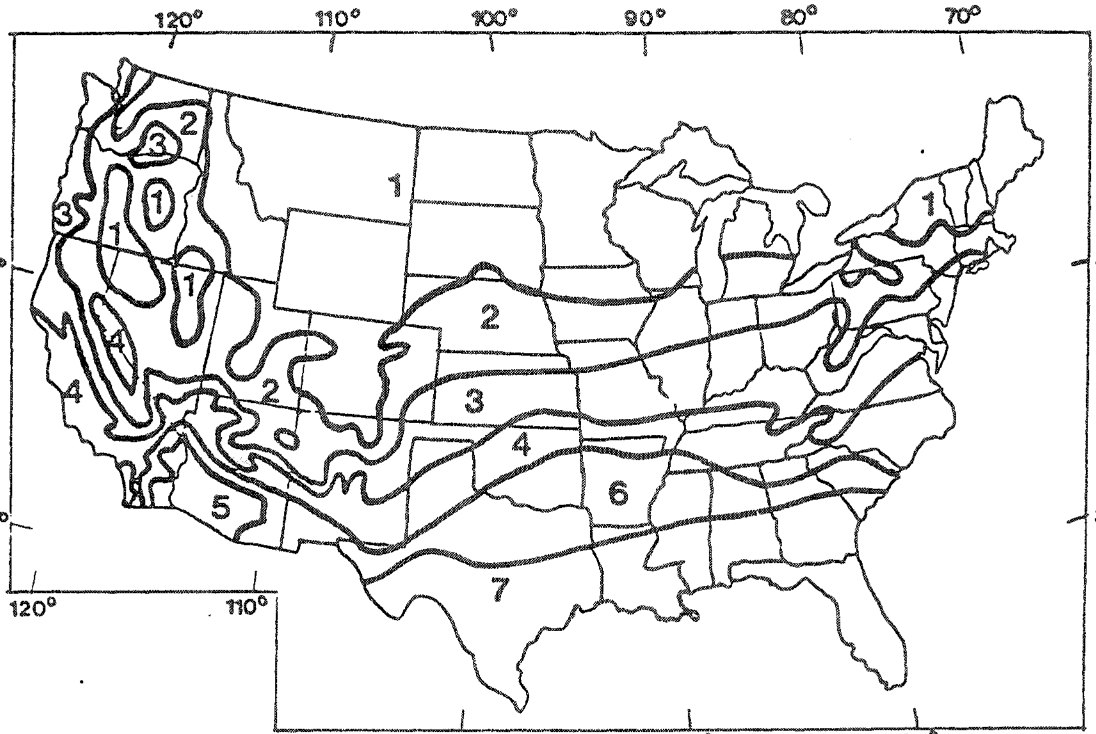


Figure 6 Climatic characterization for BEPS Baseline Survey Project (AIA Research Corp., 1978, Research and Design Quarterly).

Region 1	Less than (() 2,000 Cooling Degree Days (CDD) More than ()) 7,000 Heating Degree Days (HDD)		
Region 2	(2,000 CDD 5,500-7,000 HDD	Region 5	(2,000 CDD (2,000 HDD
Region 3	(2,000 CDD 4,000-5,500 HDD	Region 6	)2,000 CDD (2,000 HDD
Region 4	(2,000 CDD 2,000-4,000 HDD	Region 7	)2,000 CDD 2,000-4,000 HDD

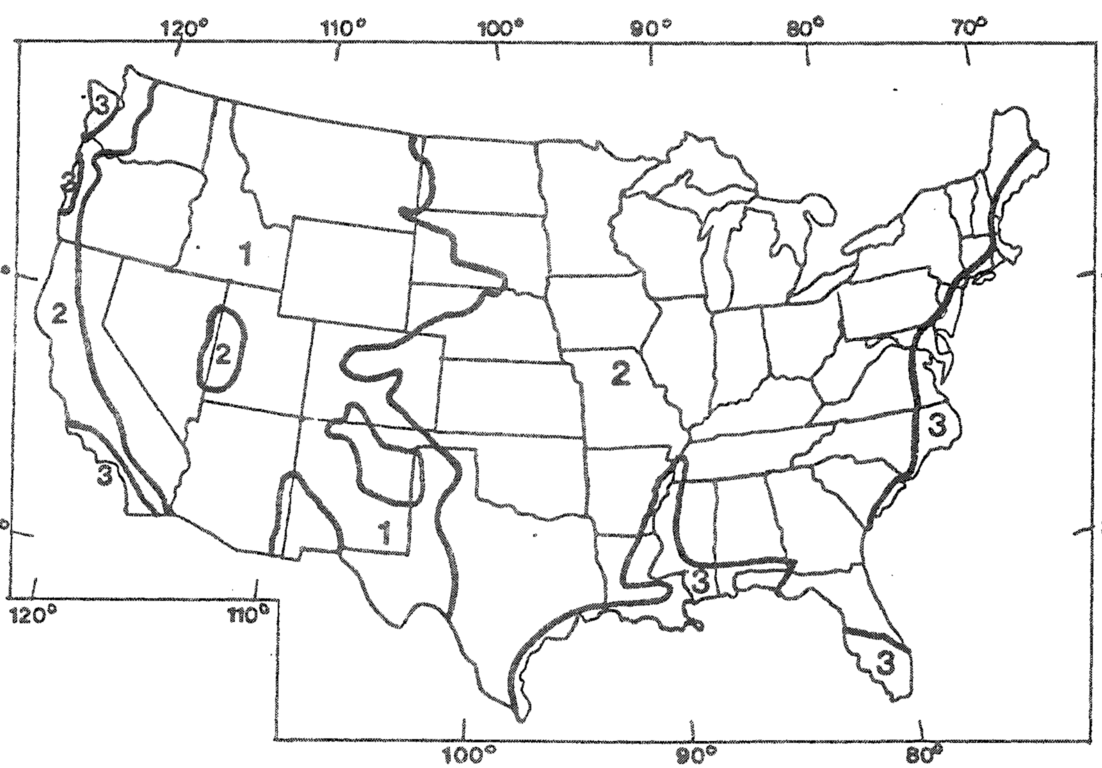


Figure 7 Zones of relative daily temperature fluctuation (1=high; 2=medium; 3=low) (Watson and Labs, 1980).

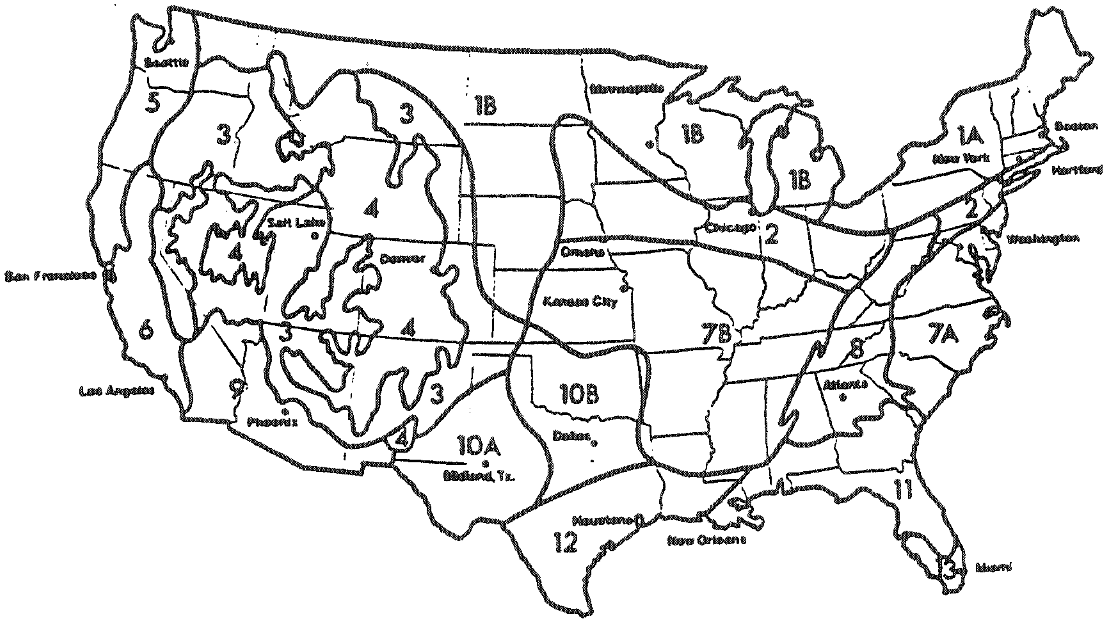
United States climatic design regions in a recent publication by the AIA Research Corporation (1978) (Figure 8). Long-term hourly weather data were analyzed to evaluate passive heating and cooling strategies in the United States, assuming conventional building construction standards. The zones define areas in which various passive design strategies might be considered, using a rating system based on temperature, wind, moisture, and sun.

Such characterization of climatic design strategies is only partially useful. Mapping shows areas where climatic conditions might exist that would favor passive designs based on limited selection criteria. However, passive solar heating or cooling can be used in any area of the United States. Maps such as Figure 8 indicate design priorities but do not demonstrate that special building design of solar windows, thermal storage, or ventilation can in fact overcome local climatic liabilities. Important local distinctions in building type, microclimatic variation, or conventional fuel costs are often lost in the regional mapping approach. As will be discussed in the following sections, new climatic design methods using computer simulation enable site-specific and building-type-specific analysis that may short-cut generalized regional approaches.

CLIMATIC DATA FOR UNITED STATES LOCATIONS

Detailed climatic data for U.S. locations, based upon airport weather station readings, are available from the National Oceanic and Atmospheric Administration (NOAA)*. The data are reported in various formats, including annual summaries for each city and for individual states or regions. These climatological summaries include temperature, humidity, wind, and precipitation means and extremes. Sky cover data are reported in terms of mean-percent of possible sunshine, but measured solar radiation has not been included in airport readings. For use in computer simulation, solar radiation has been calculated and corrected

*National Climatic Center, Asheville, NC 28801.



