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Assessment of the Energy Conservation Potential of Active (Variable Thermal Resistance and Switchable Absorptance) Building Thermal Insulation Systems

H. A. Fine
D. L. McElroy

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Metals and Ceramics Division

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H. A. Fine and D. L. McElroy

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NOTICE: This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

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ACRONYMS

ACH	air changes per hour
BTESM	Building Thermal Envelope Systems and Materials
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
ESPRE	EPRI Simplified Program for Residential Energy
HSPF	heating seasonal performance factor
HVAC	heating, ventilating, and air conditioning
NBS	National Bureau of Standards, now known as National Institute of Standards and Technology (NIST)
SEER	seasonal energy efficiency ratio
TARP	Thermal Analysis Research Program
TMY	typical meteorological year

ASSESSMENT OF THE ENERGY CONSERVATION POTENTIAL OF ACTIVE (VARIABLE THERMAL RESISTANCE AND SWITCHABLE ABSORPTANCE) BUILDING THERMAL INSULATION SYSTEMS*

H. A. Fine† and D. L. McElroy

ABSTRACT

The Electric Power Research Institute (EPRI) Simplified Program for Residential Energy (ESPRE) was used to determine the heating and cooling loads for a hypothetical 1600-ft^2 structure located in three climates (hot, moderate, and cold) and equipped with either passive or active insulation systems. The passive (i.e., time-invariant) insulation systems studied included thermal resistance values for the attic, floor, and walls of 0.5, 19, and 38 $h \cdot ft^2 \cdot °F/Btu$; absorptance values for the roof and walls of 0.1, 0.5, and 0.8; and window transmittance values of 0.1, 0.5, and 0.8. The annual heating-plus-cooling load was calculated for 430 passive systems. The wide variety of passive insulation systems were then optimized using a postsimulation program to establish the minimum load that would result if a set of passive systems could be made active (i.e., switchable from one passive system to another, depending on which passive system produced the lowest heating-plus-cooling load). The annual heating-plus-cooling load was established for 171 active systems.

The predicted annual loads with passive insulation systems having an attic thermal resistance of 38 and floor and wall resistances of 19 were Phoenix, Arizona, 58 MBtu; Lexington, Kentucky, 62 MBtu; and Minneapolis, Minnesota, 90 MBtu. The most energy-conserving systems predicted savings of 20 to 25 MBtu/year in all three climates. Because active fenestration systems yielded nearly half of this potential savings, these systems deserve further study.

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1. INTRODUCTION

Research on the potential for energy conservation with improved insulation systems has increased dramatically since the 1973 embargo by the oil-producing and -exporting countries. Significant research has been undertaken by the U.S. Department of Energy's (DOE's) Building Thermal Envelope Systems and Materials (BTESM) Program, by other federally funded programs, and by private industry.[1-4] Assessments of this research indicate that the potential for energy conservation through improved insulation is great: approximately one quad* for residential structures,[5] one quad for commercial structures,[5] one quad for residential and commercial refrigeration equipment,[5] and one quad for industrial processes.[6] The research to date, however, has almost exclusively studied systems with fixed-insulation-resistance levels and the resulting energy savings that might be achieved by increasing the resistance levels.[7-11] Such time-invariant or fixed systems are considered passive systems in this work.

With the development of "smart" structures, a logical extension of the previous work is the study of the potential for energy conservation of smart or active insulation systems whose thermal resistance and/or surface properties (e.g., absorptance, emittance, and transmittance) might change as the outer temperature and solar insolation vary. Simulations of residential[12] and commercial[13] buildings with active fenestration systems have indicated that significant energy conservation may result from the use of these systems.

The results of heating and cooling load calculations for building envelopes with passive (i.e., fixed) insulation systems and active insulation systems that may have variable attic, wall, and/or floor thermal resistance; variable roof and/or wall absorptance; and/or variable window transmittance are presented in this work. The potential for energy savings for the hypothetical structure located in a cold climate, moderate climate, and hot climate is estimated from the calculated annual heating-plus-cooling loads for the structure because

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*One quad = 1×10^{15} Btu.

these are not affected by the choice of the characteristics of the heating and cooling system. Predictions for the heating and cooling loads for the test structure with passive systems were made using the Electric Power Research Institute (EPRI) Simplified Program for Residential Energy (ESPRE). The load savings that resulted when the systems were made active were then calculated with the aid of a database management program. The methodology and results of these calculations are described in this report.

2. ESPRE

The ESPRE program, which runs on a microcomputer, provides a simple-to-use tool for estimating seasonal, daily, and hourly average energy use. Calculations performed at hourly increments are based on thermal and moisture balances for average transfer rates for the increment (i.e., quasi-steady state), for a user-defined structure in a user-specified location, and for typical meteorological year (TMY) weather data. Summation of the hourly loads yields the loads for the desired period. The program also contains models for several heating and cooling systems so that energy-use information may be obtained.

Comparisons of the loads calculated by ESPRE and those measured for a 2550-ft^2 test structure* in Columbus, Ohio, and a National Bureau of Standards (NBS) test house show very good agreement.[14] Excellent agreement was also found between the predictions of more sophisticated programs such as the Thermal Analysis Research Program (TARP)[15] and ESPRE.[14] ESPRE is available from the Electric Power Software Corporation, Dallas, Texas.

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*Although the policy of the Oak Ridge National Laboratory is to report its work in SI units, customary units are used in this report. The insulation industry in the United States at present operates entirely with customary units. The use of the SI units would limit the usefulness of this report for the primary readership.

3. METHODOLOGY

The ESPRE program was used to perform the analysis for heating and cooling loads for the hypothetical structure with passive insulation systems. These results were then analyzed with the aid of a database management program to determine the heating and cooling loads for the structure with active insulation systems. The flow chart for these calculations is shown in Fig. 1 and is described in the following section.

3.1 PASSIVE INSULATION SYSTEMS

ESPRE is capable of performing many calculations relating to the energy and moisture balances on a user-defined structure in a user-specified location. Once the properties of the structure are defined and the location and corresponding TMY weather data file are supplied, the program will calculate the hourly heating and cooling loads for the structure (Fig. 1). A complete list of the parameters that must be supplied to ESPRE to describe the structure is presented in Appendix A. The reader should refer to the *ESPRE User's Manual*, Vol. 1, for a complete description of the program.[14] In addition to the set of 8760 hourly heating and cooling loads (24 h/d × 365 d/year), the program also calculates the set of 288 monthly average hourly loads (24 h/month × 12 months/year) and the set of 365 average daily loads. The monthly average hourly heating or cooling load is the summation of the heating or cooling load for that hour for all days in the month divided by the number of days in the month. The monthly average hourly heating-plus-cooling loads were used in the analyses performed in this study because of memory limitations of the microcomputer on which the study was performed.

3.1.1 Simulated Structure

Analyses were performed for a hypothetical 1600-ft^2 one-floor structure with crawl space, a single heating/cooling zone, and an attic or cathedral ceiling. The structure was 40 × 40 × 8 ft. Each wall had 50 ft^2 of double-pane windows. The other values required for the

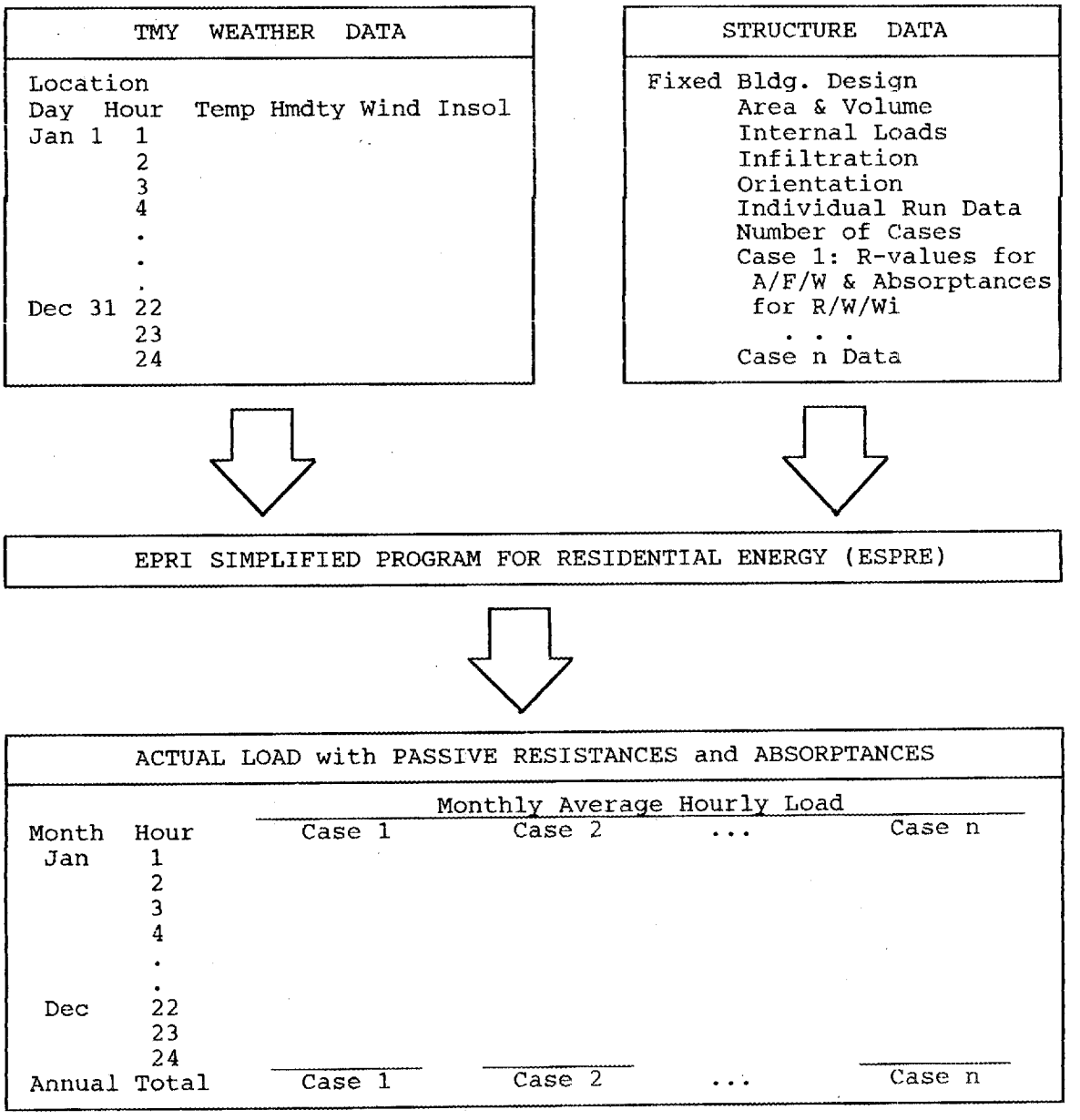

Fig. 1. Flow chart of simulation process for structures with passive and active insulation systems.

TERMINOLOGY
Temp: Dry Bulb Temperature, °F Hmdty: Humidity Ratio Wind: Wind Velocity, mph Insol: Insolation Rate, Btu/h ft^2 Infiltration: air changes per hour TMY: Typical Meteorological Year A: Attic F: Floor W: Walls R: Roof Wi: Windows

DATABASE MANAGEMENT PROGRAM

MIN. LOAD with ACTIVE SYSTEMS		
Month	Hour	Minimum load for cases 1 to n
Jan	1	
	2	
	3	
	4	
	.	
	.	
Dec	22	
	23	
	24	
Annual Total		Active System

Fig. 1. (continued)

structure model were those recommended in the *ESPRE User's Manual*,[16] Vol. 2, or by experts in the area of residential energy consumption modeling.[17] A brief description of the hypothetical test structure is presented in Table 1. A complete list of the structure parameters required by ESPRE is given in Appendix A.

A series of simulations was performed for the structure with passive (i.e., fixed) insulation systems. Insulation system descriptions required an attic (or cathedral ceiling), floor and wall thermal resistances; and the solar absorptances for the roof, walls, and window transmittance. A summary of the passive systems studied is presented in Table 2.

3.1.2 TMY Data

The ESPRE program requires TMY data to be supplied by the user for the location to be simulated. This data include such weather information as the hourly dry-bulb temperature, wind velocity, humidity ratio, and solar insolation rate. TMY files used in the program must be in a very specific format as described in the *ESPRE User's Manual*,[16] Vol. 2. TMY data files* for Lexington, Kentucky; Minneapolis, Minnesota; and Phoenix, Arizona, were used in the current study. A summary of averaged data for the three locations studied is presented in Table 3.[18]

3.2 ACTIVE SYSTEMS

The heating and cooling loads for the hypothetical structure with active systems were determined using the results of the passive simulations. An active system consisted of the set of *n* passive cases that contained all of the resistance and absorptance/transmittance levels that the active system could attain. Starting with January and hour 1, the resistance and absorptance/transmittance levels of the active system were allowed to "switch" hourly to the levels for the

---

*Files were obtained from R. L. Merriam of Arthur D. Little, Inc., Cambridge, Mass.

Table 1. Description of simulated hypothetical structure

Floor area - 1600 ft^2

Ceiling height - 8 ft

Design - One floor, single space, crawl space, attic or cathedral ceiling

Infiltration - 1.0 air change per hour

Exterior Walls -
- Area (including windows) - 320 ft^2/wall
- Direction - N, E, S, and W
- Windows - 50 ft^2/wall
- Solar absorptance - 0.8, 0.5, or 0.1
- R-value - 38, 19, or 0.5 $h \cdot ft^2 \cdot °F/Btu$
- Mass - 10 lb/ft^2 floor area

Attic -
- Area - 1600 ft^2
- Roof R-value - 1.2
- Roof absorptance - 0.8, 0.5, or 0.1
- Ceiling R-value - 38, 19, or 0.5
- Roof pitch - 0.33 ft/ft
- Ventilation - 0.1 CFM/ft^2

Crawl Space -
- Area - 1600 ft^2
- Ceiling R-value - 38, 19, or 0.5
- Wall R-value - 0
- Ventilation - 0.2 CFM/ft^2

Windows -
- Number of panes - 2
- Shading (transmittance) - 0.8, 0.5, or 0.1
- Insulation - None

Systems - heating and air conditioning
- Cooling on - 5/1
- Thermostat - 76°F
- Heating on - 9/1
- Thermostat - 70°F
- Humidity control - None

Table 2. Passive insulation cases simulated

Location	Resistance ($h \cdot ft^2 \cdot °F/Btu$)			Absorptance/transmittance		
	Attic	Floor	Walls	Roof	Walls	Windows
Resistance systems (81)[a]						
Lexington, Ky.	38	38	38	0.8	0.5	0.5
Minneapolis, Minn.	19	19	19			
Phoenix, Ariz.	0.5	0.5	0.5			
Absorptance/transmittance systems (297)[a]						
Lexington, Ky.	38	19	19	0.8	0.8	0.8
	38	38	38	0.5	0.5	0.5
	10c[c]	19	19	0.1	0.1	0.1
	19c[c]	19	19			
	38c[c]	19	19			
Minneapolis, Minn.	38	19	19			
	38	38	38			
	19c[c]	19	19			
Phoenix, Ariz.	38	19	19			
	38	38	38			
	19c[c]	19	19			
Miscellaneous systems (52)[a]						
Other passive cases			22			
HVAC system tests			18			
Infiltration analysis			12			

[a]Number of passive systems.

[b]Brackets indicate a matrix.

[c]Structures with cathedral ceilings.

Table 3. Typical meteorological year weather data for simulated sites

	Lexington	Minneapolis	Phoenix
Heating degree days (65°F basis)	4814	8007	1442
Cooling degree days (70°F basis)	594	302	2721
Average daily solar insolation (Btu/ft^2)	1300	1200	2100
Mean air temperature (°F)	55	40	60
Mean relative humidity (%)	70	70	35

passive system that achieved the lowest monthly average hourly heating-plus-cooling load for that hour. The comparison of the *n* monthly average hourly heating-plus-cooling loads for each of the 288 monthly average hours was performed to establish the insulation levels to be switched to at each hour, with the aid of a database management program. Once the insulation level was determined, the monthly average hourly heating-plus-cooling load for that insulation level was also determined. These values were multiplied by the number of days in the month in which that hour occurred and summed to obtain the annual heating-plus-cooling load for the active system. A summary of the active systems studied and the passive cases that comprised the active systems is presented in Table 4. A simplified example for a 5-h period for an active system consisting of three passive systems follows:

	Load for passive system number			
Hour	1	2	3	Active system load
1	10	20	30	10
2	15	20	14	14
3	20	10	15	10
4	25	30	25	25
5	30	25	30	25
Total	100	105	114	84

Table 4. Active insulation systems simulated

Location	Active element	Active levels
	Resistance systems (84)[a]	
Lexington, Ky.	Attic (A)	38 or 19[b]
Minneapolis, Minn.	Floor (F)	19 or 0.5[b]
Phoenix, Ariz.	Walls (W)	38 or 0.5[b]
	A&F	38 or 19 or 0.5[b]
	A&W	
	F&W	
	A&F&W	
	Absorptance/transmittance systems (84)[a]	
Lexington, Ky.	Roof (R)	0.8 or 0.5[c]
Minneapolis, Minn.	Walls (W)	0.5 or 0.1[c]
Phoenix, Ariz.	Windows (Wi)	0.8 or 0.1[c]
	R&W	0.8 or 0.5 or 0.1[c]
	R&Wi	
	W&Wi	
	R&W&Wi	
	Resistance and emittance/transmittance systems (3)[a]	
Lexington, Ky.	A&F&W + R&W&Wi	38 or 0.5[b] + 0.8 or 0.1[c]
Minneapolis, Minn.		
Phoenix, Ariz.		

[a]Number of active systems.

[b]Resistance level in $h \cdot ft^2 \cdot {}^\circ F/Btu$.

[c]Absorptance/transmittance level.

This example illustrates that passive system 1, with a total load of 100 for the 5-h period, was the most energy efficient. The active insulation system would start with the insulation levels in passive system 1 for period 1 but would switch to those of passive system 3 for period 2. In period 3, the active system would switch to the levels of passive system 2 and so on for the remaining periods. The total load with the active system was then found by summing the loads for each period, which equaled 84. (If the periods in the example corresponded to monthly average hours, it would also be necessary to multiply by the number of days in the month to get the total load for the month.) In the example, there are four possible active systems: active system 1, which would involve possible switching between the insulation levels in passive 1 and passive 2; active system 2, which would include switching between passive 1 and passive 3; active system 3, which would include passive 2 and passive 3; and active system 4, which would include all three passive system levels for which the example calculation was done.

Comparisons were made for many subsets of passive insulation levels (Table 4). In all of the comparisons, the criterion for switching was *minimize the total load* for a given monthly average hour. The number or frequency of switches that could be made during the year was not limited.

4. RESULTS

Summaries of the passive cases and active systems that were studied are presented in Tables 2 and 4, respectively. A description of the results of these simulations follows.

4.1 ACCURACY

A series of simulations were conducted to compare the results of the calculations based on the 288 monthly average hourly loads and those of the complete set of 8760-h results. Three passive insulation systems and the four active sets that could be made from the three passive cases were compared. As shown in Table 5, the results for the passive cases agreed to within 0.1 MBtu. A slightly larger error, but less than 0.7 MBtu, resulted for the active cases.