CLIMATE	CITY WITH PROTOTYPICAL CLIMATE	BASIC CLIMATE CONDITION % CONDITIONING PER YEAR BASED ON TEMPERATURE AND HUMIDITY ALONE	DESIGN PRIORITIES: CLIMATIC LIABILITIES				DESIGN PRIORITIES: CLIMATIC ASSETS				POTENTIAL CLIMATE CONDITION % CONDITIONING PER YEAR BASED ON SIMPLE BUILDING RESPONSES TO CLIMATE AT LEAST	% IMPROVED COMFORT AT LEAST
			TEMP	WIND	MOISTURE	SUN	TEMP	WIND	MOISTURE	SUN		
1A	HARTFORD CT	13% TOO HOT FOR COMFORT				4		5			9% TOO HOT FOR COMFORT	37%
		75% TOO COOL FOR COMFORT	1	2						3	53% TOO COOL FOR COMFORT	
1B	MADISON WI	10% TOO HOT FOR COMFORT				5	4	6			7% TOO HOT FOR COMFORT	28%
		80% TOO COOL FOR COMFORT	1	2						3	68% TOO COOL FOR COMFORT	
2	INDIANAPOLIS IN	20% TOO HOT FOR COMFORT	4			5		6			9% TOO HOT FOR COMFORT	30 %
		60% TOO COOL FOR COMFORT	1	2						3	50% TOO COOL FOR COMFORT	
3	SALT LAKE CITY UT	11% TOO HOT FOR COMFORT				6	3	5	4		1% TOO HOT FOR COMFORT	38%
		77% TOO COOL FOR COMFORT		2			3			1	81% TOO COOL FOR COMFORT	
4	ELY NV	9% TOO HOT FOR COMFORT					4				9% TOO HOT FOR COMFORT	34%
		89% TOO COOL FOR COMFORT	1	3			4			2	79% TOO COOL FOR COMFORT	
5	MEDFORD OR	9% TOO HOT FOR COMFORT									8% TOO HOT FOR COMFORT	34%
		79% TOO COOL FOR COMFORT		3						2	69% TOO COOL FOR COMFORT	
6	FRESNO CA	17% TOO HOT FOR COMFORT				4	3	5	6		9% TOO HOT FOR COMFORT	52%
		63% TOO COOL FOR COMFORT		7			3			1	43% TOO COOL FOR COMFORT	
7A	CHARLESTON SC	43% TOO HOT FOR COMFORT	1		6	4		2			29% TOO HOT FOR COMFORT	34%
		46% TOO COOL FOR COMFORT	2	5						3	33% TOO COOL FOR COMFORT	
7B	LITTLE ROCK AR	26% TOO HOT FOR COMFORT	1		6	5		3			24% TOO HOT FOR COMFORT	34%
		62% TOO COOL FOR COMFORT	1	4						2	42% TOO COOL FOR COMFORT	
8	KNOXVILLE TN	28% TOO HOT FOR COMFORT			6	4	2	3			16% TOO HOT FOR COMFORT	38%
		58% TOO COOL FOR COMFORT	1	5			2			4	45% TOO COOL FOR COMFORT	
9	PHOENIX AZ	37% TOO HOT FOR COMFORT	1			2	4	7	3		18% TOO HOT FOR COMFORT	52%
		49% TOO COOL FOR COMFORT	5				4			6	30% TOO COOL FOR COMFORT	
10A	MIDLAND TX	29% TOO HOT FOR COMFORT	4			3	7	6	1		19% TOO HOT FOR COMFORT	53%
		56% TOO COOL FOR COMFORT	4	5			7			2	37% TOO COOL FOR COMFORT	
10B	FORT WORTH TX	39% TOO HOT FOR COMFORT			6	3	5	1	6		24% TOO HOT FOR COMFORT	45%
		47% TOO COOL FOR COMFORT		4			5			2	39% TOO COOL FOR COMFORT	
11	NEW ORLEANS LA	37% TOO HOT FOR COMFORT			4	2	3	1			39% TOO HOT FOR COMFORT	38%
		38% TOO COOL FOR COMFORT		6			3			5	25% TOO COOL FOR COMFORT	
12	HOUSTON TX	54% TOO HOT FOR COMFORT	1		4	3		2			43% TOO HOT FOR COMFORT	37%
		38% TOO COOL FOR COMFORT	7	5						6	25% TOO COOL FOR COMFORT	
13	MIAMI FL	88% TOO HOT FOR COMFORT	6		4	2		3			30% TOO HOT FOR COMFORT	64%
		11% TOO COOL FOR COMFORT	8							5	7% TOO COOL FOR COMFORT	

Figure 8 Climatic Regions defined in the AIA/RC Passive Solar Homes Report (AIA Research Corp., 1978, Regional Guidelines).

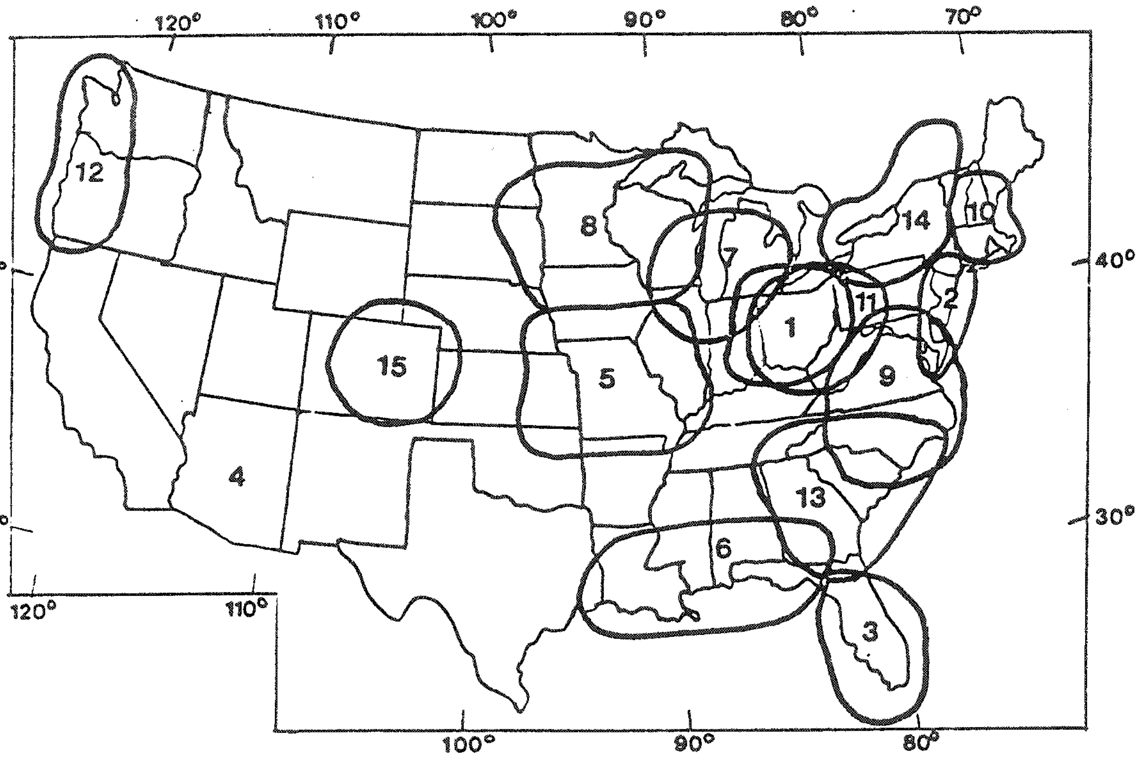
by using measured cloud-cover data and is available in handbook form, such as the solar data used with the NBS-LD program (Kusuda and Ishii, 1977). Recently, "SOLMET" tapes have been compiled from measured solar radiation and are available in handbook form (Cinquemani, et al., 1979). Other data that are needed for passive design, such as night sky temperatures and below-ground temperatures, have not been recorded.

The airport weather data for more than 150 U.S. cities are available from NOAA on computer tapes, in most cases with hourly data over a 15-year period or longer. The use of computer simulation of building energy performance relies upon edited and corrected versions of these weather tapes, to which measured or calculated solar irradiation and ground temperature data can be added.

The climatic data that are available can be used in various ways. The 1949 House Beautiful Climate Control Project, an early but notable effort, was based upon such data for various U.S. regions (Figure 9) and led to specific design recommendations. An improved format for reporting existing climatic data and for recording and reporting additional data for use by building designers has been compiled by the AIA Research Corporation (1979), and submitted to NOAA. Recommended formats include graphs of annual variations of temperature, humidity, and radiation, similar to the 1949 Climate Control Project, as well as wind roses and solar and daylighting graphs. One of the recommendations is that annual variations of local dry-bulb and wet-bulb temperature readings be charted on the psychrometric chart (Figure 10), to permit analysis such as proposed in Givoni's Building Bioclimatic Chart (Figure 11).

Givoni's Building Bioclimatic Chart shows that various passive techniques are effective within particular climatic parameters and supports his argument that regional climatic variations have to be defined in terms of the building design elements that help achieve interior comfort conditions, rather than by exterior climate.

By reference to Givoni's parameters (Figure 12), Table 1 summarizes the data for twenty representative U.S. cities. Also indicated are the relative percentages of time (hours per year) that the local climate falls within the parameters established by Givoni for various strategies



1	Mid-Ohio	AIA Bulletin	Sept.	1949	
2	Metropolitan New York & N.J.	"	Nov.	1949	
3	South Florida-Miami	"	Jan.	1950	
4	Arid Southwest	"	Mar.	1950	
5	Mid-Mississippi	"	May	1950	
6	Gulf Coast	"	Jul.	1950	
7	Chicago, Illinois	"	Sept.	1950	
8	St. Paul-Minneapolis, Minn.	"	Nov.	1950	
9	Washington, D.C.	"	Jan.	1951	
10	Boston, Mass.	"	Mar.	1951	Supplement
11	Pittsburgh, Pa.	"	May	1951	"
12	Portland, Ore.	"	Jul.	1951	"
13	Charleston, S.C.	"	Sept.	1951	"
14	Albany, N.Y.	"	Nov.	1951	"
15	Denver, Co.	"	Jan.	1952	"

Figure 9 U.S. Regions included in House Beautiful Climate Control Project (1949-1952).

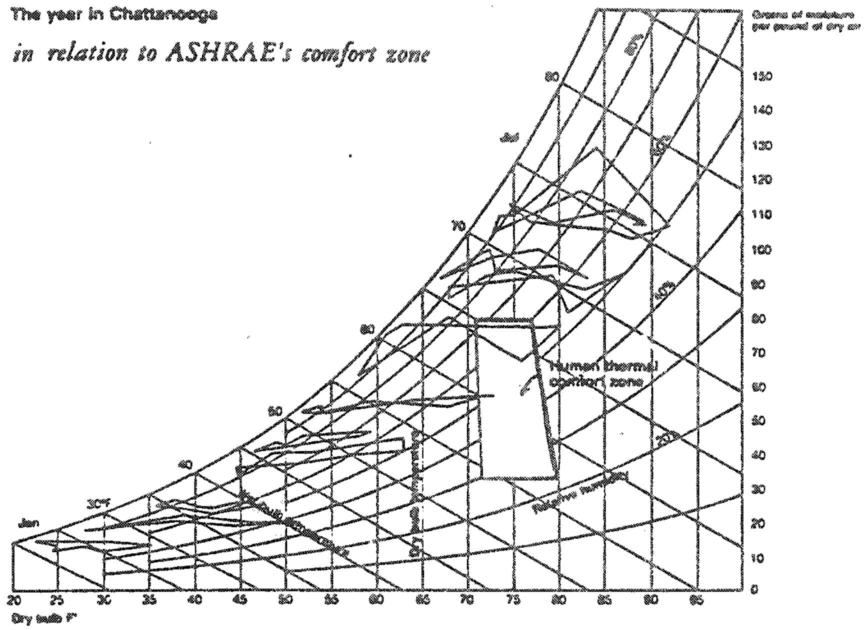


Figure 10 Weather Data Reporting Format proposed by AIA/Research Corp. (1979).