Table 5. Annual heating-plus-cooling load for simulated structure in Lexington, Kentucky, from hourly and hourly averaged data

Insulation system R-values (attic/floor/wall)	Annual load (MBtu/year)		Error (%)
	8760 hourly loads	288 monthly average hourly loads	
Passive #1 with 38/19/19	62.3	62.3	0.0
Passive #2 with 38/19/38	59.0	59.0	0.0
Passive #3 with 38/19/0.5	120.1	120.0	-0.1
Active with #1 + #2	58.7	58.7	0.0
Active with #1 + #3	59.4	60.0	1.0
Active with #2 + #3	55.8	56.5	1.3
Active with #1 + #2 + #3	55.8	56.4	1.1

4.2 VARIABLE THERMAL RESISTANCE SYSTEMS

4.2.1 Passive Systems

Three locations (Lexington, Minneapolis, and Phoenix), three attic insulation levels (R = 38, 19, or 0.5 $h \cdot ft^2 \cdot °F/Btu$), three floor insulation levels (R = 38, 19, or 0.5), and three wall insulation levels (R = 38, 19, or 0.5), for a total of 81 passive insulation cases, were simulated at fixed roof and wall absorptances of 0.8 and 0.5, respectively, and window transmittance values of 0.5. The results of a few of these simulations are shown in Table 6. The results for all of the simulations are presented in Appendix B.

Results are given for various attic/floor/wall R-value levels. The case labeled 38/19/19 is the recommended insulation levels for new construction in Lexington and Minneapolis as determined from the *DOE Insulation Fact Sheet*.[19] The recommended levels for Phoenix were 30/0/19. The 38/19/19 levels were, however, used as the base or reference case for all of the comparisons at all three locations.

Table 6. The annual load (MBtu/year) for selected cases

Resistance for attic/floor/walls (h•ft²•°F/Btu)	Roof absorptance/wall absorptance/window transmittance			
	0.8/0.8/0.8 Passive[b]	0.8/0.5/0.5 Passive[b]	0.1/0.1/0.1 Passive[b]	0.8 or 0.1[a] Passive[c]
Lexington, Kentucky				
0.5/0.5/0.5	182.8	182.7	181.6	
19/19/19		66.1		
38/19/19	65.1	62.3	59.7	47.9
38/38/38	57.9	54.7	51.6	40.7
10c/19/19[d]	78.6	76.3	73.6	59.8
19c/19/19[d]	70.6	67.9	65.3	52.5
38c/19/19[d]	65.7	62.9	60.2	48.1
38 or 0.5[a]		51.1[e]		39.0[f]
Minneapolis, Minnesota				
0.5/0.5/0.5	231.0	231.0	231.1	
38/19/19	90.7	90.2	91.7	76.8
38/38/38	78.8	77.9	78.7	64.7
19c/19/19[d]	99.2	99.0	100.7	84.8
or 0.5[a]		75.4[e]		63.5[f]
Phoenix, Arizona				
0.5/0.5/0.5	134.0	135.2	137.7	
30/0.5/19		87.6		
19/19/19		59.5		
38/19/19	63.1	57.6	48.8	40.8
38/38/38	58.1	51.4	43.2	36.4
19c/19/19[d]	67.3	61.3	52.6	43.4
38 or 0.5[a]		50.5[e]		36.3[f]

[a]Active system high or low levels.

[b]Passive resistance and absorptance/transmittance cases except as noted.

[c]Passive resistance but active absorptance/transmittance cases except as noted.

[d]Structure with cathedral ceiling.

[e]One active resistance case for each location.

[f]Active resistance and absorptance/transmittance case.

The results of these calculations for each location showed that an uninsulated home (R-values of 0.5 for the attic, floor, and walls) that was insulated to the 38/19/19 level would reduce the heating-plus-cooling loads from 183 to 62, 231 to 90, and 135 to 58 MBtu/year for Lexington, Minneapolis, and Phoenix, respectively, at absorptance/transmittance levels of 0.8/0.5/0.5. Similar reductions occurred at other absorptance/transmittance levels. Once the 38/19/19 insulation levels were attained, increasing the levels to "super" insulation (i.e., levels of 38/38/38), resulted in conservation of an additional 8, 12, and 6 MBtu/year (Table 6).

The heating-plus-cooling loads that resulted from the various passive insulation levels are presented in Table B.1. The changes that resulted from the various passive insulation levels at roof and wall absorptance levels of 0.8 and 0.5, respectively, and window transmittance levels of 0.5 are shown in Figs. 2(*a*), 3(*a*), and 4(*a*) for Lexington, Minneapolis, and Phoenix, respectively. The various points on the diagrams correspond to the annual heating-plus-cooling load that resulted when the attic (A), floor (F), or wall (W) thermal resistance or combination of any two or all three of these resistances was changed from 19 to the value specified on the abscissa of the diagram. Clearly, more insulation is better. The figures show the trends and should not be used for interpolation or extrapolation to other values.

Loads were similar but slightly higher for structures with cathedral ceilings than for attics with the same insulation level. This was expected because the air gap in the attic and the roofing material produced a slightly higher resistance for the attic system.

4.2.2 Active Systems

A very large set of possible combinations of the 27 passive cases for each location exists, making the number of possible variable resistance systems very large. This number was reduced to a manageable size by limiting the resistance levels for the active systems to high or low values of either 38 or 19, 19 or 0.5, or 38 or 0.5 for all elements that were active in a given system. Simulations were also done for active resistance systems with high, medium, or low resistance levels of

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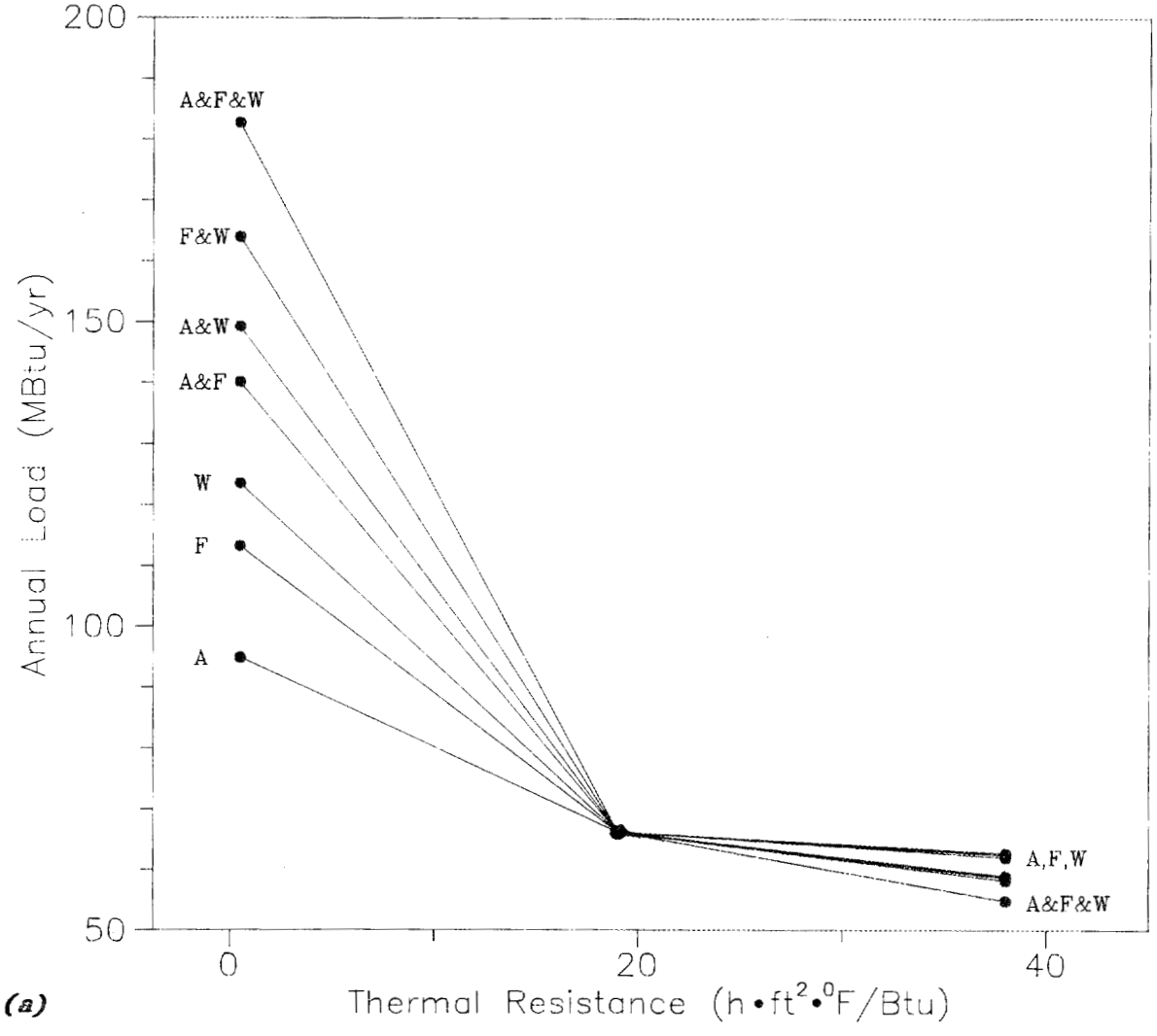

(a)

Fig. 2. Summary of results for simulated structure with (*a*) passive and (*b*) active resistance systems in Lexington, Kentucky.

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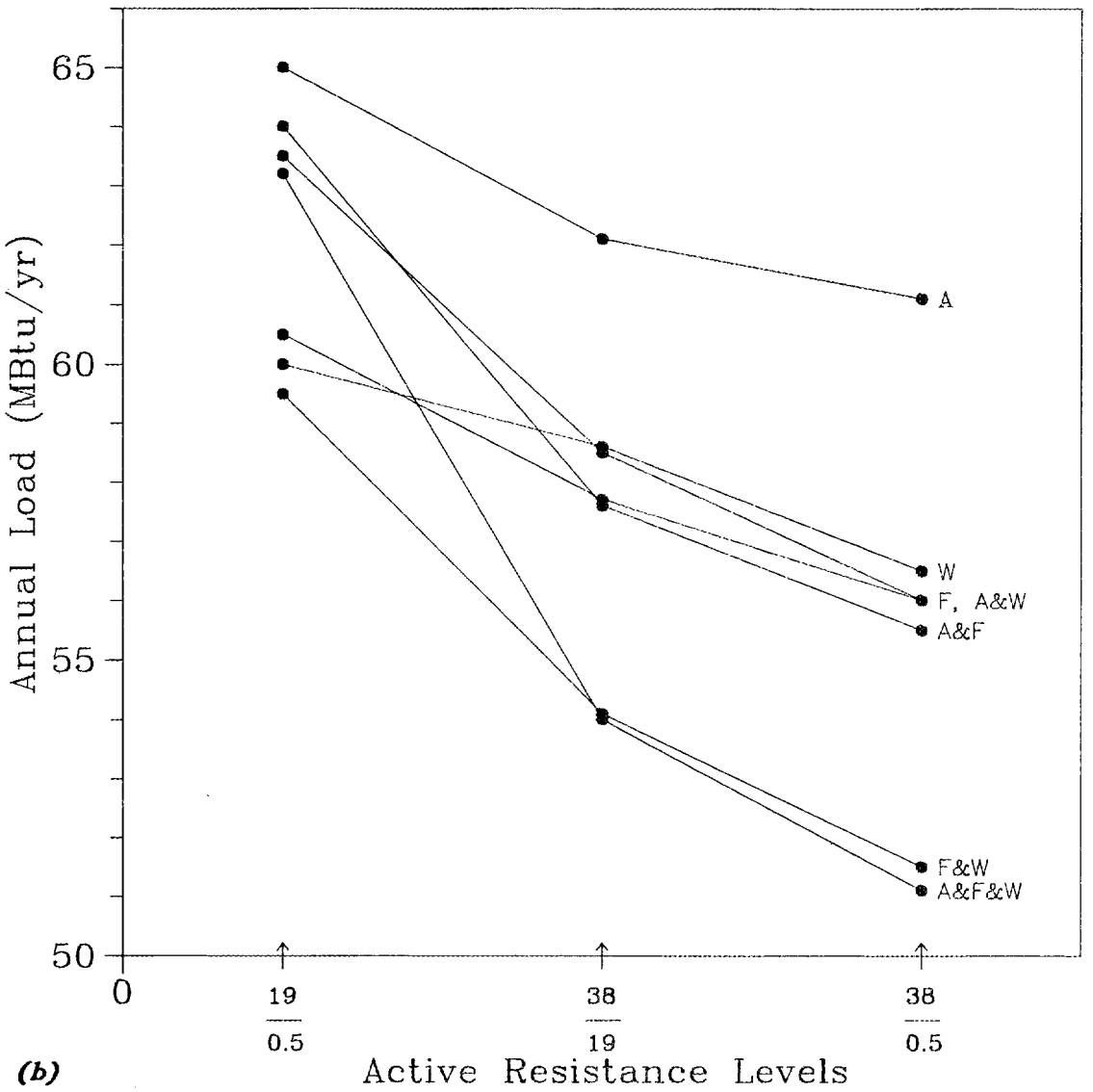

(b)

Fig. 2. (continued)

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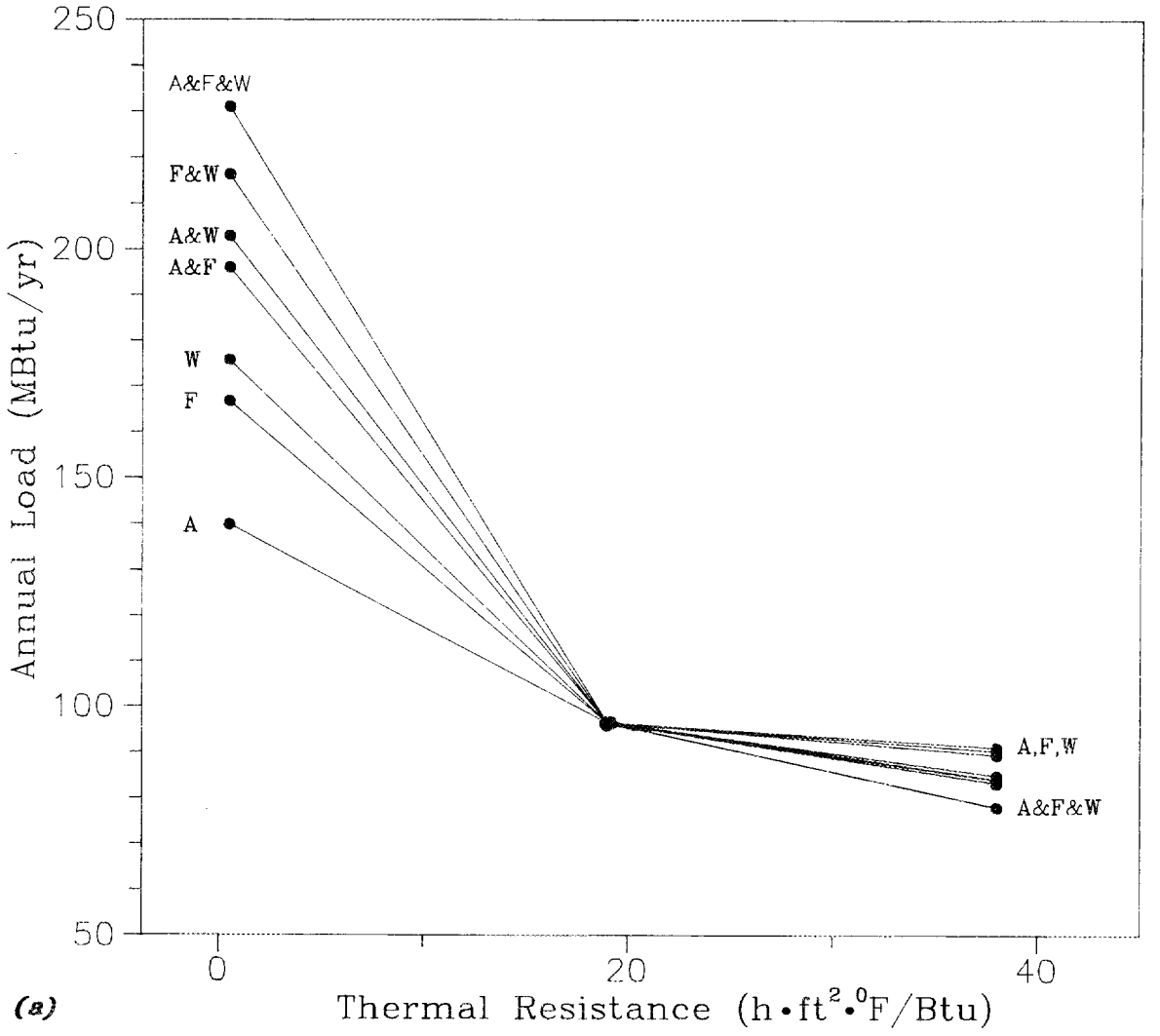

Fig. 3. Summary of results for simulated structure with (*a*) passive and (*b*) active resistance systems in Minneapolis, Minnesota.

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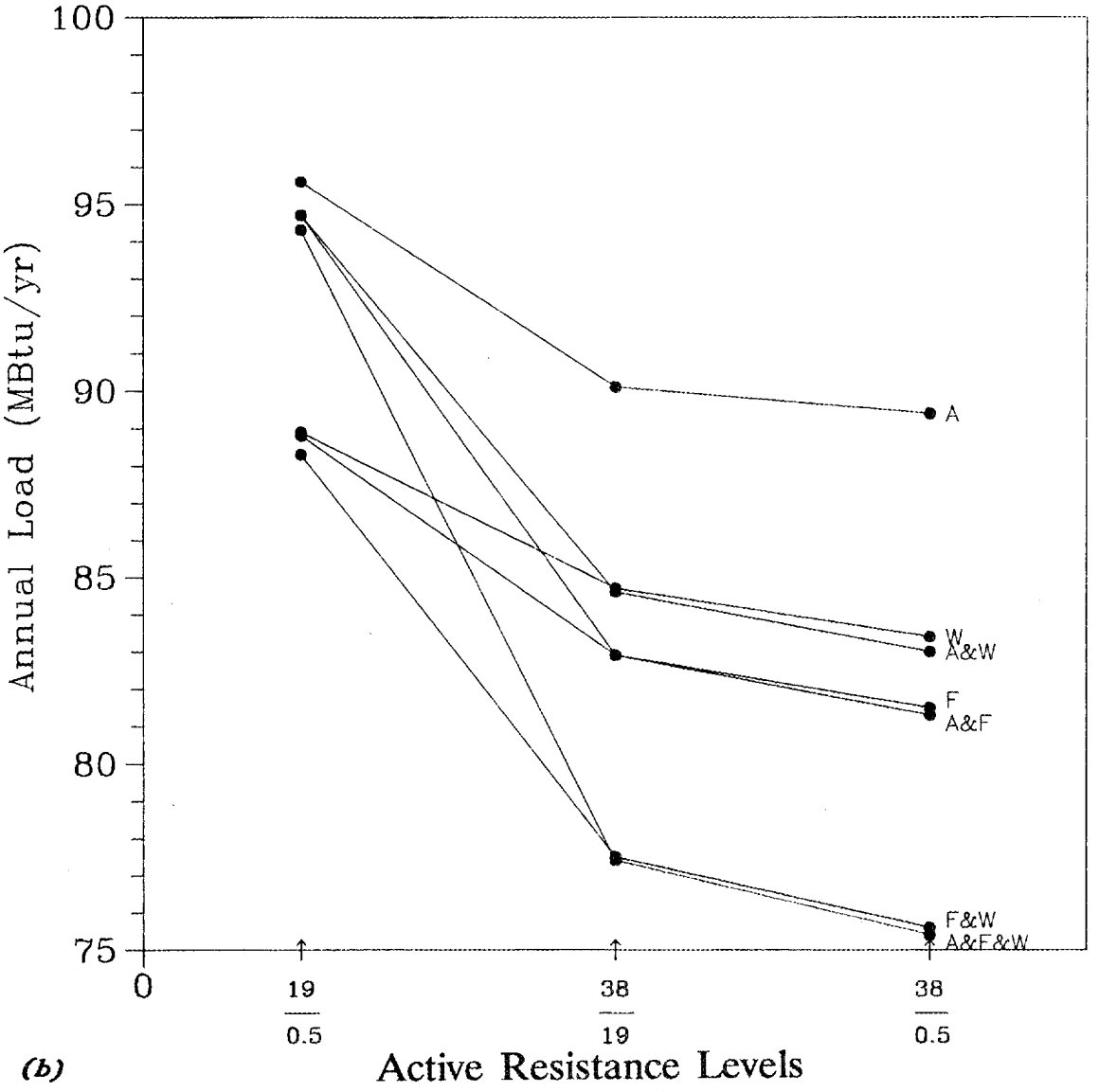