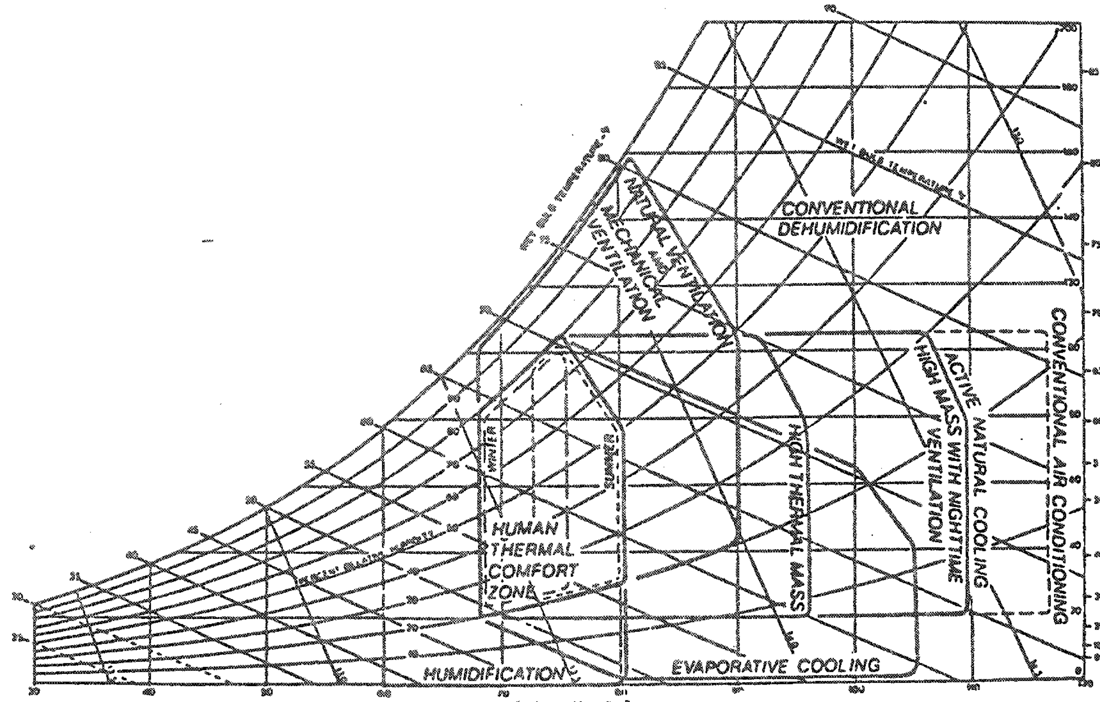


Figure 11 Building bioclimatic chart (Givoni and Milne, 1979).

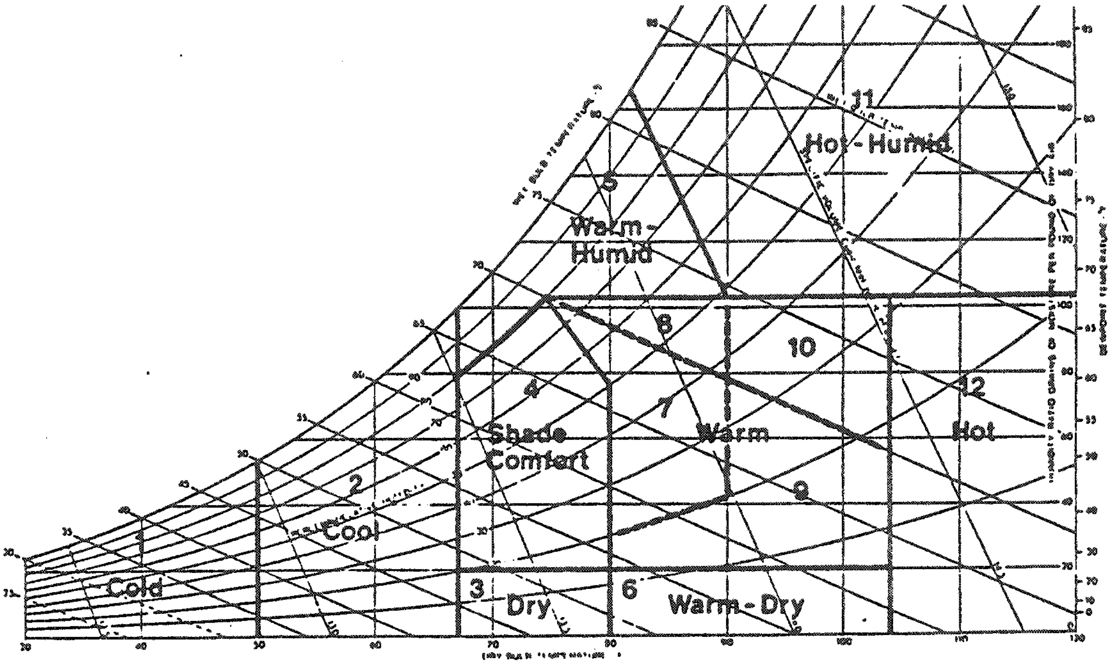


Figure 12 Psychrometric chart divisions designated in Table 1 (Watson and Labs, 1980).

	MINNEAPOLIS D	MINNEAPOLIS N	CHICAGO D	CHICAGO N	SEATTLE D	SEATTLE N	OMAHA D	OMAHA N	HARTFORD D	HARTFORD N	DENVER D	DENVER N	SALT LAKE CITY D	SALT LAKE CITY N	KANSAS D	KANSAS N	BOSTON D	BOSTON N	NEW YORK D	NEW YORK N
1 COLD	43	63	39	57	39	63	36	55	35	54	35	63	38	62	31	48	39	56	35	53
2 COOL	26	26	25	27	48	34	24	26	26	26	31	29	26	26	23	26	33	32	31	31
3 DRY											04									
4 SHADE COMFORT	18	06	19	09					11	02	16	07	17	11	19	12	17	06	18	06
5 WARM-HUMID	05	04	06	06	11		02	04	05	05					09	09	04	05	10	09
6 WARM-DRY											02		01							
7 WARM	04		06		02		23	08	06	01	06		08	01	06	02	04		03	
8 WARM	03		04	01			05	02	04						06	03	02	01	03	01
9 WARM											06		10		01					
10 WARM	01		02				02								05				01	
11 HOT-HUMID			–				07	04	01											
12 HOT																				

	WASHINGTON D	WASHINGTON N	DALLAS D	DALLAS N	ATLANTA D	ATLANTA N	NEW ORLEANS D	NEW ORLEANS N	SAN FRANCISCO D	SAN FRANCISCO N	HOUSTON D	HOUSTON N	MIDLAND, Tx. D	MIDLAND, Tx. N	PHOENIX D	PHOENIX N	LOS ANGELES D	LOS ANGELES N	MIAMI D	MIAMI N
1 COLD	28	46	15	28	19	33	07	16	09	32	05	10	16	34	06	23	03	12	01	02
2 COOL	29	31	24	31	30	37	24	37	78	67	26	37	25	32	24	35	64	82	08	21
3 DRY													02		02	01				
4 SHADE COMFORT	16	08	16	12	18	10	16	04	12		09	04	21	21	18	18	29	04	23	16
5 WARM-HUMID	11	12	16	16	17	17	39	42			56	48	02	03	02	02	01	02	52	56
6 WARM-DRY													01		01					
7 WARM	07	01	06	02	06		03		01				14	07	08	08	01		03	
8 WARM	06	02	08	08	08	03	07	01			03	01	04	01	03	04			11	04
9 WARM			01										11	01	22	05				
10 WARM	02		13	02	03		04						04		10	03			01	
11 HOT-HUMID	02																			
12 HOT															04					

%hrs/year D-Day N-Night

Table 1 Climatic data summary for 20 U.S. locations (Watson and Labs, 1980).

(Table 2). Thus, for localities where weather data are available on computer tapes, it can be determined how much solar radiation is available during the underheated periods (Zones 1 and 2 on Figure 12) or what the windspeed and direction are when ventilation is needed (Zones 5, 7, and 8 on Figure 12). Table 2 refers to Washington, D.C., daytime hours. Similar charts could be produced for any U.S. city recorded on NOAA weather tapes for any intervals that require detailed analysis.

The recent development of passive design models for computer programs indicates that it is possible to simulate specific building design elements in specific climates. The analytic capability of computer simulation is indicated by the preliminary research on northern U.S. climatic design elements reported in the following section.

COMPUTER-BASED RESEARCH ON CLIMATIC DESIGN FOR THE NORTHERN UNITED STATES

Many energy conserving and passive design options are available to reduce energy consumption in buildings in northern United States locations: changing the building shape or orientation, increasing the insulation, and using "passive" solar elements such as south windows or greenhouses, with or without thermal mass. The research reported in this section was undertaken to review the effectiveness of these climate design elements in different U.S. climates, specifically, to compare climate design elements based on their relative merit in improving the heating energy savings of a base building (in this case, a "typical" house). Annual savings of heating and cooling are also compared for selected elements. The questions at the outset were whether particular strategies are superior for particular U.S. cities and whether there are common characteristics between different strategies and between different cities. Additionally, it was intended to determine how the conclusions would be affected by different selection criteria, such as between a winter "design week" and annual results.

corresponding area on psychrometric chart
windspeed knots
% hrs/year
insolation-horiz. surface Btu/hr.
wind direction

		<5	5-10	> 10
/ 3/	N			
/ 3/	E			
/ 3/	S			
/ 3/	W			
/ 6/	N			
/ 6/	E			
/ 6/	S			
/ 6/	W			
/ 9/	N			
/ 9/	E			
/ 9/	S			
/ 9/	W		0.1	0.1
/12/	N			
/12/	E			
/12/	S			
/12/	W			
/ 1/	N	0.9	3.8	4.1
/ 1/	E	0.9	2.1	0.7
/ 1/	S	1.7	4.8	1.2
/ 1/	W	0.9	3.9	6.5
/ 4/	N	0.4	2.1	1.1
/ 4/	E	0.5	1.7	0.6
/ 4/	S	0.5	3.1	1.6
/ 4/	W	0.3	1.6	1.3
/ 7/	N	0.1	0.8	0.4
/ 7/	E	0.2	0.6	0.2
/ 7/	S	0.2	1.4	1.0
/ 7/	W	0.1	1.1	0.8
/10/	N		0.2	
/10/	E		0.1	
/10/	S		0.4	0.2
/10/	W		0.4	0.2
/ 2/	N	0.8	3.7	3.3
/ 2/	E	0.8	2.3	1.0
/ 2/	S	1.2	4.8	2.7
/ 2/	W	0.5	2.4	3.3
/ 5/	N	0.2	0.8	0.3
/ 5/	E	0.3	0.8	0.3
/ 5/	S	0.5	3.1	0.9
/ 5/	W	0.2	0.7	0.2
/ 8/	N	0.1	0.7	0.2
/ 8/	E	0.2	0.5	0.1
/ 8/	S	0.2	1.7	0.8
/ 8/	W	0.1	0.9	0.3
/11/	N		0.1	
/11/	E		0.1	
/11/	S		0.5	0.3
/11/	W		0.3	0.1

	CALM	TOTAL	HOURS	BTU
/ 3/		0.06	42	168.
/ 6/			0	0.
/ 9/		0.25	185	183.
/12/			0	0.
/ 1/	1.1	32.68	24341	67.
/ 4/	0.2	14.97	11152	144.
/ 7/	0.1	6.95	5173	172.
/10/		1.64	1223	197.
/ 2/	0.7	27.40	20408	93.
/ 5/	0.2	8.57	6384	101.
/ 8/	0.1	6.08	4529	155.
/11/		1.49	1107	176.

Table 2 Washington, D.C., Simultaneous weather data for daytime hours (© ARGA Associates).

WASHINGTON, D C

MONTH	DB AVE	STD	DAY AVE	NTE AVE	BTU AVE	WS AVE	STD	RH AVE	STD
JANUARY	36.2	9.1	38.4	34.8	697.2	9.0	3.7	63.1	16.0
FEBRUARY	38.1	8.7	40.2	36.4	985.7	9.3	3.7	60.8	17.2
MARCH	44.8	8.9	47.4	42.4	1283.9	10.0	3.5	57.6	17.3
APRIL	56.2	8.7	58.7	53.2	1603.4	9.6	2.9	58.3	16.7
MAY	65.5	6.9	67.9	61.9	1828.5	8.3	2.4	64.0	14.9
JUNE	74.0	6.0	76.2	70.1	1874.6	7.8	2.3	65.9	11.9
JULY	78.2	4.2	80.6	74.4	1847.9	7.3	2.0	66.7	11.1
AUGUST	76.2	4.4	78.9	72.7	1611.7	7.1	2.2	69.3	10.9
SEPTEMBER	69.4	7.0	72.2	66.4	1285.3	7.4	2.5	69.6	11.1
OCTOBER	59.1	7.3	62.6	56.1	973.6	7.7	3.1	67.9	12.8
NOVEMBER	47.8	8.3	50.5	45.9	657.9	8.1	3.5	64.3	15.2
DECEMBER	37.5	8.6	39.8	36.2	640.1	8.2	3.3	63.0	17.2

DB AVE = Dry Bulb Temperature Average (°F)
STD = standard deviation
DAY AVE = Dry Bulb Temperature Average during Daytime Hours (sunrise to sunset)
NTE AVE = Dry Bulb Temperature Average during Nighttime Hours (sunset to sunrise)
BTU AVE = Average Insolation on Horizontal Surface* (Btu/day)
WS AVE = Wind Speed Average (knots)
RH AVE = Relative Humidity Average

* Insolation is not measured but is calculated from corrected NBS-LD Sun Routine

Table 3 Washington, D.C., monthly summary based on 17 years NOAA data (© ARGA Associates).

Computer simulations of 24 climate design elements were executed for 20 climatically representative test cities for winter conditions (Tables 4 and 5). The results are tabulated as percentage improvements over the performance of a base house in each city and their rank order based on each strategy's effectiveness in each city. From these results, annual heating and cooling benefits were evaluated for selected strategies in 4 climatically representative locations (Tables 6 and 7). The rank orderings are shown to be independent of the one-air-change-per-hour (ach) infiltration rate, and a method for converting to an effective solar fraction is discussed.

The Climate Design Elements

Six different types of strategies are included in the study with reference to their relative effectiveness during a severe winter week in 20 U.S. locations. These are grouped below, and are based on a consistency of behavior that the simulation results showed over the 20-city spectrum: Type 1--geometric modifications; Type 2--buffer zone additions; Type 3--thermal mass additions; Type 4--insulation additions; Type 5--direct solar gain strategies; Type 6--indirect solar gain strategies. In Table 4, the first row for each house (each with a distinct climate design element) is its rank order (out of 24) for each of the 20 cities. The second row is its actual percentage of energy savings during the winter design week, compared to the base house in each city.

Type 1: geometric modifications. This group includes the base house (ws0), the same house facing east (ws9), a house the same in all respects except for a square plan to minimize the external envelope (ws8), and the base house without an attic to give a measure of how much that helps (ws15). It can be seen that the results of these modifications are consistent across all 20 cities.

	MINNEAPOLIS MINN	CHICAGO CHIC	SEATTLE SEAT	OMAHA OMAH	HARTFORD HART	DENVER DENV	SALT LAKE SALT	KANSAS CITY KANS	BOSTON BOST	NEW YORK NYRK	WASHINGTON WASH	DALLAS DALL	ATLANTA ATLA	NEW ORLEANS NEWN	SAN FRANCISCO FRAN	HOUSTON HOUS	MIDLAND, TX MIDL	PHOENIX PHNX	LOS ANGELES LOSA	MIAMI MIAM	
TYPE 1																					
WS0 :	22 0	22 0	21 0	22 0	22 0	22 0	22 0	21 0	22 0	22 0	22 0	21 0	22 0	22 0	22 0	22 0	22 0	21 0	21 0	21 0	BASE HOUSE
WS9 :	23 0	23 0	22 0	23 0	23 0	23 0	23 0	22 0	23 0	23 0	23 0	22 0	23 0	23 1	23 1	23 0	23 0	22 1	22 1	22 0	EAST-WEST FACING
WS8 :	19 -1	20 -1	19 -1	20 -1	23 -1	21 -1	20 -1	20 -1	21 -1	20 -1	20 -1	20 -1	21 -1	21 -1	21 -1	21 -1	21 -1	20 -1	20 0	20 0	SQUARE PLAN
WS15:	24 1	24 2	23 2	24 2	24 2	24 2	24 2	24 2	24 2	24 2	24 2	24 2	24 2	24 3	24 3	24 2	24 2	23 3	23 3	23 4	NO ATTIC (flat roof)
TYPE 2																					
WS22:	6 -5	10 -5	12 -5	13 -5	12 -5	13 -5	14 -5	13 -5	13 -5	14 -5	14 -5	10 -6	12 -6	14 -6	14 -6	13 -7	12 -6	13 -6	15 -7	15 -9	VESTIBULES AT DOORS
WS23:	15 -3	16 -3	17 -3	17 -3	17 -3	17 -3	17 -2	18 -2	17 -3	17 -3	17 -3	16 -4	18 -4	18 -3	18 -4	18 -4	18 -4	17 -5	14 -9	11 -26	NORTH BUFFER ZONE
WS11:	14 -3	14 -3	13 -3	15 -3	15 -3	14 -3	15 -4	15 -4	15 -3	15 -3	15 -4	13 -5	15 -4	15 -5	15 -5	15 -5	15 -5	16 -5	17 -5	18 -5	EARTH BERMS: E,N,W
TYPE 3																					
WS24:	11 -4	12 -5	11 -5	14 -5	14 -5	12 -5	12 -6	11 -5	12 -5	13 -6	13 -6	9 -6	11 -6	10 -10	8 -11	9 -9	11 -6	6 -17	6 -27	4 -74	SLAB, NO INSULATION
WS16:	9 -5	9 -5	10 -6	12 -6	11 -5	8 -6	11 -6	12 -5	11 -6	12 -6	11 -6	8 -6	13 -5	13 -7	12 -10	14 -6	14 -5	8 -12	7 -22	5 -65	SLAB, PERIMETER INSUL
WS19:	21 0	19 -1	15 -3	15 -1	19 -1	19 -2	19 -2	19 -2	19 -2	18 -2	18 -3	12 -5	14 -5	11 -9	10 -11	8 -1C	16 -5	9 -12	8 -21	8 -53	INTERIOR MASONRY
WS30:	20 -1	21 -1	20 -1	21 0	21 -1	20 -1	21 0	23 0	20 -1	21 -1	21 -1	18 -3	20 -1	20 -2	17 -4	2C -3	20 -1	14 -6	11 -16	7 -54	EXTERIOR MASONRY
TYPE 4																					
WS60:	1 -28	1 -31	1 -36	2 -33	2 -33	1 -33	1 -36	1 -34	1 -34	2 -35	1 -38	1 -37	1 -42	1 -52	1 -55	1 -46	2 -41	1 -55	2 -67	2 -88	"SUPER-INSULATION"
WS40:	4 -8	5 -8	4 -9	7 -9	5 -9	6 -9	6 -10	6 -9	6 -9	7 -9	10 -6	5 -10	6 -11	6 -14	7 -14	6 -13	7 -12	7 -15	9 -19	13 -25	R15 NIGHT-SHADES
W28D:	6 -6	7 -6	7 -6	10 -6	13 -5	9 -6	10 -6	9 -6	10 -6	11 -6	9 -7	7 -8	9 -8	12 -9	13 -10	12 -8	10 -8	12 -10	13 -12	14 -17	COMBINE 28b and 28c
W28A:	12 -4	11 -5	8 -6	11 -6	13 -5	10 -6	9 -7	8 -6	9 -6	10 -6	8 -7	15 -4	10 -7	9 -10	9 -11	11 -8	13 -6	11 -11	12 -15	12 -26	INSULATED FLOOR
W28B:	16 -3	15 -3	14 -3	16 -3	16 -3	16 -3	16 -3	16 -3	16 -3	16 -3	16 -3	17 -4	17 -4	16 -5	16 -5	17 -4	17 -4	15 -5	16 -6	16 -9	INCREASE WALL INSUL
W28C:	18 -2	18 -2	18 -2	18 -2	19 -2	18 -2	18 -2	17 -2	18 -2	19 -2	19 -2	19 -3	19 -3	17 -3	20 -3	19 -3	19 -3	19 -3	19 -4	17 -6	INCREASE CEIL INSUL
TYPE 5																					
WS64:	2 -26	2 -27	2 -23	1 -37	1 -35	2 -30	2 -35	2 -31	2 -33	1 -38	2 -37	2 -31	2 -40	2 -51	2 -53	2 -46	1 -49	2 -50	3 -63	3 -88	WS19,W28a,W28d,W42a
W42A:	3 -18	3 -20	3 -15	3 -28	3 -26	3 -21	3 -25	3 -23	3 -23	3 -29	3 -25	3 -20	3 -28	4 -30	4 -31	3 -3C	4 -33	4 -25	5 -28	9 -33	WS42 w/R15 SHADES
WS42:	17 -2	17 -2	24 3	5 -11	8 -7	15 -3	13 -5	14 -4	14 -4	6 -10	12 -6	23 0	16 -4	19 -3	19 -4	16 -4	9 -8	24 5	24 7	24 17	SOUTH GLASS 26%FA
WS41:	13 -4	13 -4	16 -3	8 -8	7 -3	11 -6	8 -8	10 -5	8 -7	9 -8	6 -10	14 -5	7 -9	8 -11	11 -10	1C -8	6 -12	18 -5	18 -5	19 -3	SOUTH GLASS 10%FA
TYPE 6																					
WS29:	5 -6	4 -9	9 -6	4 -15	4 -13	4 -13	4 -16	4 -10	4 -17	4 -17	4 -19	4 -16	4 -20	3 -41	3 -42	4 -29	3 -35	3 -49	1 -74	1 -94	TROMBE WALL/R5 SHADE
W20A:	7 -5	6 -7	5 -8	6 -1C	6 -9	5 -9	5 -11	5 -9	5 -11	5 -11	5 -12	6 -9	5 -12	5 -22	5 -24	5 -17	5 -15	5 -23	4 -35	6 -57	GREENHOUSE w/SHADES
WS20:	10 -5	8 -6	6 -7	9 -7	9 -7	7 -7	7 -8	7 -7	7 -8	8 -8	7 -9	11 -6	8 -9	7 -13	6 -14	7 -11	8 -9	10 -12	10 -17	10 -29	GREENHOUSE