(b)

Fig. 3. (continued)

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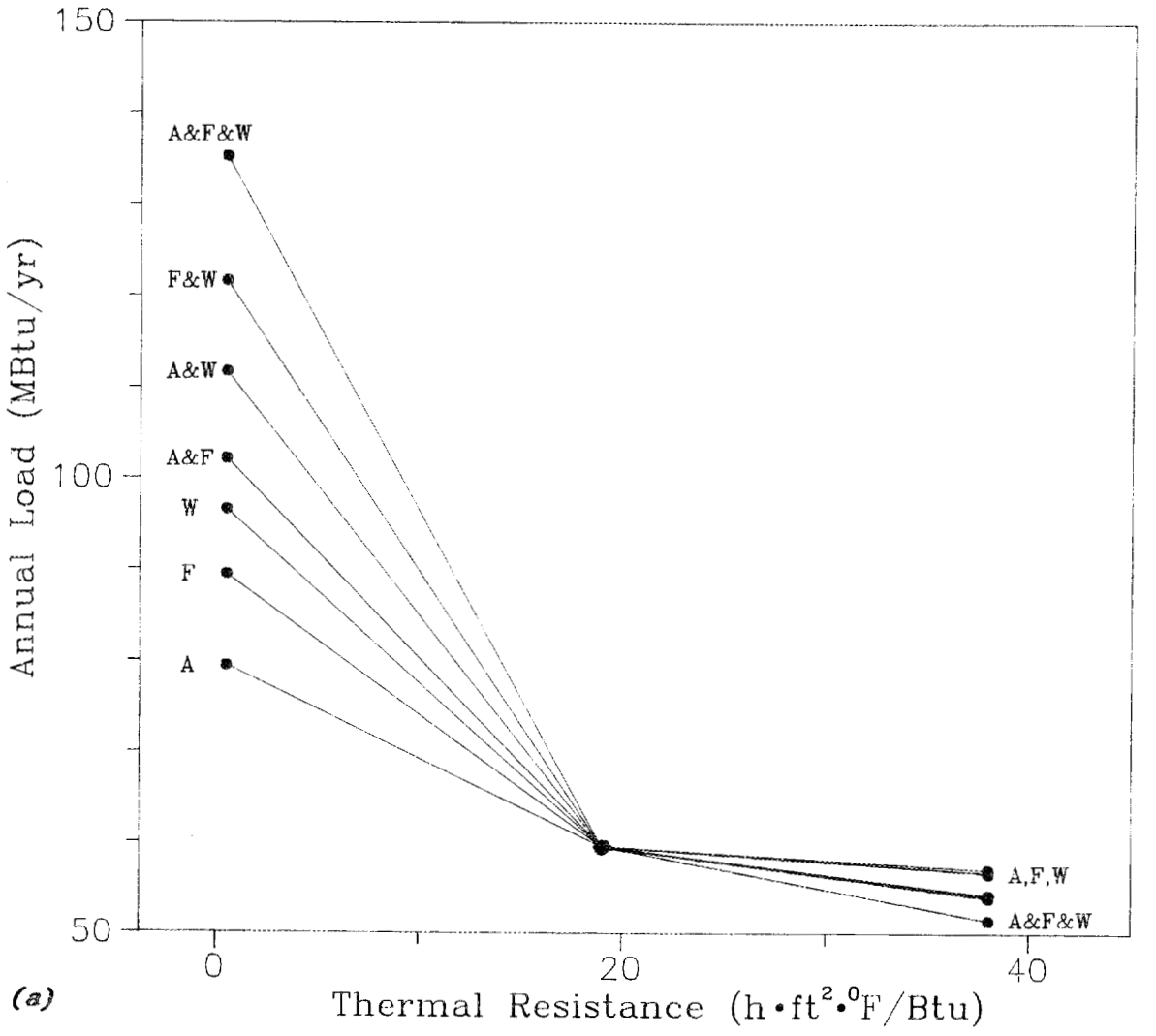

Fig. 4. Summary of results for simulated structure with (*a*) passive and (*b*) active resistance systems in Phoenix, Arizona.

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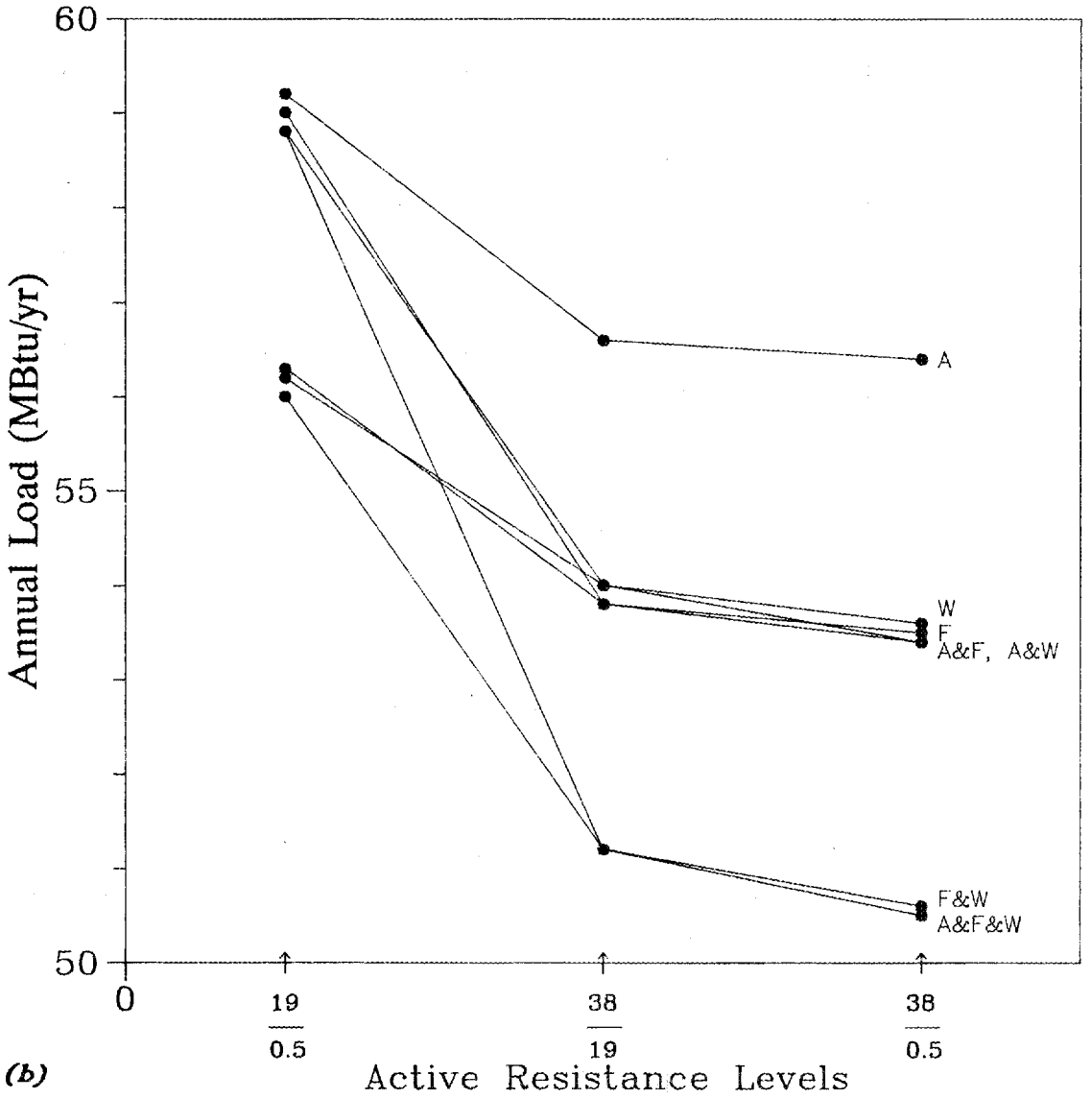

(b)

Fig. 4. (continued)

38, 19, or 0.5. The active elements in the systems studied were the attic only, floor only, walls only, attic and floors only, attic and walls only, floor and walls only, and attic, floor, and walls (Table 4). Variable resistance systems were studied only at absorptance/transmittance levels of 0.8/0.5/0.5.

The results for all of the active systems are given in Appendix B. The systems with high, medium, or low levels of 38, 19, or 0.5 yielded heating-plus-cooling loads equal to those for the 38 or 0.5 high or low systems, within the accuracy of the calculations, 0.7 MBtu/year. The energy-conserving potentials of the various active systems are shown in Figs. 2(*b*), 3(*b*), and 4(*b*) for Lexington, Minneapolis, and Phoenix, respectively. The ordinate in these diagrams is the annual heating-plus-cooling load for the active systems. The abscissa shows the ratio of the high-to-low resistance level of the active system.

An active system with the same high resistance limits as the corresponding passive system will in all cases be more energy efficient. The variable resistance system with the greatest potential for energy conservation was the system with active attic, floor, and wall insulations at high or low levels of 38 or 0.5. This system yielded heating-plus-cooling loads of 4, 3, and 1 MBtu/year below those for the super insulated structures for Lexington, Minneapolis, and Phoenix, respectively (Table 6).

The potential for energy conservation by changing the passive levels or incorporating active systems into structures in Lexington, Minneapolis, and Phoenix that have resistances of 38/19/19 are summarized in Tables 7-9.

4.3 SWITCHABLE ABSORPTANCE SYSTEMS

4.3.1 Passive Systems

Simulations were performed at five passive resistance levels for Lexington and at three passive resistance levels for Minneapolis and Phoenix with three roof and wall absorptances (0.8, 0.5, and 0.1) and with three window transmittances (0.8, 0.5, and 0.1). Some of the results of the 297 cases are shown in Table 6, and a complete summary of

Table 7. Energy conservation potential for simulated structure in Lexington, Kentucky[a]

MBtu/year	Passive		Active	
	System	Level	System	Level
1-2	R&W	0.1&0.1	A	38 or 0.5
	W&Wi	0.8&0.1	F	19 or 0.5
	R&W&Wi	0.5&0.8&0.1	W	0.8 or 0.5
	R&W&Wi	0.1&0.8&0.1	R&W	0.8 or 0.5
	Wi	0.1		
2-3	R&Wi	0.5&0.1	W	19 or 0.5
	R&Wi	0.1&0.1	F&W	19 or 0.5
	W&Wi	0.1&0.1	W	0.5 or 0.1
	R&W&Wi	0.5&0.1&0.1		
	R&W&Wi	0.1&0.1&0.1		
3-4	W	38	W	38 or 19
	F&W	38[b]	A&W	38 or 19
			R&W	0.5 or 0.1
			Wi	0.8 or 0.5
			W	0.8 or 0.1
			R&Wi	0.8 or 0.5
4-5	F	38	F	38 or 19
			A&F	38 or 19
			R&W	0.8 or 0.1
			W&Wi	0.8 or 0.5
			R&W&Wi	0.8 or 0.5
5-6			W	38 or 0.5
6-7			F	38 or 0.5
			A&W	38 or 0.5
			A&F	38 or 0.5
7-8	F&W	38	Wi	0.5 or 0.1
			R&Wi	0.5 or 0.1
8-9			F&W	38 or 19
			A&F&W	38 or 19
9-10			W&Wi	0.5 or 0.1
10-11	F&W	38 + 0.1	F&W	38 or 0.5
	R&W&Wi		R&W&Wi	0.5 or 0.1
			Wi	0.8 or 0.1

Table 7. (continued)

MBtu/year	Passive		Active	
	System	Level	System	Level
11-12			A&F&W R&Wi	38 or 0.5 0.8 or 0.1
13-14			W&Wi	0.8 or 0.1
14-15			R&W&Wi	0.8 or 0.1
21-22			F&W at 38 + R&W&Wi	 0.8 or 0.1
23-24			A&F&W + R&W&Wi	38 or 0.5 + 0.8 or 0.1

[a]Simulated structure consumes 62.3 MBtu/year with R-values of 38/19/19 and absorptances/transmittance of 0.8/0.5/0.5.

[b]Attic R-value also reduced to 19.

Table 8. Energy conservation potential for simulated structure in Minneapolis, Minnesota[a]

MBtu/year	Passive		Active	
	System	Level	System	Level
1-2			W	19 or 0.5
			F	19 or 0.5
			F&W	19 or 0.5
			W	0.8 or 0.5
			R&W	0.8 or 0.5
			W	0.5 or 0.1
2-3			R&W	0.5 or 0.1
3-4			W	0.8 or 0.1
			R&W	0.8 or 0.1
4-5			Wi	0.8 or 0.5
			R&Wi	0.8 or 0.5
5-6	W	38	W	38 or 19
			A&W	38 or 19
			Wi	0.5 or 0.1
			W&Wi	0.8 or 0.5
			R&W&WI	0.8 or 0.5
6-7	F&W	38[b]	W	38 or 0.5
	F	38	R&Wi	0.5 or 0.1
7-8			A&W	38 or 0.5
			F	38 or 19
			A&F	38 or 19
			W&Wi	0.8 or 0.5
			R&W&Wi	0.8 or 0.5
8-9			F	38 or 0.5
			A&F	38 or 0.5
9-10			Wi	0.8 or 0.1
10-11			R&Wi	0.5 or 0.1
12-13	F&W	38	F&W	38 or 19
			A&F&W	38 or 19
			W&Wi	0.8 or 0.1
13-14			R&W&Wi	0.8 or 0.1

Table 8. (continued)

MBtu/year	Passive		Active	
	System	Level	System	Level
14-15			F&W	38 or 0.5
			A&F&W	38 or 0.5
25-26			F&W at 38	
			+ R&W&Wi	0.8 or 0.1
26-27			A&F&W	38 or 0.5
			+ R&W&Wi	0.8 or 0.1

[a]Simulated structure consumes 90.2 MBtu/year with R-values of 38/19/19 and absorptances/transmittance of 0.8/0.5/0.5.

[b]Attic R-value also reduced to 19.

Table 9. Energy conservation potential for simulated structure in Phoenix, Arizona[a]

MBtu/year	Passive		Active	
	System	Level	System	Level
1-2	W	0.1	R	0.5 or 0.1
			R	0.8 or 0.1
			R&W	0.8 or 0.5
			Wi	0.8 or 0.5
2-3	F&W	38[b]	W	38 or 19
	W	38	A&W	38 or 19
	F	38	F	38 or 19
	R&W	0.5&0.1	A&F	38 or 19
	R&W	0.1&0.1	W	38 or 0.5
			R&Wi	0.8 or 0.5
			W&Wi	0.8 or 0.5
			W	0.5 or 0.1
			R&W&Wi	0.8 or 0.5
3-4			F	38 or 0.5
			A&F	38 or 0.5
			A&W	38 or 0.5
			W	0.8 or 0.1
4-5	W&Wi	0.8&0.1	R&W	0.5 or 0.1
	R&W&Wi	0.5&0.8&0.1	R&W	0.8 or 0.1
5-6	F&W	38	F&W	38 or 19
	R&W&Wi	0.1&0.8&0.1	A&F&W	38 or 19
	Wi	0.1	F&W	38 or 0.5
	R&Wi	0.5&0.1		
6-7	R&W&Wi	0.1&0.5&0.1	A&F&W	38 or 0.5
7-8	W&Wi	0.1&0.1		
	R&W&Wi	0.5&0.1&0.1		
	R&W&Wi	0.1&0.1&0.1		
9-10			Wi	0.5 or 0.1
10-11			R&Wi	0.5 or 0.1
11-12			Wi	0.8 or 0.1
12-13			W&Wi	0.5 or 0.1
			R&Wi	0.8 or 0.1

Table 9. (continued)

MBtu/year	Passive		Active	
	System	Level	System	Level
13-14	F&W + R&W&Wi	38 + 0.1	R&W&Wi	0.5 or 0.1
14-15			W&Wi	0.8 or 0.1
15-16			R&W&Wi	0.8 or 0.1
20-21			F&W at 38 + R&W&Wi	0.8 or 0.1
			A&F&W + R&W&Wi	38 or 0.5 0.8 or 0.1

[a]Simulated structure consumes 56.6 MBtu/year with R-values of 38/19/19 and absorptances/transmittance of 0.8/0.5/0.5.

[b]Attic R-value also reduced to 19.

the results is presented in Appendix B. The change in heating-plus-cooling load that resulted from passive changes in one or more of the absorptance/transmittance levels at resistances of 38/19/19 are shown in Figs. 5(*a*), 6(*a*), and 7(*a*). These results are presented as the annual load that results when one or more of the absorptance/transmittance levels is changed from 0.5 to the level specified on the abscissa.

Selection of coatings that yielded roof and wall solar absorptances and a window transmittance of 0.1 yielded load reductions from those for 0.8/0.5/0.5 that *averaged* 3 and 8 MBtu/year for all cases except the uninsulated cases in Lexington and Phoenix, respectively. Even larger reductions of 6 and 14 MBtu/year would result on average, if the starting case was 0.8/0.8/0.8. The effect of passive absorptance/transmittance changes in Minneapolis averaged less than 1 MBtu/year, with 0.8/0.5/0.5 having the lowest total load.

4.3.2 Active Systems

Once again the number of combinations of switchable surfaces and levels was very large. Therefore, it was decided that with the exception of a few cases that would be used to study orientation effects, all walls and/or all windows would be switched together. The active systems were roof only; walls only; windows only; roof and walls only; roof and windows only; walls and windows only; and roof, walls, and windows. Allowable levels to which the active system could switch were high or low values of either 0.8 or 0.5, 0.5 or 0.1, or 0.8 or 0.1 and high, medium, or low levels of 0.8, 0.5, or 0.1. The cases which were employed to estimate the orientation effect on active windows were limited to high or low transmittances of 0.8 or 0.1 for windows on the north, east, south, or west side of the structure.

The energy-conserving potentials of the active surface systems with high, medium, or low levels of 0.8, 0.5, or 0.1 were equal to those for the active systems with high or low levels of 0.8 or 0.1, within the accuracy limits of the calculations. The active system with the most potential for energy saving was the system with roof, walls, and windows with levels of 0.8 or 0.1. This system conserved an average of 12, 14,

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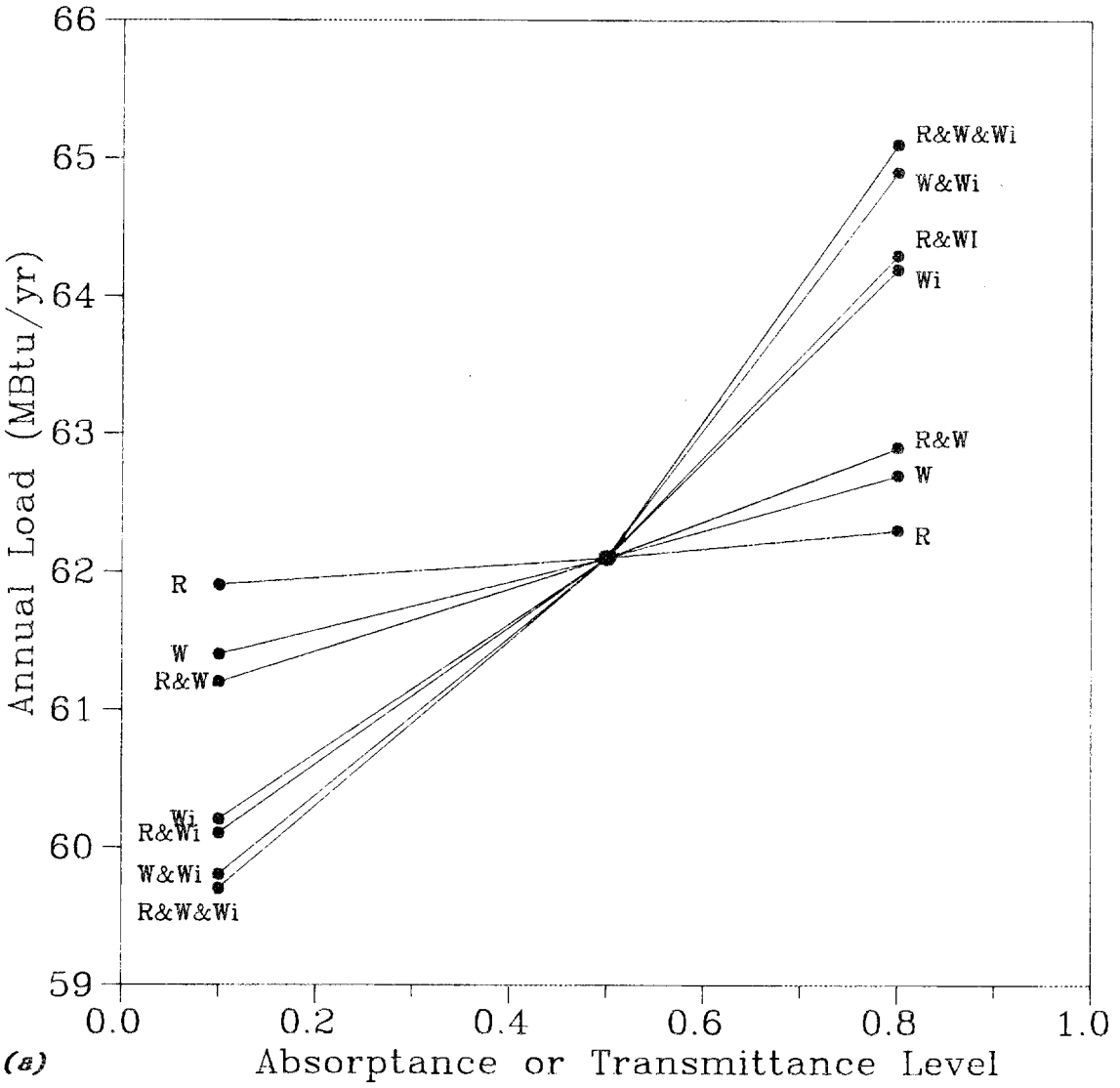

(a)

Fig. 5. Summary of results for simulated structure with (*a*) passive and (*b*) active absorptance/transmittance systems in Lexington, Kentucky.

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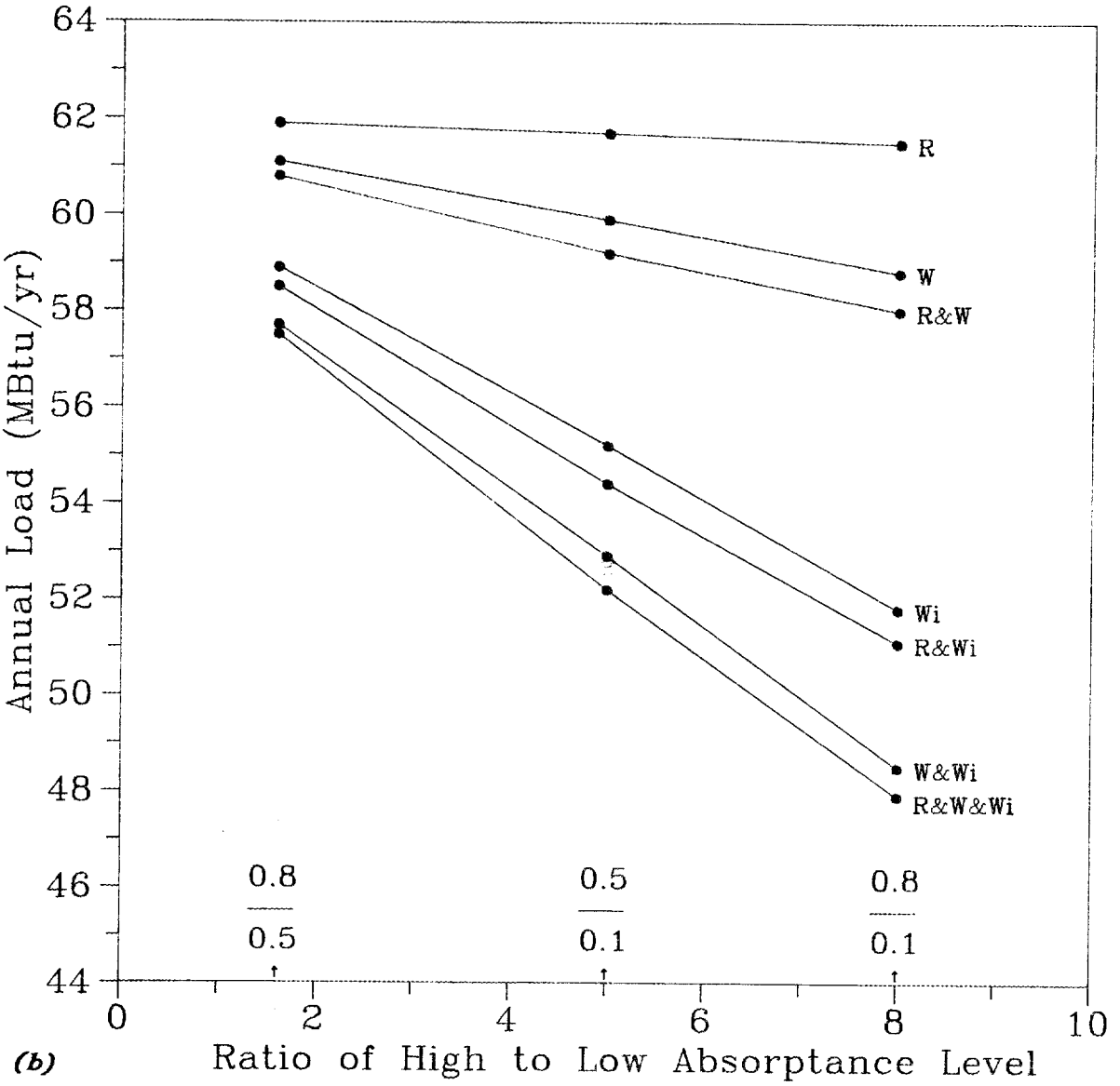

Fig. 5. (continued)

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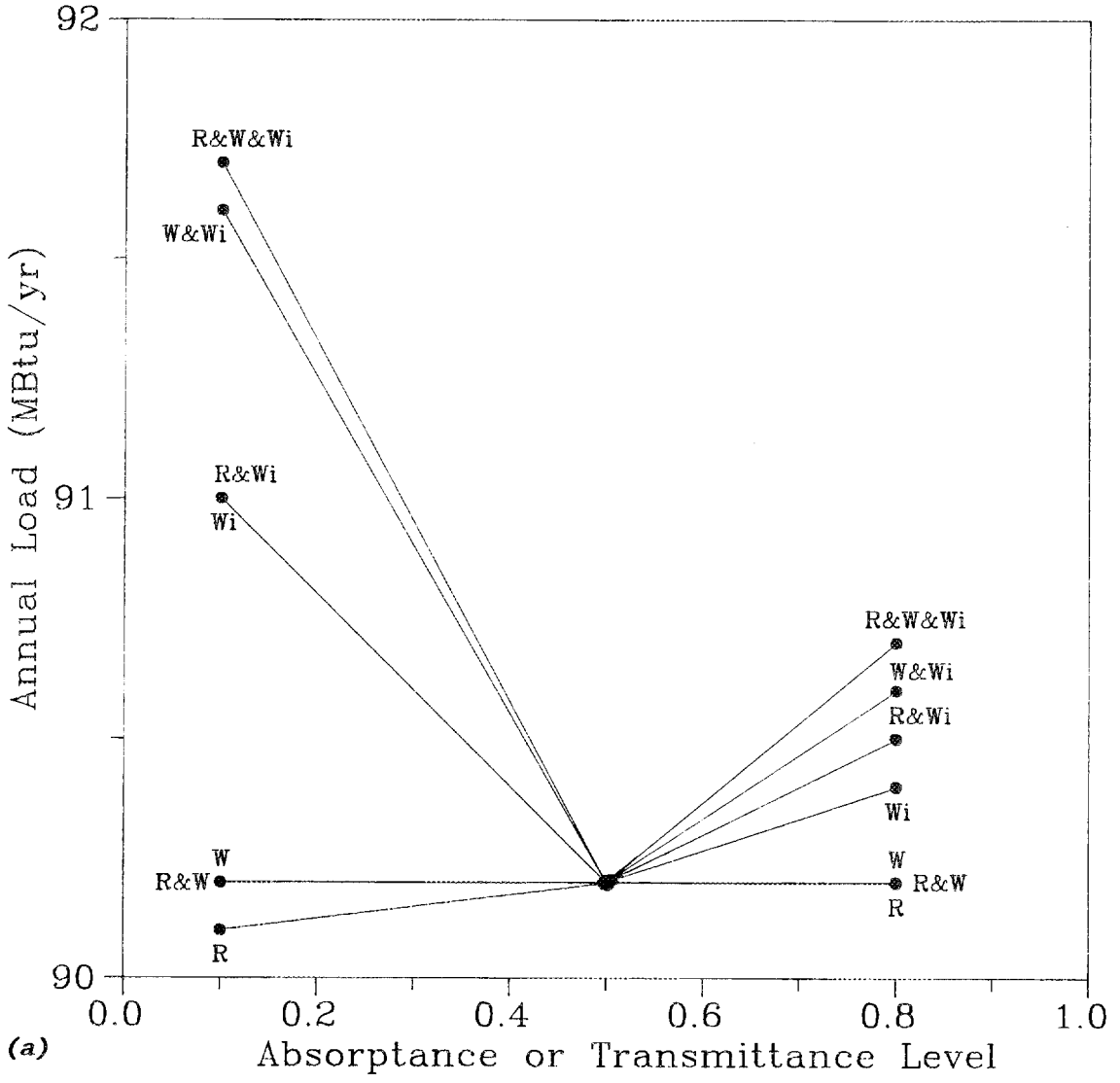

Fig. 6. Summary of results for simulated structure with (*a*) passive and (*b*) active absorptance/transmittance systems in Minneapolis, Minnesota.

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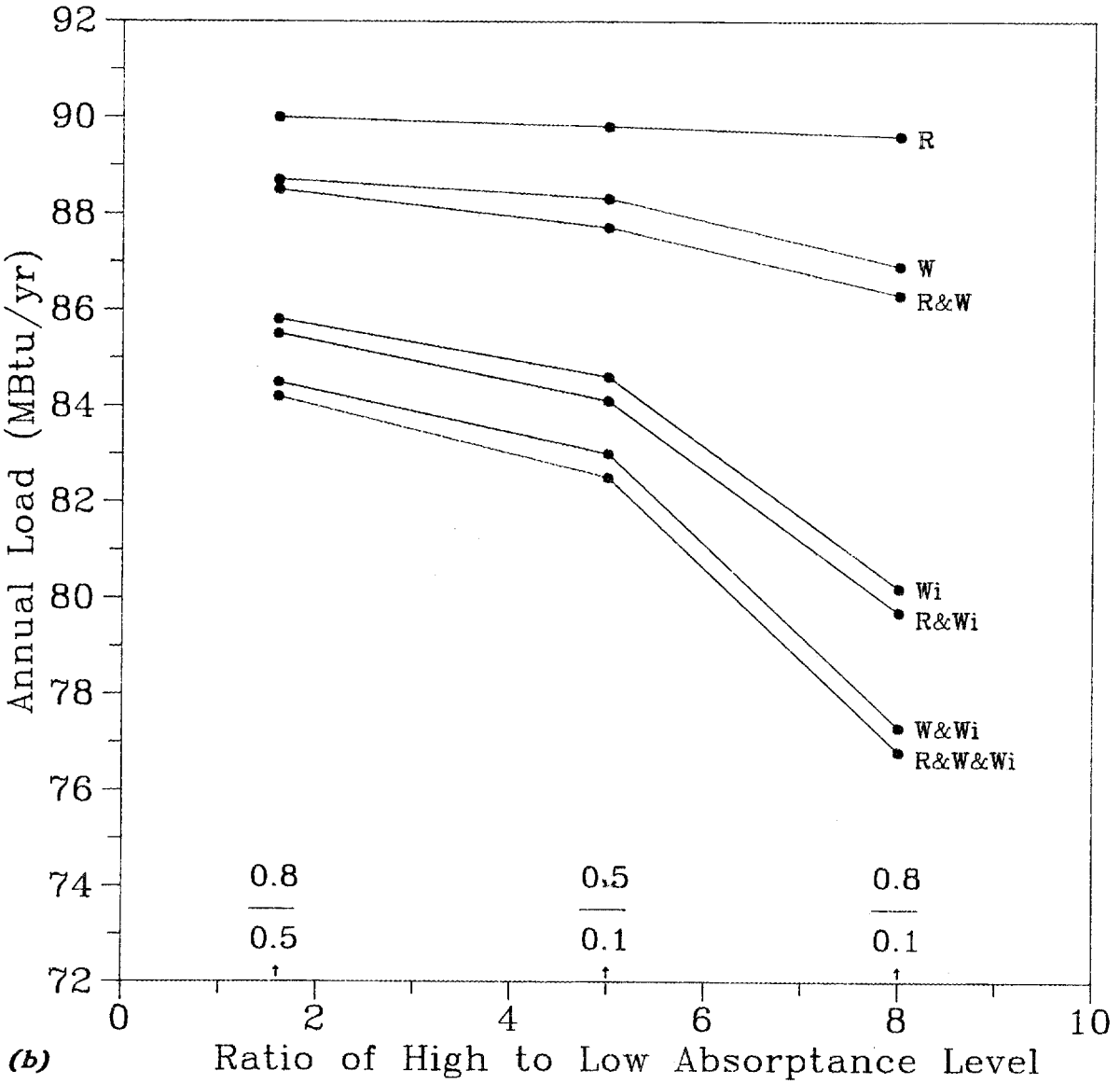

Fig. 6. (continued)

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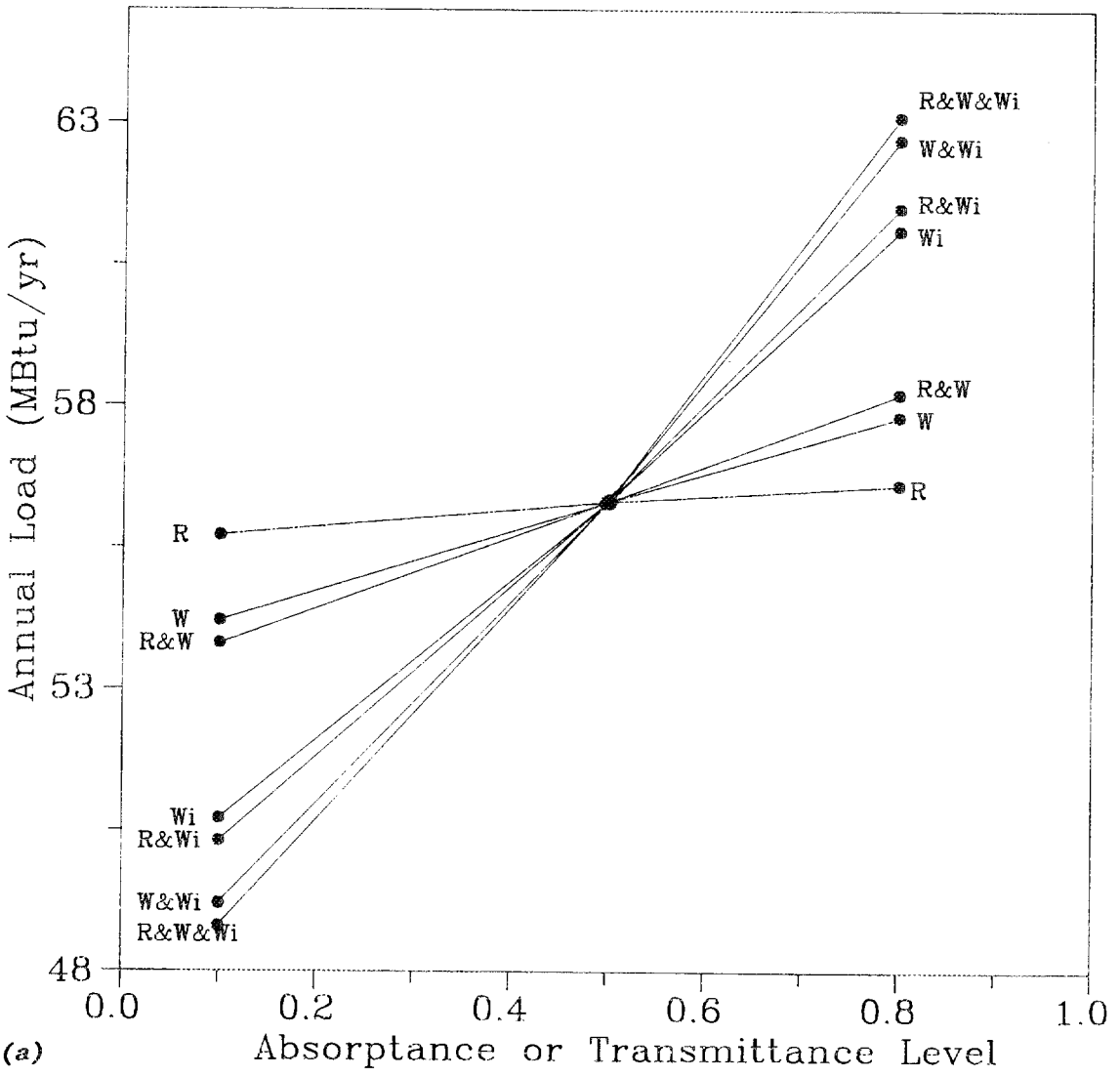

(a)

Fig. 7. Summary of results for simulated structure with (*a*) passive and (*b*) active absorptance/transmittance systems in Phoenix, Arizona.