Table 4 Evaluation of 24 design elements by type and by city (winter week)

ORDER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
ZONE 1																								
MINN	TAVE -3	TLOW -16	DBTU 485	WINC 12	TGRD 38	DGD 488	INFL 69	ENVL 31																
	WS60 -28	WS64 -24	W42A -18	WS40 -8	WS29 -6	W28D -6	W20A -5	WS22 -5	WS16 -5	WS20 -5	WS24 -4	W28A -4	WS41 -4	WS11 -3	WS23 -3	W28B -3	WS42 -2	W28C -2	WS8 -1	WS30 -1	WS19 0	WS0 0	WS9 0	WS15 1
CHIC	TAVE 10	TLOW 0	DBTU 674	WINC 11	TGRD 42	DGD 382	INFL 70	ENVL 30																
	WS60 -31	WS64 -27	W42A -20	WS29 -9	WS40 -8	W20A -7	W28D -6	WS20 -6	WS16 -5	WS22 -5	W28A -5	WS24 -5	WS41 -4	WS11 -3	W28B -3	WS23 -3	WS42 -2	W28C -2	WS19 -1	WS8 -1	WS30 -1	WS0 0	WS9 0	WS15 2
SEAT	TAVE 26	TLOW 23	DBTU 291	WINC 10	TGRD 45	DGD 256	INFL 73	ENVL 27																
	WS60 -36	WS64 -23	W42A -15	WS40 -5	W20A -8	WS20 -7	W28D -6	W28A -6	WS29 -6	WS16 -6	WS24 -5	WS22 -5	WS11 -3	W28B -3	WS19 -3	WS41 -3	WS23 -3	W28C -2	WS8 -1	WS30 -1	WS0 0	WS9 0	WS15 2	WS42 3
SUM ZON1	WS60 -32	WS64 -25	W42A -17	WS40 -8	W20A -7	WS29 -7	W28D -6	WS20 -6	WS16 -5	WS22 -5	W28A -5	WS24 -5	WS41 -4	WS11 -3	W28B -3	WS23 -3	W28C -2	WS19 -1	WS8 -1	WS30 -1	WS42 0	WS0 0	WS9 0	WS15 2
ZONE 2																								
OMAH	TAVE 9	TLOW 1	DBTU 848	WINC 9	TGRD 43	DGD 391	INFL 72	ENVL 28																
	WS64 -37	WS60 -33	W42A -28	WS29 -15	WS42 -11	W20A -10	WS40 -9	WS41 -8	WS20 -7	W28D -6	W28A -6	WS16 -6	WS22 -5	WS24 -5	WS11 -3	W28B -3	WS23 -3	W28C -2	WS19 -1	WS8 -1	WS30 0	WS0 0	WS9 0	WS15 2
HART	TAVE 12	TLOW -4	DBTU 728	WINC 10	TGRD 43	DGD 370	INFL 72	ENVL 28																
	WS64 -35	WS60 -33	W42A -26	WS29 -13	WS40 -9	W20A -9	WS41 -8	WS42 -7	WS20 -7	W28D -6	WS16 -5	WS22 -5	W28A -5	WS24 -5	WS11 -3	W28B -3	WS23 -3	W28C -2	WS19 -1	WS8 -1	WS30 -1	WS0 0	WS9 0	WS15 2
DENV	TAVE 15	TLOW -2	DBTU 822	WINC 11	TGRD 43	DGD 346	INFL 72	ENVL 28																
	WS60 -33	WS64 -30	W42A -21	WS29 -13	W20A -9	WS40 -9	WS20 -7	WS16 -6	W28D -6	W28A -6	WS41 -6	WS24 -5	WS22 -5	WS11 -3	WS42 -3	W28B -3	WS23 -3	W28C -2	WS19 -2	WS30 -1	WS8 -1	WS0 0	WS9 0	WS15 2
SALT	TAVE 15	TLOW 0	DBTU 825	WINC 5	TGRD 43	DGD 345	INFL 72	ENVL 28																
	WS60 -36	WS64 -35	W42A -25	WS29 -16	W20A -11	WS40 -10	WS20 -8	WS41 -8	W28A -7	W28D -6	WS16 -6	WS24 -6	WS42 -5	WS22 -5	WS11 -4	W28B -3	WS23 -2	W28C -2	WS19 -2	WS8 -1	WS30 0	WS0 0	WS9 0	WS15 2
KANS	TAVE 17	TLOW 5	DBTU 792	WINC 7	TGRD 44	DGD 332	INFL 72	ENVL 28																
	WS60 -34	WS64 -31	W42A -23	WS29 -10	W20A -5	WS40 -9	WS20 -7	W28A -6	W28D -6	WS41 -5	WS24 -5	WS16 -5	WS22 -5	WS42 -4	WS11 -4	W28B -3	W28C -2	WS23 -2	WS19 -2	WS8 -1	WS0 0	WS9 0	WS30 0	WS15 2
BOST	TAVE 19	TLOW 10	DBTU 729	WINC 13	TGRD 41	DGD 319	INFL 74	ENVL 26																
	WS60 -34	WS64 -33	W42A -23	WS29 -17	W20A -11	WS40 -9	WS20 -8	WS41 -7	W28A -6	W28D -6	WS16 -6	WS24 -5	WS22 -5	WS42 -4	WS11 -3	W28B -3	WS23 -3	W28C -2	WS19 -2	WS30 -1	WS8 -1	WS0 0	WS9 0	WS15 2
NYRK	TAVE 23	TLOW 10	DBTU 793	WINC 14	TGRD 44	DGD 292	INFL 75	ENVL 25																
	WS64 -38	WS60 -35	W42A -29	WS29 -17	W20A -11	WS42 -10	WS40 -9	WS20 -8	WS41 -8	W28A -6	W28D -6	WS16 -6	WS24 -6	WS22 -5	WS11 -3	W28B -3	WS23 -3	WS19 -2	W28C -2	WS8 -1	WS30 -1	WS0 0	WS9 0	WS15 2
WASH	TAVE 23	TLOW 17	DBTU 798	WINC 10	TGRD 44	DGD 288	INFL 70	ENVL 30																
	WS60 -36	WS64 -37	W42A -25	WS29 -19	W20A -12	WS41 -10	WS20 -9	W28A -7	W28D -7	WS40 -6	WS16 -6	WS42 -6	WS24 -6	WS22 -5	WS11 -4	W28B -3	WS23 -3	WS19 -3	W28C -2	WS8 -1	WS30 -1	WS0 0	WS9 0	WS15 2
DALL	TAVE 20	TLOW 22	DBTU 856	WINC 7	TGRD 61	DGD 239	INFL 80	ENVL 20																
	WS60 -37	WS64 -31	W42A -20	WS29 -16	WS40 -13	W20A -9	W28D -8	WS16 -6	WS24 -6	WS22 -6	WS20 -6	WS19 -5	WS11 -5	WS41 -5	W28A -4	WS23 -4	W28B -4	WS30 -3	W28C -3	WS8 -1	WS0 0	WS9 0	WS42 0	WS15 2
SUM ZON2	WS60 -36	WS64 -33	W42A -24	WS29 -15	W20A -13	WS40 -9	WS20 -8	WS41 -7	W28D -7	W28A -6	WS16 -6	WS24 -5	WS42 -5	WS22 -5	WS11 -4	W28B -3	WS23 -3	W28C -2	WS19 -2	WS8 -1	WS30 0	WS0 0	WS9 0	WS15 2
ZONE 3																								
ATLA	TAVE 34	TLOW 10	DBTU 800	WINC 7	TGRD 55	DGD 213	INFL 83	ENVL 17																
	WS60 -42	WS64 -40	W42A -28	WS29 -20	W20A -12	WS40 -11	WS41 -9	WS20 -9	W28D -8	W28A -7	WS24 -6	WS22 -6	WS16 -5	WS19 -5	WS11 -4	WS42 -4	W28B -4	WS23 -4	W28C -3	WS30 -1	WS8 -1	WS0 0	WS9 0	WS15 2
NEWN	TAVE 42	TLOW 33	DBTU 965	WINC 6	TGRD 56	DGD 156	INFL 96	ENVL 4																
	WS60 -52	WS64 -51	WS29 -41	W42A -30	W20A -22	WS40 -14	WS20 -13	WS41 -11	W28A -10	WS24 -10	WS19 -9	W28D -9	WS16 -7	WS22 -6	WS11 -5	W28B -5	W28C -3	WS23 -3	WS42 -3	WS30 -2	WS8 -1	WS0 0	WS9 1	WS15 3
FRAN	TAVE 43	TLOW 41	DBTU 689	WINC 7	TGRD 57	DGD 152	INFL 100	ENVL 0																
	WS60 -55	WS64 -53	WS29 -42	W42A -31	W20A -24	WS20 -14	WS40 -14	WS24 -11	W28A -11	WS19 -11	WS41 -10	WS16 -10	W28D -10	WS22 -6	WS11 -5	W28B -5	WS30 -4	WS23 -4	WS42 -4	W28C -3	WS8 -1	WS0 0	WS9 1	WS15 3
HOUS	TAVE 44	TLOW 33	DBTU 868	WINC 14	TGRD 61	DGD 115	INFL 99	ENVL 1																
	WS60 -46	WS64 -46	W42A -30	WS29 -29	W20A -17	WS40 -13	WS20 -11	WS19 -10	WS24 -9	WS41 -8	W28A -8	W28D -8	WS22 -7	WS16 -6	WS11 -5	WS42 -4	W28B -4	WS23 -4	W28C -3	WS30 -3	WS8 -1	WS0 0	WS9 0	WS15 2
MIDL	TAVE 30	TLOW 21	DBTU 1240	WINC 9	TGRD 61	DGD 239	INFL 84	ENVL 16																
	WS64 -49	WS60 -41	WS29 -35	W42A -33	W20A -15	WS41 -12	WS40 -12	WS20 -9	WS42 -8	W28D -8	WS24 -6	WS22 -6	W28A -6	WS16 -5	WS11 -5	WS19 -5	W28B -4	WS23 -4	W28C -3	WS30 -1	WS8 -1	WS0 0	WS9 0	WS15 2
SUM ZON3	WS64 -46	WS60 -46	WS29 -34	W42A -30	W20A -13	WS40 -13	WS20 -11	WS41 -10	W28D -9	W28A -8	WS24 -8	WS19 -8	WS16 -7	WS22 -6	WS11 -5	WS42 -5	W28B -4	WS23 -4	W28C -3	WS30 -2	WS8 -1	WS0 0	WS9 0	WS15 3
ZONE 4																								
PHNX	TAVE 44	TLOW 40	DBTU 969	WINC 4	TGRD 65	DGD 145	INFL 99	ENVL 1																
	WS60 -55	WS64 -50	WS29 -49	W42A -25	W20A -23	WS24 -17	WS40 -15	WS16 -12	WS19 -12	WS20 -12	W28A -11	W28D -10	WS22 -6	WS30 -6	W28B -5	WS11 -5	WS23 -5	WS41 -5	W28C -3	WS8 -1	WS0 0	WS9 1	WS15 3	WS42 5
LOSA	TAVE 49	TLOW 46	DBTU 1047	WINC 7	TGRD 57	DGD 107	INFL 118	ENVL -18																
	WS29 -74	WS60 -67	WS64 -63	W20A -35	W42A -24	WS24 -27	WS16 -22	WS19 -21	WS40 -19	WS20 -17	WS30 -16	W28A -15	W28D -12	WS23 -9	WS22 -7	W28B -6	WS11 -5	WS41 -5	W28C -4	WS8 0	WS0 0	WS9 1	WS15 3	WS42 7
MIAM	TAVE 60	TLOW 54	DBTU 1100	WINC 6	TGRD 61	DGD 42	INFL 161	ENVL -61																
	WS29 -94	WS60 -88	WS64 -88	WS24 -74	WS16 -65	W20A -57	WS30 -54	WS19 -53	W42A -33	WS20 -29	WS23 -26	W28A -26	WS40 -25	W28D -17	WS22 -9	W28B -9	W28C -6	WS11 -5	WS41 -3	WS8 0	WS0 0	WS9 0	WS15 4	WS42 17
SUM ZON4	WS29 -72	WS60 -70	WS64 -67	WS24 -39	W20A -39	WS16 -33	W42A -28	WS19 -28	WS30 -25	WS40 -20	WS20 -19	W28A -18	WS23 -14	W28D -13	WS22 -7	W28B -7	WS11 -5	W28C -5	WS41 -4	WS8 0	WS0 0	WS9 1	WS15 4	WS42 10