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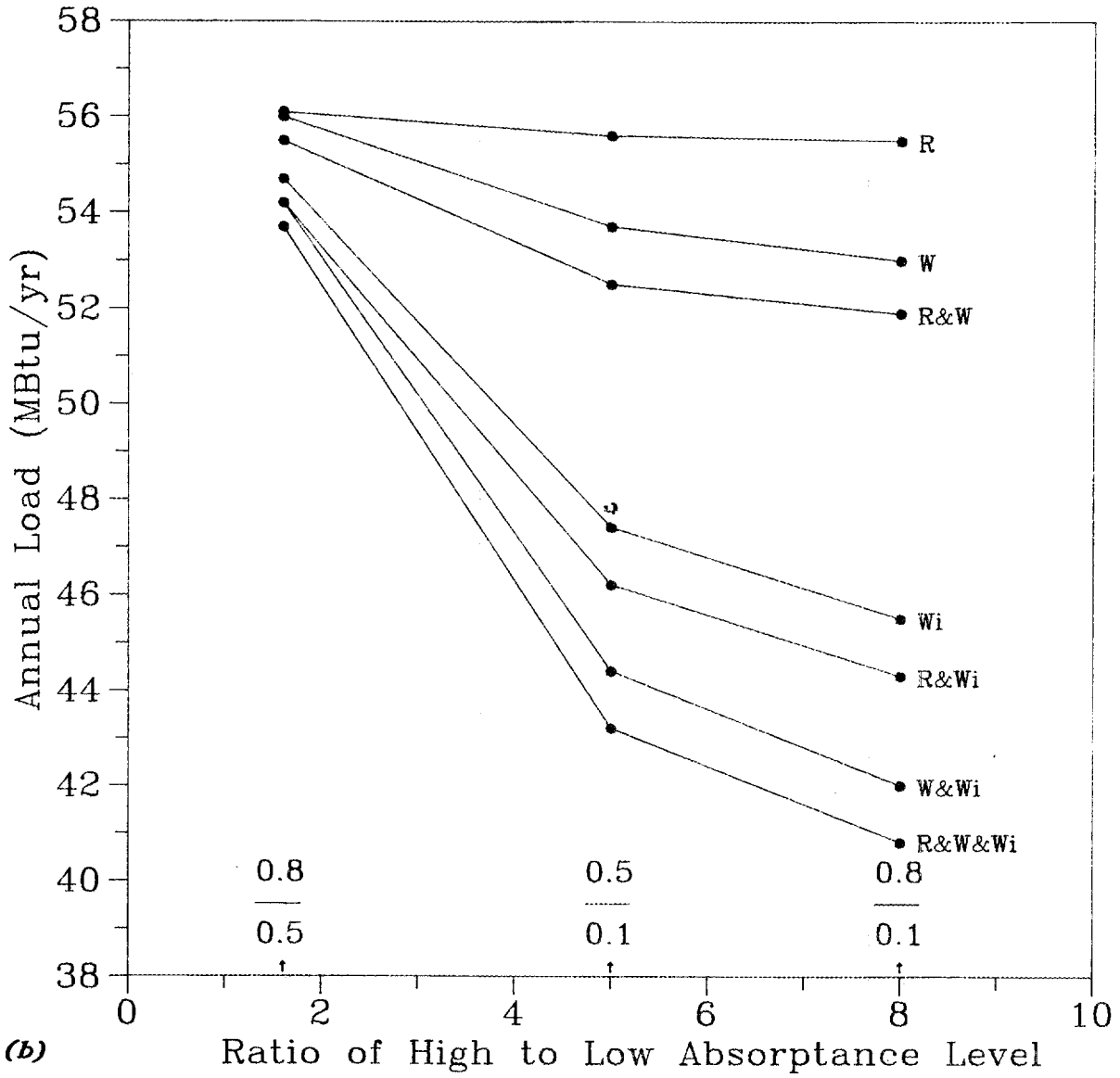

(b)

Fig. 7. (continued)

and 9 MBtu/year over the most energy efficient passive surfaces for Lexington, Minneapolis, and Phoenix, respectively (Table 6).

The contributions of the various active systems to the overall energy savings potential of the active surface systems are shown in Figs. 5(*b*), 6(*b*), and 7(*b*) for Lexington, Minneapolis, and Phoenix, respectively. The seven lines on each figure show that increasing the ratio of high to low values attainable by the active system increases the potential for energy conservation for any of the active systems. Changing the ratio of the levels for the active systems in Minneapolis from 5 (0.5/0.1) to 8 (0.8/0.1) had a much larger impact than the change from 1.6 (0.8/0.5) to 5 (0.5/0.1). In Lexington, the effect of changes in limits had the same result. In Phoenix, most of the energy conservation occurred with a change in limits from 1.6 (0.8/0.5) to 5 (0.5/0.1).

In all three locations, active roofs had small energy savings potential, followed by active walls; roof and walls; windows; roof and windows; walls and windows; and roof, walls, and windows. The potential for energy conservation of active windows was two-thirds of that for active roof, walls, and windows. In addition, active windows on the east, south, or west walls had equal energy-conserving potential. Windows on the north wall had the potential to conserve about half the energy of the other walls.

The energy-conserving potential for various passive and active surface-coating systems are shown in Tables 7-9. These potentials were grouped into categories according to their potential for savings in MBtu/year when included in a structure with resistances of 38/19/19 and absorptance/transmittance of 0.8/0.5/0.5 in Lexington, Minneapolis, or Phoenix.

4.4 VARIABLE THERMAL RESISTANCE AND SWITCHABLE ABSORPTANCE SYSTEMS

4.4.1 Passive Systems

The energy-conserving potential that resulted from passive changes in the thermal resistance levels and surface absorptance/transmittance was about equal to the sum of the energy-conserving potential of the two separate passive changes. For example, the energy savings associated

with increasing the floor and wall thermal resistances to 38 in Lexington was 7 to 8 MBtu/year. The energy conservation potential for changing the absorptance/transmittance to 0.1/0.1/0.1 from 0.8/0.5/0.5 was 2 to 3 MBtu/year. When both passive changes were made, the maximum possible energy conservation potential resulting from passive changes occurred for Lexington, which was the sum of the two potentials for the individual changes or 10 to 11 MBtu/year.

The maximum energy savings potential for passive systems was achieved by similar changes in Phoenix and equals 13 to 14 MBtu/year. As noted previously, the passive cases with the lowest energy consumption in Minneapolis had absorptance/transmittance of 0.8/0.5/0.5. Hence, the maximum energy savings potential arose from changing the floor and wall resistances to 38 and equals 12 to 13 MBtu/year (Tables 7-9). The potential for other passive systems that involve both resistance and absorptance/transmittance changes can be found by adding the savings in Tables 7-9 for the individual savings potentials of resistance and absorptance/transmittance changes.

4.4.2 Active Systems

The greatest potential for energy conservation was achieved with an active system that had attic, floor, and wall variable thermal resistances with levels of 38 or 0.5 and switchable roof and wall absorptances and window transmittance with levels of 0.8 or 0.1. The energy conservation potential for the active systems was 13, 13, and 7 MBtu/year higher than that for the best passive systems in Lexington, Minneapolis, and Phoenix, respectively.

As with a combination of a passive change in thermal resistance and absorptance/transmittance, the conservation potential for a passive change in thermal resistance and an active absorptance/transmittance system was additive. Adding the potentials for active resistance and absorptance/transmittance systems yielded an energy savings potential that was about 10% too high (Table 6), showing that the law of diminishing returns begins to apply for these systems.

The results presented in Sects. 4.1 through 4.4 are summarized and discussed in a previously published paper, which is included as Appendix C.

4.5 INFILTRATION AND INTERNAL LOADS

A set of simulations was performed to establish the annual heating and cooling load that resulted from heat flow through the envelope. This research was accomplished by setting the infiltration rate to 0.05 air changes per hour (ACH), the minimum allowed by ESPRE, and reducing the internal load to zero from the value used in all previous calculations, 3000 Btu/h. The results of these 12 cases (3 locations × 4 insulation levels) are shown in Table 10. As expected, these results show significantly lower annual loads.

Table 10. Annual load for simulated structure without infiltration[a] or internal loads

Passive insulation system, A/F/W	Annual load (MBtu/year)		
	Lexington	Minneapolis	Phoenix
38/19/19	32.5	49.1	29.0
38/38/19	28.2	42.1	26.3
38/19/38	29.1	43.8	26.6
38/38/38	24.8	36.8	24.1

[a]Infiltration rate 0.05 ACH.

4.6 HVAC SYSTEMS

Several simulations were run for the hypothetical test structure with passive and active resistance systems in Lexington. These simulations were run to establish if the type of heating, ventilation, and air-conditioning (HVAC) system had an effect on the annual heating and cooling loads (Table 11). The four heating systems studied included resistance, heat pump, and gas with and without a heat pump. The cooling systems studied included air conditioning with and without a dehumidifier system.

Table 11. Annual load for simulated structure with various HVAC systems in Lexington, Kentucky

R-Values	Annual load (MBtu/year)		
Attic/Floor/Walls	Without humidity control	With humidity control	With humidity and dehumidifier controls
	Passive system		
0.5/0.5/0.5	182.7	183.8	186.4
19/19/19	66.1	69.5	73.1
38/19/19	62.3	65.6	69.3
38/38/19	58.1	61.5	65.1
38/19/38	58.8	62.2	65.9
38/38/38	54.7	58.1	61.8
	Active system		
Above six systems	52.0	55.3	58.7

The annual heating-plus-cooling loads were identical for all of the systems without humidity or dehumidification control. When humidity control was added to the heating system, the annual load increased. The addition of dehumidification control to the cooling system resulted in a further increase in the annual heating-plus-cooling loads (Table 11).

4.7 CONTROL STRATEGIES

The active system with the greatest potential to conserve energy was, in all three locations, a system with high- or low-thermal resistances of 38 or 0.5 for the attic; walls; and floor, roof, and wall solar absorptances and window transmittance high or low levels of 0.8 or 0.1 (Tables 7-9). The control strategies that yielded these potential energy savings for the three locations simulated are shown in Tables 12-14.

The active system with the potential for the highest energy conservation for Lexington, Kentucky, initially should have high thermal resistance and absorptance/transmittance levels and does not begin to

Table 12. Lowest load active system settings in Lexington

Hour	Resistance[a] and absorptance[b] levels during time period											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	H&H	H&H	H&H	H&H	H&H	L&L	L&L	L&L	H&L	H&H	H&H	H&H
2	H&H	H&H	H&H	H&H	H&H	L&L	L&L	L&L	H&L	H&H	H&H	H&H
3	H&H	H&H	H&H	H&H	H&H	L&L	L&L	L&L	H&L	H&H	H&H	H&H
4	H&H	H&H	H&H	H&H	H&H	L&L	L&L	L&E	H&L	H&H	H&H	H&H
5	H&H	H&H	H&H	H&H	H&H	L&L	L&L	L&E	H&L	H&H	H&H	H&H
6	H&H	H&H	H&H	H&H	H&H	L&E	L&E	L&E	H&L	H&H	H&H	H&H
7	H&H	H&H	H&H	H&H	H&H	L&E	L&E	L&E	H&L	H&H	H&H	H&H
8	H&H	H&H	H&H	H&H	H&H	L&L	L&L	L&E	H&L	H&H	H&H	H&H
9	H&H	H&H	H&H	H&H	H&H	L&L	L&L	L&L	H&L	H&H	H&H	H&H
10	H&H	H&H	H&H	H&H	H&L	L&L	L&L	L&L	H&L	H&H	H&H	H&H
11	H&H	H&H	H&H	H&H	H&L	H&L	L&L	H&L	H&L	H&H	H&H	H&H
12	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&H	H&H	H&H
13	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&H	H&H	H&H
14	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&H	H&H	H&H
15	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&H	H&H	H&H
16	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&H	H&H	H&H
17	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&H	H&H	H&H
18	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&H	H&H	H&H
19	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&H	H&H	H&H
20	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&H	H&H	H&H
21	H&H	H&H	H&H	H&H	H&L	H&L	H&L	L&L	H&L	H&H	H&H	H&H
22	H&H	H&H	H&H	H&H	H&L	L&L	H&L	L&L	H&L	H&H	H&H	H&H
23	H&H	H&H	H&H	H&H	H&L	L&L	L&L	L&L	H&L	H&H	H&H	H&H
24	H&H	H&H	H&H	H&H	H&L	L&L	L&L	L&L	H&L	H&H	H&H	H&H

[a]H (high) = 38, L (low) = 0.5, and E = either.

[b]H (high) = 0.8, L (low) = 0.1, and E = either.

Table 13. Lowest load active system settings in Minneapolis

Hour	Resistance[a] and absorptance[b] levels during time period											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	H&H	H&H	H&H	H&H	H&H	L&L	L&L	L&L	H&H	H&H	H&H	H&H
2	H&H	H&H	H&H	H&H	H&H	L&L	L&L	L&E	H&H	H&H	H&H	H&H
3	H&H	H&H	H&H	H&H	H&H	L&E	L&E	L&E	H&H	H&H	H&H	H&H
4	H&H	H&H	H&H	H&H	H&H	L&E	L&E	L&E	H&H	H&H	H&H	H&H
5	H&H	H&H	H&H	H&H	H&H	L&E	L&E	L&E	H&H	H&H	H&H	H&H
6	H&H	H&H	H&H	H&H	H&H	L&L	L&L	L&E	H&H	H&H	H&H	H&H
7	H&H	H&H	H&H	H&H	H&H	L&L	L&L	L&L	H&H	H&H	H&H	H&H
8	H&H	H&H	H&H	H&H	H&H	L&L	L&L	L&L	H&L	H&H	H&H	H&H
9	H&H	H&H	H&H	H&H	H&L	E&L	L&L	L&L	H&L	H&H	H&H	H&H
10	H&H	H&H	H&H	H&H	H&L	H&L	H&L	E&L	H&L	H&H	H&H	H&H
11	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&H	H&H	H&H
12	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&H	H&H	H&H
13	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&H	H&H	H&H
14	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&H	H&H	H&H
15	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&H	H&H	H&H
16	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&H	H&H	H&H
17	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&H	H&H	H&H
18	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&H	H&H	H&H
19	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&H	H&H	H&H
20	H&H	H&H	H&H	H&H	H&L	H&L	H&L	E&L	H&L	H&H	H&H	H&H
21	H&H	H&H	H&H	H&H	H&H	H&L	L&L	L&L	H&H	H&H	H&H	H&H
22	H&H	H&H	H&H	H&H	H&H	L&L	L&L	L&L	H&H	H&H	H&H	H&H
23	H&H	H&H	H&H	H&H	H&H	L&L	L&L	L&L	H&H	H&H	H&H	H&H
24	H&H	H&H	H&H	H&H	H&H	L&L	L&L	L&L	H&H	H&H	H&H	H&H

[a]H (high) = 38, L (low) = 0.5, and E = either.

[b]H (high) = 0.8, L (low) = 0.1, and E = either.

Table 14. Lowest load active system settings in Phoenix

Hour	Resistance[a] and absorptance[b] levels during time period											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&E	H&H	H&H
2	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&E	H&H	H&H
3	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&E	H&H	H&H
4	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&E	H&H	H&H
5	H&H	H&H	H&H	H&H	H&L	L&L	H&L	H&L	H&L	H&E	H&H	H&H
6	H&H	H&H	H&H	H&H	H&L	L&L	H&L	H&L	H&L	H&E	H&H	H&H
7	H&H	H&H	H&H	H&H	H&L	L&L	H&L	H&L	H&L	H&E	H&H	H&H
8	H&H	H&H	H&H	H&H	L&L	H&L	H&L	H&L	H&L	H&E	H&H	H&H
9	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&E	H&H	H&H
10	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	E&E[c]	H&H	H&H
11	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	E&E	E&H	H&H
12	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	E&E	E&E[c]	H&H
13	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	E&E	E&E[c]	H&H
14	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	E&E	E&E[c]	H&H
15	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	E&E	E&E[c]	H&H
16	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	E&E	E&E[c]	H&H
17	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	E&E	E&E[c]	H&H
18	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	E&E	H&E	H&H
19	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	E&E	H&E	H&H
20	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	E&E	H&H	H&H
21	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	E&E	H&H	H&H
22	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	E&E[c]	H&H	H&H
23	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&H	H&H	H&H
24	H&H	H&H	H&H	H&H	H&L	H&L	H&L	H&L	H&L	H&H	H&H	H&H

[a]H (high) = 38, L (low) = 0.5, and E = either.

[b]H (high) = 0.8, L (low) = 0.1, and E = either.

[c]Except the L&L settings.

"switch" until hour 10 of an average day in May (Table 12). At that time and for the remainder of the average day in May, the absorptance/transmittance levels should be switched to the low (0.1) level to reduce the heating-plus-cooling loads. The absorptance/transmittance levels should remain low for June through September and switch back to the high levels for October through December. During June, July, and August, the thermal resistance levels should switch to the low level (0.5) for the late night through early morning time period: hours 22 through 10 for June, hours 23 through 11 for July, and hours 21 through 11 for August.

A very similar strategy would apply for Minneapolis, Minnesota. The only difference with that of the strategy for Lexington would be the times at which the switching would occur. The strategy for Phoenix, Arizona, would suggest that the absorptance/transmittance levels be high for all of January through April and October through December and low for May through August. Thermal resistance would be high and switching would be minimal, hour 8 in May and hours 5 through 7 in June.

5. DISCUSSION

The results for the passive and active systems described previously show significant energy savings potential for many of the cases investigated. The potential energy and monetary savings that may result from the optimal passive and active systems are discussed in this section. Brief discussions of an error analysis and suggested control strategies that may be used to achieve the predicted savings are also presented.

The calculation of monetary savings potentials was made by assuming that the HVAC system consisted of a heat pump with a seasonal energy efficiency ratio (SEER) of 8 for cooling and a heating seasonal performance factor (HSPF) of 7 for heating. Because the heating and cooling loads were combined in the previous analyses, an average rating of 7.5 Btu/Wh was assumed for the unit. At an electricity cost of $0.08/kWh, a load reduction of 1 MBtu would correspond to a monetary savings of approximately $11.

5.1 ERROR ANALYSIS

There are several sources of errors in the results presented above. A brief discussion of these follows with details of efforts that have been attempted to quantify the magnitude of each.

The database management program used in the active system simulations allowed the insulation or absorptance/transmittance level to be changed at each of the 288 monthly average hours and assumed that the load for each of the hours was not affected by what had occurred in the prior time periods. In essence, the structure was assumed to reach steady-state conditions very rapidly when the insulation or absorptance/transmittance levels were changed. The walls of the structure were assumed to be "light" (10 lb/ft^2 floor area). (Although it is believed that this was a good assumption, it has not been validated.)

Because of the memory limitations of the microcomputers and the database management program, the monthly average hour data had to be used to perform the active system analyses. To ensure that serious errors were not produced by this approach, a series of simulations were performed in which the results of the entire set of 8760 hourly loads were compared with the 288 monthly average hourly loads. The comparisons given in Table 5 for the passive cases show an average disagreement between the annual loads of <0.1%. The active cases have a maximum disagreement of +1.3% and an average absolute disagreement of <0.9%. This disagreement is partially explained as the ESPRE program reports the results in kBtu/h with only one decimal place. Thus, as the level of precision of the results is $\pm$0.05 kBtu/h, an uncertainty of $\pm$0.05 kBtu/h $\times$ 24 h/d $\times$ 30.4 d/month $\times$ 12 months/year or $\pm$0.4 MBtu/year results.

During the late spring and early fall, there are often temperature variations that require heating one day, cooling the next day, heating the next day, etc. The averaged hourly data showed this as an hour that required both heating and cooling. Another explanation for the disagreement is that the minimization selects a slightly different active system for the resulting averaged data than would be optimum for

the hourly data. The averaged data underestimate the energy savings potential by approximately 1%. This level is considered the level of accuracy of the procedure.

5.2 VARIABLE RESISTANCE SYSTEMS

5.2.1 Passive Systems

The energy-saving potential for the various systems simulated are summarized in Tables 7-9 for Lexington, Minneapolis, and Phoenix, respectively. The systems are grouped into categories that can conserve 1 to 2, 2 to 3, 3 to 4, etc., MBtu/year if incorporated into a structure that starts with attic/floor/wall resistances of 38/19/19 and roof absorptance/wall absorptance/window transmittance of 0.8/0.5/0.5 in each location. Table 15 shows the predicted energy savings and the resulting monetary savings for a few of the passive resistance changes.

Increasing the passive resistance levels of the walls from 19 to 38 reduced the energy consumption by 4, 5, and 3 MBtu/year in Lexington, Minneapolis, and Phoenix, respectively. These energy savings correspond to monetary savings of $40, $60, and $30/year. A similar change in the thermal resistance of the floor produced savings of 4, 7, and 3 MBtu/year or monetary savings of $50, $80, and $30/year for the three locations. Changing both the thermal resistances of the floor and walls yielded energy savings of 7 to 8, 12 to 13, and 5 to 6 MBtu/year or monetary savings of $80 to $90, $130 to $140 and $50 to $60/year in Lexington, Minneapolis, and Phoenix, respectively.

The potential energy and monetary savings for the passive changes in thermal resistance are cumulative. Clearly, more insulation is better because more insulation results in lower energy consumption.

5.2.2 Active Systems

The energy savings and monetary savings potential for several of the active (variable) thermal resistance systems are summarized in Table 15. Allowing the attic insulation to be active between resistance levels of 0.5 and 38 yielded energy savings of 1 MBtu/year or less and monetary savings of $10/year or less in the three locations. Active walls produced energy reductions of 6, 7, and 3 MBtu/year. These values

Table 15. Energy and monetary savings for simulated structures with passive and active resistance systems

System	Energy savings (MBtu/year)			Cost savings/year ($)
	0.8/0.8/0.8	0.8/0.5/0.5	0.1/0.1/0.1	
Lexington, Kentucky				
Passive				
Walls at 38		3.5		39
Floors at 38		4.2		46
F&W at 38	7.2	7.6	8.1	79-89
Active				
Attic at 0.5 or 38		1.2		13
Walls at 0.5 or 38		5.8		64
Floor at 0.5 or 38		6.3		69
A&F&W at 0.5 or 38		11.2		123
Minneapolis, Minneapolis				
Passive				
Walls at 38		5.4		59
Floors at 38		7.0		77
F&W at 38	11.9	12.3	13.0	131-143
Active				
Attic at 0.5 or 38		0.8		9
Walls at 0.5 or 38		6.8		75
Floor at 0.5 or 38		8.7		96
A&F&W at 0.5 or 38		14.8		163
Phoenix, Arizona				
Passive				
Walls at 38		2.5		28
Floors at 38		2.7		30
F&W at 38	5.0	5.2	5.6	55-62
Active				
Attic at 0.5 or 38		0.2		2
Walls at 0.5 or 38		3.0		33
Floor at 0.5 or 38		3.1		34
A&F&W at 0.5 or 38		6.1		67

are, however, only 1 MBtu/year greater than the energy savings that resulted from changing the wall resistance to a passive level of 38. Thus, the active system saved only $10/year more than the passive system. A similar comparison for the floors showed that active floors saved an additional 2 MBtu/year over a passive change to 38 in Lexington and Minneapolis and 1 MBtu/year in Phoenix. Making all systems active conserved 4, 3, and 1 MBtu/year more than simply raising the passive levels to 38 in Lexington, Minneapolis, and Phoenix, respectively. These energy savings correspond to monetary savings of <$40/year. It is unlikely that these small savings potentials could be economically justified. Hence, further study of these systems is not warranted.

5.3 SWITCHABLE ABSORPTANCE SYSTEMS

5.3.1 Passive Systems

Changing the passive absorptance levels of the roof to 0.1, the walls to 0.1, or the window transmittance to 0.1 reduced the annual heating-plus-cooling load by 0.4 to 1.6, 0.6 to 0.8, or 1.3 to 2.4 MBtu/year in Lexington, respectively, depending on resistance levels. Similar passive changes produced <0.4 MBtu/year energy savings in Minneapolis. In Phoenix, the passive changes in the roof absorptance, wall absorptance, or window transmittance to 0.1 yielded savings of 0.9 to 2.3, 1.7 to 2.0, or 5.4 to 6.2, respectively (Table 16). Passive changes of all three absorptances/transmittance levels yielded load savings of 2.6 to 3.1 and 7.8 to 8.7 MBtu/year in Lexington and Phoenix, respectively. These energy savings correspond to approximately $30/year in Lexington and $90 to $100/year in Phoenix. More than half of the energy-conserving potential resulted from the change to the window transmittance. Because of the small area of the windows compared to the total area of the structure, any additional work in this area should focus on windows.

5.3.2 Active Systems

Active window transmittance systems with levels of 0.1 and 0.8 can conserve 10 to 11 MBtu/year in all three locations (Table 16). These energy savings represent significant savings over the passive systems in

Table 16. Energy and monetary savings for simulated structures with passive and active absorptance/transmittance systems

System	Resistance levels (MBtu/year)					Cost savings/year ($)
	38/19/19	38/38/38	19c/19/19[a]	10c/19/19[a]	38c/19/19[a]	
Lexington, Kentucky						
Passive						
Roof at 0.1	0.4	0.4	0.9	1.6	0.6	4-18
Walls at 0.1	0.8	0.7	0.7	0.6	0.8	7-9
Windows at 0.1	2.0	2.4	1.6	1.3	2.0	14-26
R&W&Wi at 0.1	2.6	3.1	2.6	2.7	2.7	29-34
Active						
Wi at 0.1 or 0.8	10.5	10.7	10.3	10.1	10.5	111-118
R&W&WI at 0.1 or 0.8	14.4	14.0	15.4	16.5	14.8	154-182
Minneapolis, Minnesota						
Passive						
Roof at 0.1	0.1	0.3	0.4			1-4
Walls at 0.1	*b*	0.0	*b*			0
Windows at 0.1	*b*	*b*	*b*			
R&W&Wi at 0.1	*b*	*b*	*b*			
Active						
Wi at 0.1 or 0.8	10.0	10.3	9.9			109-113
R&W&WI at 0.1 or 0.8	13.4	13.2	14.2			145-156
Phoenix, Arizona						
Passive						
Roof at 0.1	0.9	1.0	2.3			10-25
Walls at 0.1	2.0	1.7	1.9			19-22
Windows at 0.1	5.6	6.2	5.4			62-68
R&W&Wi at 0.1	7.8	8.2	8.7			86-96
Active						
Wi at 0.1 or 0.8	11.1	11.2	11.2			122-123
R&W&WI at 0.1 or 0.8	15.8	15.0	17.7			165-195

[a]Structure with cathedral ceiling.

[b]Results in higher heating-plus-cooling loads.

which the window transmittance was 0.1 in Lexington and Phoenix and 0.5 in Minneapolis, that is, energy savings of 7 to 8 MBtu/year in Lexington, 5 to 6 MBtu/year in Phoenix, and 10 MBtu/year in Minneapolis. Allowing all of the absorptances/transmittance to be active between 0.1 and 0.8 increased the load savings by 3 to 6 MBtu/year in Lexington, 3 to 4 MBtu/year in Minneapolis, and 4 to 7 MBtu/year in Phoenix. The total monetary savings that resulted from a completely active absorptance/transmittance system ranged from $150 to $180/year in Lexington, $150 to $160/year in Minneapolis, and $170 to $200/year in Phoenix (Table 16). Because more than two thirds of this savings can be achieved with only active windows, these systems deserve the majority of future study.

5.4 VARIABLE RESISTANCE AND/OR SWITCHABLE ABSORPTANCE SYSTEMS

5.4.1 Passive Systems

The load and monetary savings that resulted from the most conserving passive systems are presented in Table 17. The most conserving passive systems in Lexington and Phoenix had resistances of 38 and absorptance/transmittance of 0.1 and conserved 11 and 13 MBtu/year, respectively. The most conserving system in Minneapolis had resistances of 38, but absorptance/transmittance levels that were unchanged from 0.8/0.5/0.5. This system conserved 12 MBtu/year. Approximately 75% of the conservation resulted from increased resistance in Lexington. Only 40% of the conservation was caused by an increase in resistance in Phoenix. The monetary savings potential for the best passive systems was $120, $140, and $150/year in Lexington, Minneapolis, and Phoenix, respectively.

5.4.2 Active Systems

Active absorptance/transmittance systems increased the conservation potentials over the best passive cases by 12, 14, and 7 MBtu/year in Lexington, Minneapolis, and Phoenix. Simply making the window transmittance switchable between 0.8 and 0.1 conserved 8, 10, and 3 MBtu/year in Lexington, Minneapolis, and Phoenix, respectively, over that achieved by the best passive absorptance/transmittance system. The

Table 17. Energy and monetary savings for most energy-conserving systems[a]

System	MBtu/year	Cost savings/year ($)
Lexington, Kentucky		
F&W at 38	7.6	84
Windows at 0.8-0.1	10.5	116
F&W at 38 + R&W&WI at 0.1	10.7	118
F&W at 38 + Wi at 0.8-0.1	18.3	201
F&W at 38 + R&W&Wi at 0.8-0.1	21.6	238
A&F&W at + 38-0.5 + R&W&Wi at 0.8-0.1	23.3	256
Minneapolis, Minnesota		
Windows at 0.8-0.1	10.0	111
F&W at 38	12.3	135
F&W at 38 + Wi at 0.8-0.1	22.6	249
F&W at 38 + R&W&Wi at 0.8-0.1	25.5	281
A&F&W at + 38-0.5 + R&W&Wi at 0.8-0.1	26.1	287
Phoenix, Arizona		
F&W at 38	5.2	57
Windows at 0.8-0.1	11.1	122
F&W at 38 + R&W&WI at 0.1	13.4	147
F&W at 38 + Wi at 0.8-0.1	16.4	180
F&W at 38 + R&W&Wi at 0.8-0.1	20.2	222
A&F&W at 38-0.5 + R&W&Wi at 0.8-0.1	20.3	223

[a]Based on the data for simulated structures which initially have resistances of 38/19/19 and absorptances/transmittances of 0.8/0.5/0.5.

savings increased by 2 MBtu/year in Lexington and <1 MBtu/year in Minneapolis and Phoenix when the resistances were also made active.

Active absorptance/transmittance systems, when combined with resistance levels of 38, can conserve over 20 MBtu or $220/year in Lexington and Phoenix. Over 25 MBtu or $280/year can be saved in Minneapolis with similar systems. Approximately 40 to 50% of these savings can be achieved through active transmittance window systems. These systems comprise only 200 ft^2 of the total 2880 ft^2 area of the structure. Hence, their contribution to the total energy-savings potential of the systems studied greatly outweighed their fraction of the total surface area of the structure.

5.5 INFILTRATION AND INTERNAL LOADS

Analysis of the results presented in Table 10 for the simulations with minimal infiltration and without internal loads showed that a nearly constant difference existed between the simulation run with infiltration and internal loads and the simulation without infiltration or internal loads. This difference was 29.8, 41.1, and 27.5 MBtu/year for Lexington, Minneapolis, and Phoenix, respectively. Because this difference was independent of the level of insulation for a given location, it was concluded that the difference corresponded to the load resulting solely from infiltration and the internal loads. It was also decided that the value was site-specific, and that for a given location, subtraction of this difference from the total load would yield the load resulting from heat flow through the envelope.

The total annual heating-plus-cooling loads for the test structures with passive attic/floor/wall resistances of 38/19/19 and roof/wall/window absorptances/transmittance of 0.8/0.5/0.5 were 62.3, 90.2, and 56.6 MBtu/year in Lexington, Minneapolis, and Phoenix, respectively. Subtracting the above values for loads due to infiltration and internal loads yielded total annual through-the-envelope loads of 32.5, 49.1, and 29.1 MBtu/year for Lexington, Minneapolis, and Phoenix, respectively. Thus, 50 to 70% of the through-the-envelope loads can be eliminated with the best passive resistance/active absorptance/transmittance systems.

5.6 HVAC SYSTEMS

The initial calculations to become familiar with ESPRE showed that the annual heating-plus-cooling load appeared to depend on the HVAC system. This result was traced to a humidity control option in the specifications for the gas furnace. Humidity may be controlled at the expense of energy. All HVAC systems gave the same annual loads when humidity control was turned off. Simulations were performed for six HVAC systems at six different levels of insulation and for one active system consisting of the six passive systems to establish whether humidity or dehumidification control would have a large effect on the results. As seen in Table 11, humidity control increased the annual total heating-plus-cooling load. The average increase for the seven cases studied was 3 MBtu/year. Humidity and dehumidification control produced an even larger increase in the annual load. This increase averaged 7 MBtu/year. These results are only for Lexington.

5.7 CONTROL STRATEGIES

Preliminary studies on how the database management program changed the insulation level to minimize the heating and cooling loads showed that during most of the heating season the maximum level of insulation, maximum roof and wall absorptances, and maximum window transmittance should be used. During late spring and early fall, however, the insulation resistance and absorptances/transmittance often switched to the minimum level to take advantage of the available outdoor coolness. During the heat of the day in the summer, the insulation was again varied to the maximum setting, but the absorptance/transmittance remained at the minimum levels to minimize heat gain from solar insolation.

The effect of roof and wall emittance was not investigated. Clearly, it would be expected that the variation of the emittance would be opposite to that of the absorptance, that is, low in the winter and high in the summer. This behavior would minimize heat loss in the winter and maximize cooling in the summer. Coatings with wavelength-dependent properties, which might absorb and emit at the shorter

wavelengths but not at the longer wavelengths, would produce the desired results in winter. The opposite wavelength dependence would be desirable in summer.

6. CONCLUSIONS

1. The load-savings potential for a 1600-ft^2 structure assumed to be located in Lexington, Kentucky; Minneapolis, Minnesota; or Phoenix, Arizona, and having a wide range of passive and active systems was determined. Passive systems with attic, floor, and wall insulation levels of R-0.5, R-19, and R-38 were simulated. Active systems allowed the insulation R-values to attain any of these values at any time. Passive systems, in which the absorptance of the roof and/or walls and/or transmittance of the windows was changed to either 0.8, 0.5, or 0.1, were also simulated, along with active switchable absorptance/transmittance systems that allowed the absorptance/transmittance to be switched between the various passive levels. The test matrix consisted of 430 passive and 171 active systems.

2. Examination of passive and variable-level-insulation systems indicated that the majority of savings resulted from simply increasing the level of the insulation. Increasing the passive level of insulation in the attic/floor/walls from 38/19/10 to 38/38/38 resulted in a decrease of total annual heating and cooling load by 7 to 8, 12 to 13 and 5 to 6 MBtu/year in Lexington, Minneapolis, and Phoenix, respectively. Allowing the system to become active reduced the loads by an additional 4, 2, and 1 MBtu/year. Thus, active thermal resistance systems had a very small potential for energy conservation.

3. Passive and switchable absorptance systems can significantly reduce energy consumption. A passive absorptance/transmittance system was able to reduce the annual heating-and-cooling load in Phoenix by 7 to 8 MBtu/year. Active systems were able to produce 20 MBtu/year savings in Phoenix and Lexington and 25 MBtu/year savings in Minneapolis. Active window transmittance produced 40 to 50% of this total savings potential. These systems appear to have the most potential and should receive the majority of future study.

7. FUTURE WORK

The switchable absorptance/transmittance systems appear to have the greatest potential for energy conservation. The analysis should be extended to include switchable emittance coatings as well. Because window systems showed the greatest potential for energy savings, most future work will focus on these systems. Secondary importance should be placed on looking at strategies for changing the absorptance/transmittance of walls and windows facing in different directions. Finally, a lesser effort will be undertaken to determine the possible effects variable resistance window insulation systems have on energy conservation.

The second major area of continued work will focus on the establishment of the criteria for switching active system levels. To date, the results show that switches do not have to be made frequently. The combination of conditions that suggest a change should be made are as yet unknown.

The final modeling task will consist of a study to establish what effect the transients actually have on the predicted energy savings.

Other suggestions for future work made by the reviewers of this report include

- adding a cold-sunny climate to the analysis (e.g., Denver, Colorado);
- analyzing variable thermal resistance systems which are more closely correlated to the climate with smaller increments for the high-low settings;
- performing a few simulations using a more sophisticated energy analysis program (e.g., DOE 2.1) to check the accuracy of the ESPRE program and the assumption that the transients that occur after switching in the active mode do not effect the results; and
- examining the benefits of coatings with wavelength dependent absorptance, emittance, and transmittance.

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APPENDIX A

USER-SPECIFIED STRUCTURE PARAMETERS REQUIRED BY ESPRE

RUN CONTROL DATA	
WEATHER DATA VOLUME NUMBER	20, 22, or 83
20 = Lexington, Kentucky	
22 = Minneapolis, Minnesota	
83 = Phoenix, Arizona	
STARTING MONTH (1-12)	1
STARTING DAY OF MONTH	1
ENDING MONTH (1-12)	12
ENDING DAY OF MONTH	31
DAILY INTERVALS IN ANALYSIS	1
OUTPUT INTERVALS (1-3)	1
1 = DAY 2 = MONTH 3 = YEAR	
OUTPUT DEVICE (1-3)	3
1 = SCREEN 2 = PRINT 3 = FILE	
WEATHER DATA	
WEATHER DISK GROUND TEMPS	1
1 = USE 2 = DEFINE NEW VALUE	
JAN GROUND TEMPERATURE	*a*
FEB GROUND TEMPERATURE	*a*
...	
LOTUS 1-2-3 OUTPUT	
HOURLY OUTPUT (0=NO, 1=YES)	
THERMAL LOAD	1
ELEC ENERGY USE	0
GAS ENERGY USE	0
DRY BULB TEMPERATURE	0
INSOLATION	0
DAILY OUTPUT MONTH NUMBER	0
0 = NONE 1 = JAN ... 12 = DEC	
MONTHLY SUMMARIES	0
0 = NO 1 = YES	
DESIGN OF BUILDING	
NUMBER OF SPACES (1-2)	1
SPACE VOLUME (FT^3)	12,800
SPACE THERMAL MASS (1-3)	1
1 = LIGHT 2 = MEDIUM 3 = HEAVY	
FOUNDATION TYPE (1-3)	2
1 = BASEMENT 2 = CRAWL SPACE 3 = SLAB	
SPACE 1 VOLUME (FT^3)	12,800
SPACE 1 THERMAL MASS (1-3)	1
1 = LIGHT 2 = MEDIUM 3 = HEAVY	
SPACE 2 VOLUME (FT^3)	0
SPACE 2 THERMAL MASS (1-3)	*b*
1 = LIGHT 2 = MEDIUM 3 = HEAVY	
ATTIC CONFIGURATION (1-2)	*b*
1 = SHARED 2 = SEPARATE	

WALL DATA (REPEAT FOR EACH WALL)

WALL ORIENTATION	1, 3, 5, and 7
1 = North 2 = Northeast 3 = East 4 = Southeast	
5 = South 6 = Southwest 7 = West 8 = Northwest	
TOTAL WALL AREA (FT^2)	320
WALL R VALUE ($H \cdot FT^2 \cdot °F/BTU$)	0.5, 19, or 38
WALL THERMAL MASS	1
1 = LIGHT 2 = MEDIUM 3 = HEAVY	
WALL SOLAR ABSORPTANCE	0.1, 0.5, or 0.8
WINDOW AREA (FT^2)	50
NUMBER OF PANES	2
WINDOW SHADING COEFFICIENT (TRANSMITTANCE)	0.1, 0.5, or 0.8
SOLAR GAIN TO INTERNAL MASS	50%
WINDOW INSULATION	0
0 = NO 1 = YES	

ATTIC DATA

CATHEDRAL CEILING	1 or 2
1 =NO 2=YES	
CEILING AREA (FT^2)	1600
CEILING R VALUE	0.5, 19, or 38
ROOF R VALUE	1.2
ROOF PITCH (FT/FT)	0.33
ATTIC VENTILATION (CFM/FT^2)	0.1

FOUNDATION : CRAWL SPACE

CEILING AREA (FT^2)	1600
CEILING R VALUE	0.5, 19, or 38
WALL AREA (FT^2)	256
WALL R VALUE (ENTER 0 IF OPEN MESH)	0
FLOOR R VALUE (ENTER 0 IF BARE EARTH)	0
VENTILATION RATE (CFM/FT^2)	0.2

BUILDING INFILTRATION

MODEL (1-2)	1
1 = CONSTANT 2 = VARIABLE	
RATE (AIR CHANGES/H)	1.0

SYSTEMS

SPACE 1 HEATING (1-5)	2, 3, 4, or 5
1 = NONE 2 = RESISTANCE 3=HEAT PUMP	
4 = GAS 5 = ADD-ON HEAT PUMP	
SPACE 2 HEATING (1-5)	*b*
SPACE 1 COOLING (1-3)	2 or 3
1 = NONE 2 = AIR CONDITIONER 3 = DEHUMIDIFIER SYSTEM	
SPACE 2 COOLING (1-3)	*b*