2.2.18

Table 5 Rank order of 24 design elements by city and by zone (winter week)

	RANK ORDER 1	2	3	4	5	6	
	A60	A64	A29	A11	A30	A0	
BOSTON	-60.8	-55.8	-52.7	- 7.4	- 5.7	0.0	percent SHF
	15.1	17.1	18.3	35.8	36.5	38.7	Heating
	A29	A64	A60	A30	A11	A0	
NEW ORLEANS	-91.7	-91.0	-87.4	-60.0	-11.4	0.0	percent SHF
	0.4	0.4	0.5	1.7	3.7	4.2	Heating
	A29	A60	A64	A30	A11	A0	
LOS ANGELES	-98.3	-97.8	-97.6	-72.0	-12.3	0.0	percent SHF
	0.1	0.1	0.1	1.6	5.1	5.9	Heating
	A60	A64	A29	A11	A30	A0	
SEATTLE	-67.7	-53.1	-46.2	- 7.8	- 7.2	0.0	percent SHF
	9.2	13.4	15.4	26.4	26.5	28.6	Heating

Table 6 Rank orders for 5 climate design elements in 4 representative cities

percent SHF = percent solar heating fraction equivalent to annual heating savings
Heating = annual heating energy requirement, millions of Btu
A64 = Passive combination
A60 = Super-insulation
A30 = Block wall construction (insulated on exterior)
A29 = Trombe wall with R-5 night-shade
A11 = Earth berms halfway up west, north, and east walls
A0 = Base house

	BASE CASE Y0	EARTH-BERMS Y11	TROMBE-WALLS Y29	BLOCK WALL Y30	PASSIVE COMBINATION Y64	SUPER-INSULATION Y60	
	38.7	35.8	18.3	36.5	17.1	15.1	Heating
BOSTON	6.8	6.4	11.1	4.8	10.6	10.6	Cooling
	45.5	42.2	29.4	41.2	27.7	25.7	TOTAL
	4.2	3.7	0.4	1.7	0.4	0.5	Heating
NEW ORLEANS	17.6	16.8	23.8	17.5	19.6	21.3	Cooling
	21.8	20.5	24.2	19.2	19.9	21.8	TOTAL
	5.9	5.1	0.1	1.6	0.1	0.1	Heating
LOS ANGELES	5.3	5.2	8.4	3.0	7.5	8.2	Cooling
	11.1	10.3	8.5	4.7	7.7	8.4	TOTAL
	28.6	26.4	15.4	26.5	13.4	9.2	Heating
SEATTLE	2.6	2.4	4.3	0.9	5.2	4.4	Cooling
	31.1	28.8	19.6	27.4	18.6	13.6	TOTAL

Table 7 Annual heating and cooling loads (MBtu): 6 elements in 4 cities

The base house obviously never improves upon itself; the same house without attic uses about 2 percent more energy in most places. With the square house and rotated house, there is an equal amount of glass on all 4 sides so that what is really being measured is the effect of changing wall and roof surface size and orientation. The square house shows about a 1-percent improvement, whereas the east-facing one shows a very slight increase in energy use. This does not reflect what would happen if one side of the building had more glass than the others, only the effect of changing shape.

Type 2: buffer zone additions. The three modifications included here are a north-facing unheated buffer zone (ws23), vestibules on both doors (ws22), and earth berming half-way up the side of the main living area on the east, west, and north sides (ws11). Adding vestibules corresponds to a 10-percent reduction in infiltration in the main area, a figure that is conservative but reflects the main thrust of this modification. With the earth berming, the insulation is on the outside of the walls of the house, thus precluding the berm's use as thermal mass. With these examples the gains are modest, and fairly consistent irrespective of available sunshine, although improving in the warmer climates.

Type 3: thermal mass additions. This set of modifications consists of a house with an uninsulated 4-inch concrete slab instead of a basement (ws24), and one with a perimeter-insulated 4-inch ground slab (ws16). Two more houses with basements include one with a 1-foot wide concrete wall dividing the main area into an east and west zone (ws19), and one with exterior-insulated 8-inch block walls instead of 2x4 stud walls (ws30). Here, all the modifications are considerably more effective where there is more sun to charge the mass and a lower temperature differential to drain that charge. This draining of charge is further shown by the fact that the best performers have similar ground temperatures adjacent to them (ws24 and ws16). In the next best case, the mass is located on an interior wall away from the outside walls but "out of" the direct sun (ws19). In the least effective case, its mass is in the outside wall system (ws30).

Type 4: insulation additions. Here insulation thickness is improved in various parts of the building. The uninsulated floor is given 6 inches of fiberglass resulting in an R value of 22 (w28a); the walls are increased to 5.5 inches of fiberglass, R 22 (w28b); the ceiling insulation is increased to 9 inches to yield an R 29 value (w28c), and both the wall and ceiling improvements are combined (w28d). There is also an alternative where insulating shades of R 15 were used between 6 pm and 8 am (ws40), and a super-insulated house (Saskatchewan House specifications; see Energy Research Development Group, 1979) with R 15 shades, R 60 ceiling, R 40 walls, and R 33 floor (ws60). All of these strategies can be seen to be temperature-dependent with little effect from available solar input. Adding floor insulation (w28a) is as effective as adding both wall and ceiling insulation combined (w28d), and insulating the double-glazed windows with night shades (ws40) is even more effective. The super-insulated house can be seen to be one of the two most efficient houses in all U.S. climates, although achieving the 16 inches of ceiling fiberglass, 12 inches of wall fiberglass, and 9 inches of floor insulation is costly in terms of conventional construction. In some cities, the solar passive approach is better and it is never far behind the super-insulation option in any location in the United States.

Type 5: direct solar gain strategies. This group progresses from increasing the south glass to 10 percent of the floor area or 150 square feet (ws41), to increasing it to 26 percent of the floor area or 364 (w42). To this, R 15 night shades are added (ws42a), and finally a 1-foot thick concrete wall is added, dividing it into east and west zones, and the same wall and ceiling insulation as w28d is added (ws64). Both ws41 and ws42 show that extra glass area for direct gain alone, without night shades or mass to retain the extra energy, can become a liability, although the 10-percent strategy is more moderate in its effect and is even quite helpful in some areas. Simply adding night shades greatly improves the performance of these attempts and stabilizes its benefits across all the climates. When a storage mass is added it becomes one of the best alternatives explored. A word of caution here is that these examples all tend to overheat. This means that some control must be gained to make them a more even-tempered set of strategies. This may mean venting to the outside or using the sun-shading devices for overheating periods. In Minneapolis, where the average temperature for the week was -3°F, this was not a problem.

Type 6: indirect solar gain strategies. This last group of alternatives addresses the control problems of the previous set by separating the direct gain zones from the living zones. This is done by adding an unvented 1-foot-thick Trombe wall with a night insulation of R 5 (ws29), or a 20-foot x 6-foot unheated greenhouse to the south face of the base building. One version of the greenhouse has a sliding door that is closed at night and has the regular insulated wall between the living area and the greenhouse (ws20). The other version has a 1-foot-thick concrete wall and night-closed door between zones, and R 5 shades for the greenhouse itself (w20a). None of these overheat to any extent, and the "control" gained is purely passive. This extra control does cost slightly in performance and, although the savings are quite good, there is some loss of efficiency because of the separation of functions. As with the direct gain strategies in climates with less sun, such as Seattle or Minneapolis, these are less effective because of the lack of solar gain to "drive" them.

REGIONAL CLASSIFICATION BASED UPON CLIMATE DESIGN STRATEGIES

If the data are reorganized and listed in rank order for each city (as in Table 5), a different aspect of this study comes to light. First, it has become possible to distinguish four types of zones. These zones are not based upon the traditional weather parameters, but rather, on the behavior of the set of test houses. The four zones are all defined by a house's response to the combined effect in each city of winter temperatures, wind speeds, ground temperatures, and solar flux.

In Zone 1 insulation strategies are the most effective. Solar options, both direct and indirect, are helpful but not as much as in the other zones. An example is the Trombe wall (ws29), which is half as effective as in Zone 2, even though it still averages as the sixth best alternative in Zone 1. This zone could be best characterized as a cloudy northern climate where direct solar design elements do not cause overheating and are superior to indirect solar design elements because of the lack of solar flux to overcome their inefficiencies. Seattle is most representative of this zone.

Zone 2 includes the whole mid-section of the country and the northeastern coastal cities. It is typified by the consistency of the effects of the first six strategies across all nine cities. Both direct and indirect solar options are excellent, although indirect elements still lag behind direct ones. In these cities there is only minor overheating with direct gain. Boston is most representative of this zone.