RESISTANCE HEATING SYSTEM

CAPACITY (KW)	30
DISTRIBUTION LOSSES (%)	0

HEAT PUMP	
CAPACITY AT 47 F (KBTU/HR)	34.4
CAPACITY AT 17 F (KBTU/HR)	20.2
COMPRESSOR PWR AT 47 F (KW)	3.14
COMPRESSOR PWR AT 17 F (KW)	2.39
FAN POWER (KW)	0.84
1ST STAGE BACKUP (KW)	5.0
2ND STAGE BACKUP (KW)	5.0
OUTDOOR SETPOINT (F)	20
PART LOAD FACT AT 20% DUTY	85
DISTRIBUTION LOSSES (%)	15
DEFROST (1 = NO, 2 = YES)	2
CRANKCASE HEATER POWER (KW)	0.25
OUTDOOR CONTROL TEMP (F)	50
DEFROST POWER (KW)	1
DEFROST OUTDOOR TEMP (F)	37
DEFROST ON-TIME (MIN)	6
TIME BETWEEN CYCLES (MIN)	90
GAS FURNACE	
CAPACITY (KBTU/HR)	50.
FAN POWER (KW)	0.75
RATED EFFICIENCY (%)	85.
PILOT LIGHT GAS (KBTU/HR)	15.
REL HUMIDITY CONTROL (%)	0
PART LOAD FACT AT 20% DUTY	85
DISTRIBUTION LOSSES (%)	15
GAS FURNACE WITH ADD-ON HEAT PUMP	
HP CAPACITY AT 47 F	30.
HP CAPACITY AT 17 F	16.
COMPRESSOR PWR AT 47 F	3.80
COMPRESSOR PWR AT 17 F	3.10
PART LOAD FACT AT 20% DUTY	85
GAS FURN. CAPACITY (KBTU/H)	50
RATED EFFICIENCY (%)	85
PILOT LIGHT GAS (KBTU/H)	1.5
PART LOAD FACT	85
FAN POWER FOR UNIT (KW)	0.75
SIMUL. GAS AND HEAT PUMP	0
0 = HEAT PUMP IS OFF WHEN GAS FURNACE IS ON	
1 = SIMULTANEOUS OPERATION	
SWITCH OVER TEMPERATURE (F)	35
DISTRIBUTION LOSSES	15
COOLING SYSTEM	
CAPACITY AT 95 F (KBTU/H)	34.8
CHANGE WITH DRY BULB (%/F)	-0.40
CHANGE WITH WET BULB (%/F)	1.49
COMPRESSOR PWR AT 95 F (KW)	4.15
CHANGE WITH DRY BULB (%/F)	0.77
CHANGE WITH WET BULB (%/F)	0.74
FAN POWER (KW)	0.84
PART LOAD FACT AT 20% DUTY	85.
DISTRIBUTION LOSSES (%)	15.

```
DEHUMIDIFICATION SYSTEM
     TYPE (1 = ELEC, 2 = GAS)                          2
     CAPACITY (PINTS/DAY)                              20.
     COP                                               0.8
     CONTROL HUMIDITY RATIO (%)                        1.0
     SENSIBLE GAIN (% OF LATENT)                       35.
     MOTOR POWER (KW)                                  0.1

THERMOSTAT SCHEDULE
     SETBACK OR SETUP (1-2)                            1
          1 = NO  2 = YES
     SETTING:  MID- 2 AM (F)   ...

SYSTEM OPERATING SCHEDULE
     MONTH HEATING STARTS (1-12)                       9
     MONTH HEATING ENDS   (1-12)                       5
     MONTH COOLING STARTS (1-12)                       5
     MONTH COOLING ENDS   (1-12)                       9

NATURAL VENTILATION
     SPACE 1 VENTILATION (ACH)                         0
     MINIMUM OUTDOOR TEMP (F)                          40
     MAXIMUM OUTDOOR TEMP (F)                          90
     MINIMUM INDOOR TEMP (F)                           80
     MAXIMUM INDOOR TEMP (F)                           100
     SPACE 2 VENTILATION (ACH)
     ...

INTERNAL SENSIBLE AND LATENT LOADS
     TYPE (1-2)                                        1
          1 = CONSTANT   2 = VARIABLE
     LOAD (BTU/HR)                                     3000
          MID- 2 AM (BTU/HR) ...

WEEKLY SCHEDULES ; INTERNAL LOADS                      0
          0 = SAME ALL WEEK   1 = WEEKDAY AND WEEKEND
     MONDAY    (0 OR 1
          0 = WEEKDAY   1 = WEEKEND
     TUESDAY   (0 OR 1)
     WEDNESDAY (0 OR 1)
     THURSDAY  (0 OR 1)
     FRIDAY    (0 OR 1)
     SATURDAY  (0 OR 1)
     SUNDAY    (0 OR 1)
     JAN 1st DAY OF WEEK (1-7)    1 = MON, 2 = TUE, ... 7 = SUN
```

Additional Parameters Not Employed in the Current Study

WINDOW INSULATION
- NUMBER OF SCHEDULES
- INSULATION R VALUE
- FIRST MONTH IN SEASON 1
- LAST MONTH IN SEASON 1
- FIRST HOUR IN SEASON 1
- LAST HOUR IN SEASON 1
- FIRST MONTH IN SEASON 2
- LAST MONTH IN SEASON 2
- FIRST HOUR IN SEASON 2
- LAST HOUR IN SEASON 2

PARTITION BETWEEN SPACES 1 AND 2
- AREA (SF)
- R VALUE (HR-SF-F/BTU)
- THERMAL MASS (1-3)
  - 1 = LIGHT,..., 3 = HEAVY

FOUNDATION: BASEMENT
- ABOVE-GRADE WALL AREA
- ABOVE-GRADE WALL R VALUE
- BELOW-GRADE WALL AREA
- BELOW-GRADE WALL R VALUE
- GROUND THERMAL CONDUCTIVITY
- VENTILATION RATE
- INTERNAL LOAD

FOUNDATION: SLAB
- AREA (SF)
- R VALUE OF SLAB
- PERIMETER (FT)
- EDGE INSULATION R VALUE
- GROUND THERMAL CONDUCTIVITY (CLAY: 0.5; SAND: 1.6)

SYSTEM ELECTRICAL LOAD CONTROL
- WEEKLY LOAD CONTROL
  - HR HEATING ENABLED (0-24)
  - HR HEATING DISABLED (0-24)
  - HR COOLING ENABLED (0-24)
  - HR COOLING DISABLED (0-24)
- WEEKEND LOAD CONTROL
  - HR HEATING ENABLED (0-24)
  - HR HEATING DISABLED (0-24)
  - HR COOLING ENABLED (0-24)
  - HR COOLING DISABLED (0-24)

AUXILIARY ELECTRICAL ENERGY
- JAN AUXILIARY ENERGY
- FEB AUXILIARY ENERGY

...

AUXILIARY GAS (THERM)
- JAN AUXILIARY GAS
- FEB AUXILIARY GAS

...

HOLIDAY SCHEDULES
- ENTER HOLIDAYS AS MONTH.DAY (EXAMPLE: JULY 4 IS 07.04)
- NEW YEARS DAY
- WASHINGTON'S BIRTHDAY
- MEMORIAL DAY
- INDEPENDENCE DAY
- LABOR DAY
- VETERANS' DAY
- THANKSGIVING
- CHRISTMAS
- OPTIONAL HOLIDAY
- OPTIONAL HOLIDAY

ELECTRIC RATE SCHEDULES
- MONTH SCHEDULE START
- NO. OF PEAK PERIODS
- HOUR PERIOD 1 BEGINS
- HOUR PERIOD 1 ENDS
- HOUR PERIOD 2 BEGINS
- HOUR PERIOD 2 ENDS

BLOCK-TYPE ELECTRIC RATE SCHEDULE
- DEMAND CHARGE (p/KW)
- NUMBER OF RATE BLOCKS (1-4)
- ENERGY COST (/KWH)
- FOR FIRST KWH USAGE (KWH)
- ENERGY COST (/KWH)
- FOR NEXT KWH USAGE (KWH)
- ENERGY COST (/KWH)
- FOR NEXT KWH USAGE (KWH)
- ENERGY COST (/KWH)
- FOR REMAINING KWH USAGE

BLOCK-TYPE GAS RATE SCHEDULE
- NUMBER OF SCF GAS PER THERM
- NUMBER OF RATE BLOCKS
- ENERGY COST (/THERM)
- FOR FIRST BLOCK (THERM)
- ENERGY COST (/THERM)
- FOR NEXT BLOCK (THERM)

...

DESIGN LOAD CALCULATION
- HEATING SEASON DESIGN
- ROOM TEMPERATURE (F)
- OUTDOOR TEMPERATURE (F)
- GROUND TEMPERATURE (F)
- COOLING SEASON DESIGN
- ROOM TEMPERATURE (F)
- OUTDOOR TEMPERATURE (F)

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[a]Values from TMY data file.

[b]Not applicable to the current study.

APPENDIX B

ANNUAL HEATING-PLUS-COOLING LOADS FOR ALL PASSIVE AND ACTIVE INSULATION SYSTEMS SIMULATED

Table B.1. Annual heating-plus-cooling loads for the simulated structure with passive resistance at absorptance/transmittance of 0.8/0.5/0.5

Resistance		Walls					
		0.5		19		38	
Attic	Floor	MBtu/year	% Base	MBtu/year	% Base	MBtu/year	% Base
				Lexington, Kentucky			
0.5	0.5	182.7	293.5	140.1	225.1	137.0	220.0
	19	149.2	239.6	94.8	152.3	91.2	146.4
	38	145.3	233.3	90.3	145.0	86.7	139.2
19	0.5	164.0	263.4	113.2	181.7	109.6	176.0
	19	123.5	198.3	66.1	106.2	62.6	100.6
	38	119.2	191.4	61.9	99.4	58.5	93.9
38	0.5	161.3	259.1	109.3	175.6	105.8	169.9
	19	120.0	192.7	62.3	100.0	58.8	94.5
	38	115.6	185.6	58.1	93.2	54.7	87.9
				Minneapolis, Minnesota			
0.5	0.5	231.0	256.0	196.0	217.3	192.9	213.8
	19	202.9	224.9	139.8	154.9	134.5	149.1
	38	199.1	220.7	132.9	147.3	127.6	141.4
19	0.5	216.3	239.8	166.7	184.7	162.3	179.9
	19	175.7	194.8	96.3	106.8	90.9	100.8
	38	170.5	189.0	89.3	99.0	83.9	93.0
38	0.5	214.0	237.3	161.8	179.3	157.2	174.3
	19	171.3	189.9	90.2	100.0	84.8	94.0
	38	165.7	183.7	83.2	92.2	77.9	86.4
				Phoenix, Arizona			
0.5	0.5	135.2	238.9	102.1	180.4	104.8	185.2
	19	111.7	197.4	79.4	140.2	77.0	136.1
	38	109.4	193.3	76.7	135.5	74.3	131.3
19	0.5	121.6	214.9	89.4	158.0	87.1	153.9
	19	96.5	170.5	59.5	105.1	57.0	100.7
	38	94.0	166.1	56.7	100.2	54.2	95.8
38	0.5	107.6	190.2	86.9	153.5	84.5	149.3
	19	94.3	166.7	56.6	100.0	54.1	95.5
	38	91.8	162.2	53.9	95.2	51.4	90.7

Table B.2. Annual heating-plus-cooling loads for simulated structure with active resistance at absorptance/transmittance of 0.8/0.5/0.5

Active system	High-low settings					
	38-19		19-0.5		38-0.5	
	MBtu/year	% Passive[a]	MBtu/year	% Passive[a]	MBtu/year	% Passive[a]
Lexington, Kentucky						
Attic (A)	62.1	99.8	65.0	98.3[b]	61.1	98.2
Floor (F)	57.7	99.4[c]	60.5	97.2	56.0	96.4[c]
Walls (W)	58.6	99.6[d]	60.0	96.4	56.5	96.0[d]
A&F	57.6	99.2[c]	64.0	96.7[b]	55.5	95.6[c]
A&W	58.5	99.4[d]	63.5	96.1[c]	56.0	95.2[d]
F&W	54.1	98.8[e]	59.5	95.6	51.5	94.0[e]
A&F&W	54.0	98.6[e]	63.2	95.5[b]	51.1	93.4[e]
Minneapolis, Minnesota						
Attic (A)	90.1	99.9	95.6	99.2[b]	89.4	99.1
Floor (F)	82.9	99.7[c]	88.8	98.4	81.5	97.9[c]
Walls (W)	84.7	99.8[d]	88.9	98.6	83.4	98.4[d]
A&F	82.9	99.6[c]	94.7	98.3[b]	81.3	97.7[c]
A&W	84.6	99.7[d]	94.7	98.3[c]	83.0	97.9[d]
F&W	77.5	99.4[e]	88.3	97.9	75.6	97.1[e]
A&F&W	77.4	99.3[e]	94.3	97.9[b]	75.4	96.8[e]
Phoenix, Arizona						
Attic (A)	56.6	100.0	59.2	99.5[b]	56.4	99.6
Floor (F)	53.8	99.9[c]	56.3	99.4	53.5	99.3[c]
Walls (W)	54.0	99.9[d]	56.2	99.3	53.6	99.2[d]
A&F	53.8	99.8[c]	59.0	99.2[b]	53.4	99.1[c]
A&W	54.0	99.9[d]	58.8	98.9[c]	53.4	98.8[d]
F&W	51.2	99.7[e]	56.0	99.0	50.6	98.6[e]
A&F&W	51.2	99.7[e]	58.8	98.8[b]	50.5	98.4[e]

[a]Structure with passive R-values of 38/19/19, except as noted.

[b]Structure with passive R-values of 19/19/19.

[c]Structure with passive R-values of 38/38/19.

[d]Structure with Passive R-values of 38/19/38.

[e]Structure with Passive R-values of 38/38/38.

Table B.3. Annual heating-plus-cooling loads for simulated structure with passive absorptance/transmittance systems in Lexington, Kentucky

Absorptance		Window transmittance					
		0.8		0.5		0.1	
Roof	Walls	MBtu/year	% Base	MBtu/year	% Base	MBtu/year	% Base
				R-Values = 38/19/19			
0.8	0.8	65.1	104.6	62.9	101.0	60.7	97.5
	0.5	64.3	103.3	62.3	100.0	60.3	96.9
	0.1	63.4	101.8	61.5	98.8	59.9	96.2
0.5	0.8	64.9	104.3	62.7	100.8	60.6	97.4
	0.5	64.2	103.1	62.1	99.8	60.2	96.7
	0.1	63.2	101.5	61.4	98.5	59.8	96.1
0.1	0.8	64.7	104.0	62.5	100.4	60.5	97.2
	0.5	64.0	102.7	61.9	99.5	60.1	96.5
	0.1	63.0	101.2	61.2	98.2	59.7	95.9
				R-Values = 38/38/38			
0.8	0.8	57.9	105.8	55.3	101.0	52.6	96.1
	0.5	57.2	104.5	54.7	100.0	52.3	95.6
	0.1	56.4	103.0	54.0	98.7	51.9	94.8
0.5	0.8	57.7	105.4	55.1	100.6	52.5	95.9
	0.5	57.0	104.2	54.6	99.7	52.2	95.3
	0.1	56.2	102.6	53.9	98.4	51.8	94.6
0.1	0.8	57.4	104.9	54.9	100.2	52.3	95.6
	0.5	56.8	103.8	54.3	99.2	52.0	95.0
	0.1	56.0	102.2	53.6	98.0	51.6	94.3
				R-Values = 19c/19/19[a]			
0.8	0.8	70.6	103.9	68.5	100.9	66.6	98.1
	0.5	69.9	102.8	67.9	100.0	66.3	97.6
	0.1	68.9	101.5	67.2	99.0	65.9	97.0
0.5	0.8	70.1	103.1	68.1	100.2	66.3	97.5
	0.5	69.4	102.1	67.6	99.5	65.9	97.1
	0.1	68.5	100.8	66.9	98.5	65.6	96.6
0.1	0.8	69.4	102.2	67.5	99.4	65.8	96.9
	0.5	68.8	101.2	67.0	98.7	65.5	96.5
	0.1	67.9	100.0	66.4	97.7	65.3	96.1

Table B.3. (continued)

Absorptance		Window transmittance					
		0.8		0.5		0.1	
Roof	Walls	MBtu/year	% Base	MBtu/year	% Base	MBtu/year	% Base
				R-Values = 10c/19/19[a]			
0.8	0.8	78.6	103.0	76.9	100.7	75.3	98.6
	0.5	78.0	102.1	76.3	100.0	75.0	98.2
	0.1	77.2	101.1	75.7	99.2	74.6	97.0
0.5	0.8	77.7	101.9	76.1	99.7	74.7	97.8
	0.5	77.1	101.0	75.6	99.1	74.4	97.5
	0.1	76.3	100.0	75.0	98.3	74.2	97.2
0.1	0.8	76.7	100.4	75.1	98.4	73.9	96.8
	0.5	76.1	99.6	74.7	97.8	73.7	96.6
	0.1	75.4	98.8	74.2	97.2	73.6	96.5
				R-Values = 38c/19/19[a]			
0.8	0.8	65.7	104.5	63.5	101.0	61.3	97.6
	0.5	65.0	103.3	62.9	100.0	60.9	96.9
	0.1	64.0	101.8	62.1	98.8	60.5	96.3
0.5	0.8	65.5	104.2	63.3	100.7	61.2	97.3
	0.5	64.7	102.9	62.6	99.6	60.8	96.7
	0.1	63.8	101.4	61.9	98.4	60.4	96.1
0.1	0.8	65.1	103.6	63.0	100.2	60.9	96.9
	0.5	64.4	102.4	62.3	99.2	60.6	96.3
	0.1	63.4	100.9	61.6	98.0	60.2	95.8

[a]Cathedral ceiling.

Table B.4. Annual heating-plus-cooling loads for simulated structure with passive absorptance/transmittance systems in Minneapolis, Minnesota

Absorptance		Window transmittance					
		0.8		0.5		0.1	
Roof	Walls	MBtu/year	% Base	MBtu/year	% Base	MBtu/year	% Base
				R-Values = 38/19/19			
0.8	0.8	90.7	100.5	90.2	100.0	90.7	100.6
	0.5	90.5	100.3	90.2	100.0	91.0	100.9
	0.1	90.3	100.1	90.3	100.1	91.6	101.5
0.5	0.8	90.6	100.4	90.2	99.9	90.7	100.6
	0.5	90.4	100.2	90.2	99.9	91.0	100.9
	0.1	90.2	100.0	90.2	100.0	91.6	101.5
0.1	0.8	90.5	100.3	90.1	99.9	90.7	100.5
	0.5	90.3	100.1	90.1	99.9	91.0	100.9
	0.1	90.1	99.9	90.2	100.0	91.7	101.6
				R-Values = 38/38/38			
0.8	0.8	78.8	101.1	78.0	100.1	78.0	100.2
	0.5	78.6	100.8	77.9	100.0	78.3	100.5
	0.1	78.3	100.5	77.9	100.0	78.6	101.0
0.5	0.8	78.7	101.0	77.8	99.9	78.0	100.1
	0.5	78.4	100.7	77.8	99.9	78.2	100.4
	0.1	78.2	100.4	77.8	99.9	78.7	101.0
0.1	0.8	78.5	100.8	77.8	99.8	78.0	100.2
	0.5	78.3	100.5	77.7	99.7	78.2	100.4
	0.1	78.1	100.3	77.7	99.8	78.7	101.0
				R-Values = 19c/19/19[a]			
0.8	0.8	99.2	100.2	99.0	100.0	99.7	100.7
	0.5	99.1	100.1	99.0	100.0	99.9	101.0
	0.1	98.9	100.0	99.1	100.2	100.5	101.6
0.5	0.8	99.0	100.0	98.8	99.8	99.6	100.6
	0.5	98.9	99.9	98.8	99.9	100.0	101.0
	0.1	98.8	99.8	99.0	100.1	100.6	101.6
0.1	0.8	98.6	99.7	98.6	99.6	99.6	100.6
	0.5	98.6	99.6	98.6	99.6	100.0	101.0
	0.1	98.5	99.5	98.9	99.9	100.7	101.7

[a]Cathedral ceiling.