Zone 3 could be characterized as the warm-temperate maritime climate. In this zone the indirect solar strategies perform better than the direct gain ones, if overheating is considered they are far superior. In this zone the thermal mass additions play a more important role in heat retention and tempering. Los Angeles is most representative of this zone.

Zone 4 includes truly warm locations, with little significant winter space heating demand. What must be accomplished in these cities is best done by indirect solar gain elements and the addition of thermal mass. It is also interesting to note that insulation additions are effective and cause little overheating in themselves. New Orleans is most representative of this zone.

A RATING SYSTEM BASED UPON PERCENT SOLAR HEATING FRACTION

Table 5 gives the climatic data for each city (during the winter design week). The infiltration rate loss (INFL) and the envelope rate loss (ENVL) are shown for each location for use in the following formula, which yields an effective solar fraction for each strategy for any selected air infiltration rate:

$$\frac{\text{Savings x -100}}{\text{((rate per hour x INFL)+ENVL)}} = \text{\% solar}$$

This calculation is possible because infiltration and the other envelope heat transfers are independent of each other as long as it is assumed that enough heat will be supplied by the mechanical system to keep the room temperature constant. An example of the way this formula works for was 64 in Omaha with 1 ach follows:

$$\frac{-3/ \text{ x } -100}{((1. \text{ x } 72.)+ 28.)} = 37 \text{ percent solar}$$

The quantities for INFL and ENVL are the same as that in Table 5. For the calculation for 1/4, 1/2, 1, 2, and 4 ach the solar fractions possible for this strategy are 80, 58, 37, 22, and 12 percent, respectively. This variation points out the problems inherent in representing a solar fraction for a passive solar building. In an attempt to overcome this problem, it would be more accurate to make comparisons in terms of the "effective solar fraction," based on the 1 ach standard as in the accompanying tables. This choice of a unity figure then allows for interpolations of results to other infiltration rates and gives a clean basis for comparison between complementary studies.

COMPARING WINTER WEEK AND ANNUAL RESULTS

The approach presented here gives a basis for comparison of the performance of different building design options, to be used in the initial decisionmaking phases of the building design process. This approach is characterized by dynamic simulation of the total building as a thermal system, rather than the analysis of individual components. It can be seen from some of the winter results that the combination of two components may have more than an additive result. For example, combining the insulated shades (ws40) and the 26-percent south glazing (ws42) produces savings greater than the simple addition of their individual savings.

To further develop this approach, more work is required to study the effects of changing system sizes, changing building sizes, and exploring the relationship between the design week and the full year energy usages. Summer cooling energy costs also need to be considered. To explore the year-round implications, the most representative building element was selected from each of the six types described above and simulated with respect to the base house in the "representative city" for each of the four climatic zones (Table 6), using a standard year.

In comparison with the previous winter week simulation (Table 5), the rank ordering has remained the same when based on the annual heating load for three out of the four cities. For New Orleans, there are some changes between the winter week and the annual result, where the block construction with exterior insulation (A30) has improved greatly. This is because the winter design week is a severe case, in that the benefit of thermal mass is least effective. Thermal mass is most effective when ambient temperatures are close to comfort conditions to begin with, which typifies the New Orleans climate. In fact, in all four cities there is an across-the-board improvement in "solar fraction" due to the thermal mass effect in milder "swing" weather periods. This indicates that the solar fractions based on a severe winter week as given in Table 5 are conservative and biased away from mass addition strategies.

Table 7 represents a classification of the same climatic design elements in the same representative cities, but includes both heating and cooling loads. The first line under each element is the annual heating requirement, the second line the annual cooling requirement (assuming no venting but mechanical air conditioning above 80^{o}F), with the total in million Btu (MBtu) given on the third line. In each case, there is a significant difference in the ratio of heating load to cooling load, based not only on the city but also on the design modification. The ratio of heating load to cooling load is thus an index of the effectiveness of a particular strategy with respect to the base case and is a measure of the remaining energy expenditures required. For example, in the Boston base house, the ratio of heating load to cooling is 38.7 to 6.8 MBtu or approximately 4.7 to 1. With the superinsulated house in the same location it is 1.4 to 1; with the passive solar house, in

Boston, it is 1.6 to 1. If one of these alterations were used as the primary modification to a building, the designer would then want to consider a secondary strategy that would bring the ratio to unity. In climates biased strongly toward heating (cool climates) or cooling (warm climates), both primary and secondary modifications would be mutually supportive and beneficial, whereas in climates where there exists a balance of heating and cooling (temperate climates), there may be conflicting choices: adding insulation would reduce the heating load but might increase the cooling requirement. In Table 6, the only modifications that reduce cooling as well as heating energy are the earth-berms and the block-wall construction, but when used alone, these give the least improvement in reducing the heating energy requirement.

This analysis is limited to the specific building type, and the particular modifications considered, but it does indicate a fruitful avenue of climatic design research. From the analysis, it can be seen that neither geographical region nor degree-day variation provides an adequate index of energy requirements. With the computer simulation capability now available, climate design recommendations can be identified based on specific building design configurations, considering internal load, thermal storage, and ambient climate variations as interdependent system variables. In this way, climatic design can become building-specific, rather than being based upon extrapolation or region-wide generalizations.

CLIMATIC DESIGN APPROACHES FOR NORTHERN TEMPERATE ZONES

In the previous sections, it has been argued that a climate-based approach to building design based exclusively on macroregional climatic data is unsatisfactory if the entire range of local microclimate and resulting building system choices are not represented in the conclusions. Parametric analysis of alternatives, now possible with computer simulation, can replace the regional guideline approach and will help identify passive system combinations that can be used in any climate, subject only to differences in sizing and detailing to accommodate variations in specific interior and exterior climatic loads. A building, such as the super-insulated house or the passive solar house in Boston (Table 6), may have nearly equal annual heating and cooling loads, even though the local climate is characterized by a considerable difference between heating degree-days and cooling degree-days (Figure 6). If one accepts the Olgyays' characterization of temperate climate (as depicted in Figure 1) and represented by New York, then the temperate climate zone in the United States is predominantly underheated but has sufficient sunshine even during a severe winter week so that passive solar approaches are as effective as super-insulation, with the one caveat that the building will overheat if solar gain is not controlled in the spring, summer, and fall seasons. Thus, without having to agree on whether a locality is a "temperate" zone or not (e.g., in Table 4, the climatic design responses appropriate to Dallas, Texas, are similar in rank order to those for New York, even though Dallas is normally considered a southern climate location), a common group of problems characterizes climate design in the so-called temperate areas:

- Temperate zones experience heating <u>and</u> cooling loads, but within limits that make large contributions of passive heating and cooling both possible and practical. (The author holds that this is the case for all U.S. localities, but with reference to temperate zones, there should be little disagreement with this position.)

- In temperate zones, there is a choice of climatic design elements by which to achieve a totally passive result, any combination of which may be as effective as another.

- The balance or combination of climate design elements is the concern in temperate zones so that neither heating nor cooling requirements are increased by one element or another. (Table 3 shows examples of passive heating elements that increase the cooling load.)

- Some climatic design elements are more appropriate or practical than others in temperate zones because they serve <u>both</u> heating and cooling needs. Foremost of these are solar control/shading elements and mass elements, including underground coupling.

- Finally, with regard to international applications, comprehensive approaches to passive heating and cooling need to be incorporated into the building programs of developing nations, some of which have temperate and cool climatic zones, and nearly all of which have energy and technical resource limitations that make passive approaches mandatory.

The pathways of energy exchange between a building and its microclimate follow the principles of heat transfer by conduction, convection, radiation, and evaporation (Figure 13). The basic climatic design strategies follow these principles in order to promote heat gains and resist losses in the winter or underheated season and to resist heat gains and promote losses in the summer or overheated seasons. (Figure 14). Of these, there are only five or six major passive design strategies in each season. In the winter, one may minimize conductive heat flow, maximize solar gain, minimize external air flow, minimize infiltration, and delay periodic heat flow. In summer, the available measures are: minimizing conductive heat flow, minimizing solar gain, promoting ventilation, promoting radiant heat loss, promoting evaporative cooling, and delaying periodic heat flow.

It is possible to determine which passive design strategies will be effective in United States localities by reference to Table 1, which indicates the percentage of hours per year during which the appropriate climatic conditions exist.

Each of the passive strategies is met by climatic design elements from site planning decisions ranging to detailed envelope variations. Some elements, such as orientation to the winter sun, satisfy only one strategy (i.e., to promote winter solar gain). Others, such as underground building, satisfy multiple strategies for underheated <u>and</u> overheated seasons (in winter, minimize conductive heat flow, minimize external flow, minimize infiltration, delay periodic heat flow; in summer, minimize conductive heat flow, minimize solar gain, and delay periodic heat flow).

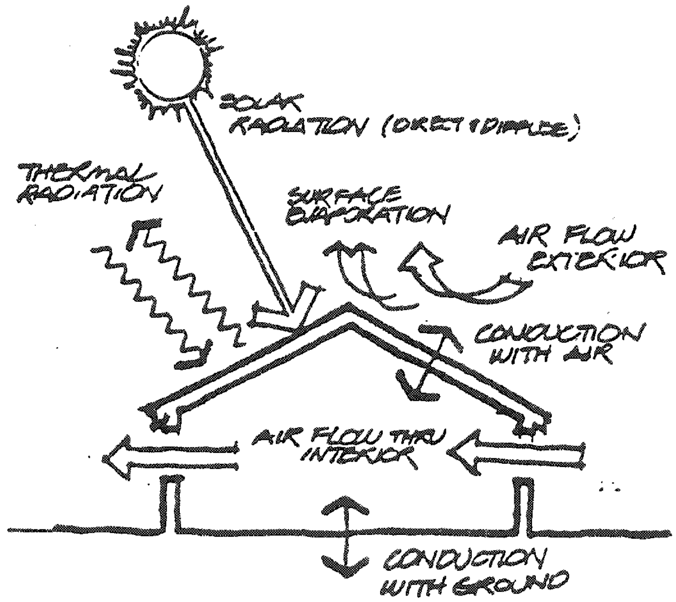


Figure 13 Paths of energy exchange in a low-rise building

		CONDUCTION	CONVECTION	RADIATION	EVAPORATION
Winter	PROMOTE GAIN	delay periodic heat flow +		maximize solar gain	
Winter	RESIST LOSS	minimize conductive flow	minimize air flow	minimize reradiation	minimize moisture loss
Summer	RESIST GAIN	minimize conductive flow	minimize air flow*	minimize solar gain	
Summer	PROMOTE LOSS	delay periodic heat flow +	promote ventilation*	promote radiant cooling	promote evap. cooling

Figure 14 Summary of climatic design strategies

Figure 15 shows various types of passive heating systems that have been built or are proposed for northern United States locations. In many of these system types, passive cooling modes can be included, as will be described below.

In all of the variations, shading during the overheated period is necessary to prevent undesired heat gain. Any fixed shading presents the problem of blocking the sun during the spring (for example, March-April, when some passive solar heating is desired) in order to also block the sun during the late summer (e.g., August-September, when the overheated period peaks.) The rule of thumb to provide 50 percent shading during the overheated period as recommended by Olgyay and Olgyay (1957) is unsatisfactory if totally effective passive heating and cooling is desired. Countering overheating effects with thermal mass provides a partial solution, but not as effectively as shading devices that can be adjusted to the changing seasonal needs. New calculation and design approaches to solar control devices are therefore part of the current research interest in passive cooling.

Direct Gain and Isolated Gain Approaches

1.a: Direct gain with earth-coupling. The "prototypical" direct gain system overheats the occupied space. Thermal storage is desirable directly exposed to the sun or, if this is not possible, then in the walls and ceiling. Earth-coupling, such as through slab-on-grade construction, offers storage capacity in the earth below the structure, provided it is insulated around its entire perimeter. Summer cooling can also be improved by the increased thermal capacity of the structure.

1.b: Direct-gain clerestory and thermal chimney. The advantages of the clerestory in a direct gain system are first, solar radiation is admitted directly to thermal storage on the north wall, and second, the high space permits temperature stratification so that the lower occupied area is somewhat relieved of the overheating effects.

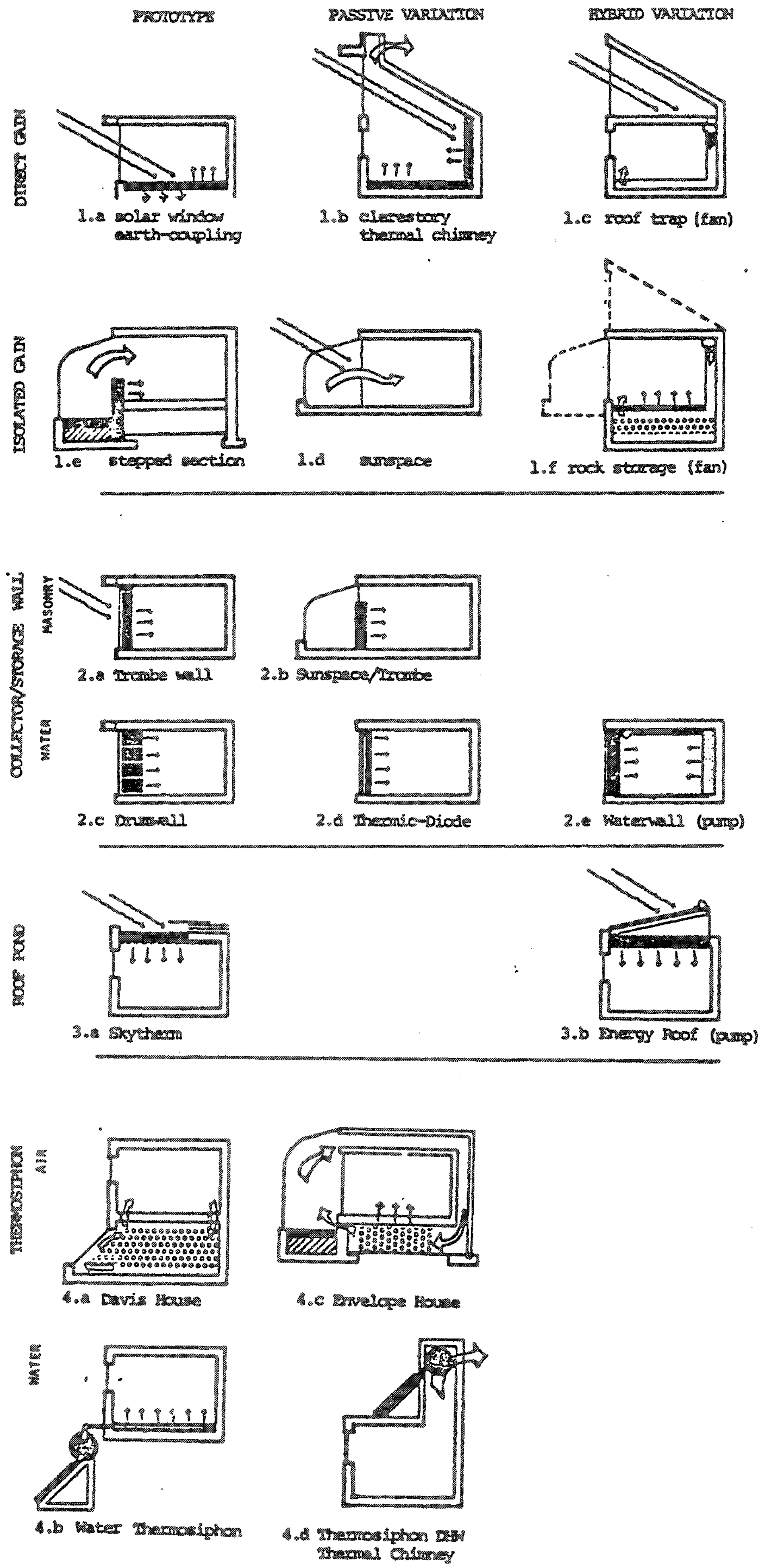


Figure 15 Passive solar heating and cooling combinations

The clerestory can be used also to control glare by indirect (ceiling-reflected) natural lighting. In summer, the high space can be designed to serve as a thermal chimney for induced ventilation by the stack effect.

1.c: Roof trap. The roof trap variation is best represented by proposals by Baruch Givoni, in which case it is a fan-assisted solar heating system in winter and a natural cooling system in summer. In United States variations, the attic space has been used as a built-in solar collector (U.S. Department of Agriculture, 1977) and combination skylight and thermal chimney ventilator.

1.d: Sunspace-isolated gain. This variation of the direct gain approach isolates the solar collector from the occupied space by a movable wall. Thermal storage placed in the sunspace would delay the "charging" time required before the air overheats so that design judgment is required to decide between designing for "quick warm-up" or for thermal storage within the sunspace itself. The latter approach is preferable if a sunspace is opened in summer for night cooling.

1.e: Sunspace - direct gain. A noteworthy variation of the isolated sunspace eliminates the operable wall between sunspace and occupied space and relies instead on a parapet wall, which creates a barrier and prevents cool air from dropping from the occupied space during winter. In houses built with this variation in Reno, Nevada, builder Paul Neuffer reports that the upper occupied zone maintains temperature swings from 65°F to 75°F, while the sunspace ranges from 90°F during the day to 50°F at night. The advantage is that some isolation and control is gained between sunspace and occupied space without adding the construction cost of an operable wall. However, there is no advantage gained for summer cooling modes over the other direct gain systems.

1.f: Rock-bed under radiant slab. An alternate to placing the thermal mass directly in the sun is to use a rock bed, usually fan charged, which stores heat recovered from direct gain or isolated gain collector spaces and releases it through a radiant slab above the rock bed. In this way, heat in the range of 75-80°F is recovered and utilized. This component has been widely used in the U.S. with passive gain systems.

(Calthorpe, 1979). Like a rock-bed in an active system, it can be cooled during summer nights in order to be available for cooling as a heat sink during the next day.

Collector / Storage Wall Approaches

2.a: Trombe collector/storage wall (masonry). This is one of the best known passive solar systems. Calculation procedures for design application have been developed by Douglas Balcomb and others at Los Alamos Scientific Laboratory (Balcomb, Hedstrom, and McFarland, 1979). Because of its time-delay capacity, it is the best of all the alternatives for winter heating in southern U.S. cities that have little daytime heat requirement and that thereby preclude direct gain approaches (Table 5).

2.b: Sunspace/Trombe combination. This is an obvious variation of the Trombe wall, offering advantages of easy window management: insulating night-shades can be closed at night manually; in summer the sunspace can be completely vented and the wall fully shaded.

2.c - 2.e Water wall variations. The "Drumwall" developed by Steve Baer is an alternative thermal mass system, and has both advantages and disadvantages when compared to masonry (Balcomb, Hedstrom, and McFarland, 1979). If the occupied space is vented during summer nights for cooling, the water wall could possibly cool more rapidly, due to the large exposed surface area. The "thermic-diode" panel (2.d) has been proposed by Professor Shawn Buckley, M.I.T. School of Mechanical Engineering, as a collector/storage wall panel for passive heating and cooling, but at present is being developed only for heating applications. It is possible to use a water wall as a collector in a pump-controlled hydronic system (2.e), but this concept has not been applied.

3.a 3.b: Roof pond systems. The Skytherm System, developed by Harold Hay with John Yellott (Sunset Homeowners Guide, 1979), and the energy roof developed by A. Lincoln Pittenger with William R. White and John Yellott (1977) are notable systems for combined passive heating and cooling, especially for lower latitudes. The Skytherm System has been used in a northern variation by Harold Hay in Concord, New Hampshire, in which the "thermo-pond" is placed in an attic roof-trap space (Sunset Homeowners Guide, 1979).

4.a-4.d: Thermosiphon systems. The Davis House in Albuquerque, New Mexico, built by Steve Baer, is a passive solar heating system (air-type) in which the collector, storage, and distribution components are separated, just as in an active system, but, by having the components placed one above the other, operates without a fan. Summer cooling can be accomplished by venting the rock bed at night.

A thermosiphon system, referred to as "the envelope house," was first built by Lee Porter Butler in Tennessee (Hudson Homes Guides, 1978), with subsequent examples in California and Colorado. A sunspace is used as the collector. A double roof and north wall and a crawl space under the house serve as a continuous air plenum. Cold air drops down the north wall, is drawn through the crawl space in which some form of thermal storage is placed, and is returned to the sunspace, where by displacement, the solar heated air is drawn along the ceiling to "drive" a thermosiphon loop. There is a good deal of disagreement between advocates and critics of this system as to whether the thermosiphon effect is sufficient to draw the solar heated air around the entire envelope and to charge the thermal mass in the crawl space (both rocks and earth-pipes have been used in system variations) (Shurcliff, 1979). While the houses have performed well in terms of comfort and low energy use, the results may also be explained by the resistance insulation value of the double-wall construction.

A thermosiphon alternative has been patented by E.M. Barber, Jr., of Sunsearch, Inc., Guilford, Connecticut (4.c), but has not been built. It has no inherent summer cooling mode, but is of interest because it is a passive heating system with the advantages of a liquid collector and storage, without relying on pump and controller components that have been troublesome in active system installations. For the same reason, thermosiphon or passive domestic hot water collector and storage systems are preferable to active arrangements. Variation 4.d shows how, by placing the water storage tank high in a clerestory space, heat loss in summer can help increase the temperature differential in a thermal chimney arrangement for induced ventilation.

This review of combined passive heating and cooling system alternatives helps to make the point that, while the current research emphasis in the United States has focused on separate components either for heating and cooling, a combination of components offers the greatest advantage for practical applications to buildings, especially in temperate climates. With newly developed computer simulation capability, combined heating and cooling passive systems can be tailored to each specific building design to fit the internal loads and the climatic limitations of each building location. Future research on climate and solar design should therefore encourage an integrated systems approach to building applications.

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