Table B.5. Annual heating-plus-cooling loads for simulated structure with passive absorptance/transmittance systems in Phoenix, Arizona

Absorptance		Window transmittance					
		0.8		0.5		0.1	
Roof	Walls	MBtu/year	% Base	MBtu/year	% Base	MBtu/year	% Base
				R-Values = 38/19/19			
0.8	0.8	63.1	111.5	58.2	102.8	52.3	92.3
	0.5	61.5	108.7	56.6	100.0	51.0	90.1
	0.1	59.4	104.9	54.6	96.5	49.5	87.4
0.5	0.8	62.7	110.8	57.8	102.1	51.9	91.8
	0.5	61.1	108.0	56.3	99.4	50.7	89.5
	0.1	59.0	104.2	54.2	95.9	49.2	86.9
0.1	0.8	62.2	109.9	57.3	101.3	51.4	90.9
	0.5	60.6	107.1	55.7	98.5	50.3	88.8
	0.1	58.5	103.4	53.8	95.1	48.8	86.2
				R-Values = 38/38/38			
0.8	0.8	58.1	113.1	52.6	102.5	46.2	90.0
	0.5	56.7	110.4	51.4	100.0	45.2	88.1
	0.1	54.9	106.9	49.7	96.8	44.0	85.6
0.5	0.8	57.7	112.3	52.2	101.7	45.9	89.4
	0.5	56.3	109.6	51.0	99.2	44.9	87.4
	0.1	54.5	106.1	49.3	96.0	43.6	85.0
0.1	0.8	57.1	111.2	51.7	100.7	45.4	88.5
	0.5	55.8	108.6	50.4	98.2	44.4	86.5
	0.1	53.9	105.1	48.8	95.0	43.2	84.2
				R-Values = 19c/19/19[a]			
0.8	0.8	67.3	109.8	62.7	102.4	57.2	93.3
	0.5	65.8	107.3	61.3	100.0	55.9	91.3
	0.1	63.8	104.1	59.4	96.9	54.5	88.9
0.5	0.8	66.3	108.2	61.7	100.8	56.2	91.8
	0.5	64.8	105.8	60.3	98.4	55.1	89.9
	0.1	62.8	102.5	58.4	95.3	53.6	87.6
0.1	0.8	65.0	106.1	60.4	98.7	55.0	89.8
	0.5	63.5	103.7	59.0	96.3	53.9	88.0
	0.1	61.5	100.4	57.1	93.3	52.6	85.8

[a]Cathedral ceiling.

Table B.6. Annual heating-plus-cooling load for simulated structure with active absorptance/transmittance systems in Lexington, Kentucky

Active system	High-low settings					
	0.8-0.5		0.5-0.1		0.8-0.1	
	MBtu/year	% Base	Mbtu/year	% Base	MBtu/year	% Base
			R-Values = 38/19/19			
Roof (R)	61.9	99.4	61.7	99.1	61.5	98.8
Walls (W)	61.1	98.2	59.9	96.3	58.8	94.4
Windows (Wi)	58.9	94.6	55.2	88.6	51.8	83.2
R&W	60.8	97.6	59.2	95.0	58.0	93.2
R&Wi	58.5	94.0	54.4	87.4	51.1	82.0
W&Wi	57.9	92.9	52.9	85.0	48.5	78.0
R&W&Wi	57.5	92.4	52.2	83.9	47.9	76.9
			R-Values = 39/38/38			
Roof (R)	54.4	99.3	54.1	98.8	53.9	98.5
Walls (W)	53.9	98.4	52.8	96.5	52.0	94.9
Windows (Wi)	51.5	94.1	47.3	86.3	44.0	80.4
R&W	53.5	97.7	52.0	95.0	51.2	93.5
R&Wi	51.1	93.4	46.5	84.9	43.3	79.1
W&Wi	50.7	92.7	45.4	83.0	41.5	75.7
R&W&Wi	50.4	92.0	44.7	81.6	40.7	74.3
			R-Values = 19c/19/19[a]			
Roof (R)	67.0	98.7	66.4	97.7	65.9	97.0
Walls (W)	66.8	98.3	65.6	96.6	64.5	94.9
Windows (Wi)	64.5	94.9	61.0	89.8	57.6	84.8
R&W	65.9	97.0	63.6	93.7	62.5	92.0
R&Wi	63.6	93.6	59.1	86.9	55.6	81.9
W&Wi	63.4	93.4	58.8	86.6	54.4	80.0
R&W&Wi	62.5	92.1	56.9	83.8	52.5	77.2
			R-Values = 10c/19/19[a]			
Roof (R)	74.8	98.0	73.6	96.5	72.8	95.4
Walls (W)	75.2	98.5	74.1	97.1	73.0	95.6
Windows (Wi)	72.8	95.4	69.7	91.4	66.2	86.8
R&W	73.7	96.6	70.7	92.6	69.5	91.1
R&Wi	71.3	93.4	66.4	87.0	62.9	82.4
W&Wi	71.7	94.0	67.6	88.5	63.0	82.5
R&W&Wi	70.2	92.0	64.4	84.4	59.8	78.4
			R-Values = 38c/19/19[a]			
Roof (R)	62.4	99.2	62.0	98.6	61.7	98.2
Walls (W)	61.7	98.2	60.5	96.3	59.4	94.5
Windows (Wi)	59.5	94.6	55.8	88.7	52.4	83.3
R&W	61.2	97.4	59.4	94.5	58.3	92.7
R&Wi	59.0	93.8	54.7	87.0	51.3	81.6
W&Wi	58.4	93.0	53.6	85.2	49.1	78.2
R&W&Wi	57.9	92.2	52.5	83.6	48.1	76.6

[a]Cathedral ceiling.

Table B.7. Annual heating-plus-cooling load for simulated structure with active absorptance/transmittance systems in Minneapolis, Minnesota

Active system	High-low settings					
	0.8-0.5		0.5-0.1		0.8-0.1	
	MBtu/year	% Base	Mbtu/year	% Base	MBtu/year	% Base
			R-Values = 38/19/19			
Roof (R)	90.0	99.7	89.8	99.5	89.6	99.3
Walls (W)	88.7	98.4	88.3	97.9	86.9	96.3
Windows (Wi)	85.8	95.1	84.6	93.8	80.2	88.9
R&W	88.5	98.1	87.7	97.2	86.3	95.6
R&Wi	85.5	94.8	84.1	93.2	79.7	88.3
W&Wi	84.5	93.6	83.0	92.0	77.3	85.6
R&W&Wi	84.2	93.3	82.5	91.4	76.8	85.1
			R-Values = 38/38/38			
Roof (R)	77.6	99.6	77.4	99.4	77.3	99.2
Walls (W)	76.8	98.5	76.3	98.0	75.2	96.5
Windows (Wi)	73.6	94.5	71.9	92.3	67.6	86.8
R&W	76.5	98.2	75.7	97.2	74.6	95.7
R&Wi	73.3	94.1	71.4	91.6	67.1	86.1
W&Wi	72.5	93.1	70.6	90.6	65.2	83.8
R&W&Wi	72.3	92.8	70.0	89.9	64.7	83.1
			R-Values = 19c/18/19[a]			
Roof (R)	98.3	99.3	97.9	98.9	97.4	98.4
Walls (W)	97.5	98.5	97.1	98.1	95.7	96.7
Windows (Wi)	94.5	95.5	93.6	94.5	89.1	90.1
R&W	96.8	97.8	95.6	96.6	94.1	95.1
R&Wi	93.9	94.8	92.1	93.1	87.7	88.6
W&Wi	93.2	94.1	91.9	92.9	86.2	87.1
R&W&Wi	92.5	93.5	90.6	91.6	84.8	85.7

[a]Cathedral ceiling.

Table B.8. Annual heating-plus-cooling load for simulated structure with active absorptance/transmittance systems in Phoenix, Arizona

Active system	High-low settings					
	0.8-0.5		0.5-0.1		0.8-0.1	
	MBtu/year	% Base	Mbtu/year	% Base	MBtu/year	% Base
			R-Values = 38/19/19			
Roof (R)	56.1	99.2	55.6	98.3	55.5	98.0
Walls (W)	56.0	98.9	53.7	94.8	53.0	93.7
Windows (Wi)	54.7	96.7	47.4	83.7	45.5	80.3
R&W	55.5	98.1	52.5	92.8	51.9	91.7
R&Wi	54.2	95.8	46.2	81.7	44.3	78.3
W&Wi	54.2	95.8	44.4	78.4	42.0	74.2
R&W&Wi	53.7	95.0	43.2	76.4	40.8	72.2
			R-Values = 38/38/38			
Roof (R)	50.8	99.0	50.3	98.0	50.2	97.8
Walls (W)	50.9	99.0	49.0	95.4	48.5	94.4
Windows (Wi)	49.7	96.8	41.9	81.6	40.2	78.4
R&W	50.3	98.0	47.8	93.1	47.3	92.2
R&Wi	49.2	95.8	40.7	79.3	39.1	76.1
W&Wi	49.4	96.1	39.5	77.0	37.5	73.1
R&W&Wi	48.8	95.1	38.4	74.7	36.4	70.8
			R-Values = 19c/19/19[a]			
Roof (R)	60.0	97.9	58.6	95.6	58.3	95.1
Walls (W)	60.6	98.9	58.4	95.3	57.7	94.2
Windows (Wi)	59.2	96.7	52.2	85.1	50.1	81.8
R&W	59.3	96.8	55.4	90.4	54.7	89.3
R&Wi	58.0	94.6	49.1	80.2	47.1	76.9
W&Wi	58.7	95.8	49.2	80.3	46.7	76.2
R&W&Wi	57.4	93.7	46.2	75.4	43.6	71.2

[a]Cathedral ceiling.

APPENDIX C

ASHRAE IV PAPER

H. A. Fine and D. L. McElroy, "Assessment of the Energy Conservation Potential of Active (Variable Thermal Resistance and Switchable Absorptance) Systems for Residential Building Thermal Envelopes and Fenestration," pp. 639-58 in *Thermal Performance of the Exterior Envelopes of Buildings IV, Proceedings of the ASHRAE/DOE/BTECC/CIBSE Conference, December 4-7, 1989, Orlando, Florida*, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1989.

Assessment of the Energy Conservation Potential of Active (Variable Thermal Resistance and Switchable Absorptance) Systems for Residential Building Thermal Envelopes and Fenestration

H.A. Fine **D.L. McElroy**

ABSTRACT

The potential for energy conservation that could be achieved through the use of passive and active fenestration and insulation systems applied to a 1600 ft^2 residential building in either hot, intermediate, or cold climates was calculated. The potential for energy savings was established using the EPRI Simplified Program for Residential Energy (ESPRE). A passive insulation system was considered to be a building envelope with fixed roof, wall, and floor thermal resistance; fixed roof and wall absorptance; and fixed window transmittance. Active systems have variable thermal resistance attic, floor, and wall insulations; switchable roof and wall absorptances; and/or switchable window transmittance coatings.

The annual heating and cooling energy loads with the recommended passive insulation systems were 58, 62, and 90 MBtu/yr in Phoenix, Lexington, and Minneapolis, respectively. The most energy-conserving systems have the potential to reduce these levels by 20 to 25 MBtu/yr. Active fenestration systems deserve further study.

INTRODUCTION

Research on the potential for energy conservation with improved insulation systems has increased dramatically since the Oil Producing and Exporting Countries (OPEC) embargo in 1973. Significant research has been undertaken by the U.S. Department of Energy Building Thermal Envelope Systems and Materials Program, by other federally funded programs, and by private industry (Achenback 1982; Building Thermal Envelope Coordinating Council 1988; Bales 1986; Fine 1987). Assessments that have been performed indicate that the potential for energy conservation through improved insulation is great - approximately one quad for residential structures (Curlee 1988), one quad for commercial structures (Curlee 1988), one quad for residential and commercial refrigeration equipment (Curlee 1988), and one quad for industrial processes (Donnelly et al. 1975).

The research to date has, however, almost exclusively studied passive insulation systems and the resulting energy savings that might be achieved. The importance of active fenestration systems has been suggested by simulations of residential (Neeper and McFarland 1982) and commercial (Bartovics 1984) buildings. With the development of "smart" structures, a logical extension of the previous work is the study of the potential for energy conservation of smart or active fenestration and insulation systems.

A passive insulation system was considered to be a building envelope with fixed roof, wall, and floor thermal resistance; fixed roof and wall absorptance; and fixed window transmittance.

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An active system was considered to be a building envelope with variable resistances, absorptances, and/or transmittance that can be changed with time to minimize the building load.

The potential for energy conservation that may be achieved through the use of active thermal insulation systems is calculated and these simulations show systems which deserve further study.

METHODOLOGY

The potential for energy savings was established using the EPRI Simplified Program for Residential Energy (ESPRE) (Merriam 1986) to determine the hourly load for heating and cooling for a 1600 ft^2 lightweight structure with gray surfaces. The building was simulated to be in either Lexington, KY; Minneapolis, MN; or Phoenix, AZ.

Simulations were performed for a one-floor structure with crawlspace and a single heating/cooling zone and with an attic or cathedral ceiling. The structure was 40 ft by 40 ft and 8 ft tall. A summary of the properties of the structure are presented in Table 1. The ESPRE program calculates the heating and cooling loads for each of the 8760 hours in a year. From this, the monthly average hourly load is found by a summation of the load for a given time of day for all of the days in a month divided by the number of days in the month. Each month may then be represented by 24 hours and each year by 288 hours.

Heating and cooling load calculations (Fine and McElroy 1989) for 430 passive insulation systems were performed (Table 2). The annual load is defined as the sum of the monthly average hourly heating and cooling load multiplied by the number of days in the month. Calculations were performed in which the results of the entire set of 8760 hourly data were compared with the 288 monthly average hourly data. Results for three passive systems agreed to 0.1% (0.1 MBtu/yr) and results for four active systems agreed to 1.3% (0.7 MBtu/yr).

Structures with active systems were then simulated and the 288 monthly average hourly loads calculated using the results from sets of simulations for the same structure but with passive systems. An active system was considered to be a building envelope that could be changed with time to any of the passive levels to minimize the building load. The 171 active systems that were studied are summarized in Table 3. These systems were evaluated using the monthly average hourly loads calculated for the passive insulation systems. In the simulations of the active systems, the insulation system was allowed to change at any of the 288 hours. Starting with January and hour 1, the loads for the passive insulation systems at that time and pertinent to the active case being simulated were compared. The level of insulation resistance, absorptance, or transmittance was then set equal to that for the passive case which yielded the lowest load. The lowest load was also assumed to be the load for the active system. This process was repeated for each of the 288 hours of the year using a data base management program (see Figure 1). Summation of the hourly numbers yielded the annual building load for the active system.

RESULTS

This section compares the load calculations for the various insulation systems investigated: passive resistance, active resistance, passive absorptance/transmittance, active absorptance/transmittance, and active resistance and absorptance/transmittance systems. Annual loads for selected systems are presented in Table 4.

Passive Resistance Systems

The effect of increasing passive insulation resistance on the annual load for the building in Lexington, Minneapolis, and Phoenix is schematically represented in Figure 2 and summarized below for absorptance/transmittance levels of 0.8 for the roof, 0.5 for the walls, and 0.5 for the windows.

Annual Loads,[a] MBtu/yr, with Passive Resistance at Absorptance/Transmittance Levels of 0.8/0.5/0.5 for Roof/Walls/Windows

Resistance Levels[b] Attic	Floor	Walls	Lexington	Minneapolis	Phoenix
0.5	0.5	0.5	183	231	135
19	19	19	66	96	59
38	19	19	62	90	57
38	38	38	55	78	51

[a]Annual load is defined as the sum of the calculated heating and cooling loads.

[b]$h \cdot ft^2 \cdot {}^\circ F/Btu$.

Increasing the insulation resistances of the roof, floor, and walls from 0.5/0.5/0.5 to 19/19/19 lowers the annual loads by 117, 135, and 76 MBtu/yr for Lexington, Minneapolis, and Phoenix, respectively. A further increase to 38/19/19, the "optimum" for Lexington and Minneapolis as recommended by the Department of Energy *Insulation Fact Sheet* (DOE 1988) reduces the total load by an additional 4, 6, and 2 MBtu/yr for the three locations. "Super" insulation levels of 38/38/38 reduce the annual loads by another 7, 12, and 6 MBtu/yr. Clearly, more insulation conserves energy. Because it was not the intent of this study to determine economic insulation levels, levels between 0.5 and 19 were not simulated. Similar results are achieved at other absorptance/transmittance levels (see Table 4).

Active Resistance Systems

Active insulation systems having attic, floor, or wall resistances able to have high or low resistance levels of 38 or 19, 19 or 0.5, and 38 or 0.5, and high, medium, or low resistance levels of 38, 19, or 0.5 were studied. The results for the 38 or 0.5 and 38 or 19 or 0.5 simulations were equal, within the limits of accuracy of the calculations (0.7 MBtu/yr). As shown below, the active systems in which the attic, floor, and wall insulation levels could be 38 or 0.5 yield load savings of 4, 3, and 1 MBtu/yr over the "super" insulated passive insulation structures in Lexington, Minneapolis, and Phoenix, respectively.

Annual Loads,[a] MBtu/yr, with Passive and Active Resistance at Absorptance/Transmittance Levels of 0.8/0.5/0.5 for Roof/Walls/Windows

Resistance Levels[b] Attic	Floor	Walls	Lexington	Minneapolis	Phoenix
0.5	0.5	0.5	183	231	135
19	19	19	66	96	59
38	19	19	62	90	57
38	38	38	55	78	51
Active A&F&W between 38 or 0.5			51	75	50

[a]Annual load is defined as the sum of the calculated heating and cooling loads.

[b]$h \cdot ft^2 \cdot {}^\circ F/Btu$.

Passive Absorptance/Transmittance Systems

The effects of changing the roof absorptance, wall absorptance, or window transmittance on the annual load for structures in Lexington, Minneapolis, and Phoenix are shown below and in Figure 3 for resistance levels of 38/19/19.

Selection of a system with roof, wall absorptances, and window transmittance (R/W/Wi) of 0.1/0.1/0.1 in Lexington and Phoenix yields total annual loads 5 and 14 MBtu/yr lower than those for 0.8/0.8/0.8 cases. The effect of passive absorptance or transmittance changes in Minneapolis was generally less than 1 MBtu/yr.

Annual Loads,[a] MBtu/yr, for Passive Absorptance/Transmittance Systems at Resistance Levels of 38/19/19

Location	Roof Absorptance/Wall Absorptance/Window Transmittance		
	0.8/0.8/0.8	0.8/0.5/0.5	0.1/0.1/0.1
Lexington	65	62	60
Minneapolis	91	90	92
Phoenix	63	57	49

[a]Annual load is defined as the sum of the calculated heating and cooling loads.

Active Absorptance/Transmittance Systems

Active absorptance and/or transmittance systems were examined with high or low levels of 0.8 or 0.5, 0.5 or 0.1, and 0.8 or 0.1. Systems with high, medium, or low levels of 0.8, 0.5, or 0.1 were also investigated and found to yield results equivalent to those with high or low levels of 0.8 or 0.1. The results for one set of resistance levels (38/19/19) are presented below and in Figures 4 through 6 for Lexington, Minneapolis, and Phoenix, respectively.

Annual Loads,[a] MBtu/yr, for Passive and Active Absorptance/Transmittance Systems at Resistance Levels of 38/19/19

Location	Roof Absorptance/Wall Absorptance/Window Transmittance			
	0.8/0.8/0.8	0.8/0.5/0.5	0.1/0.1/0.1	Active 0.8 or 0.1
Lexington	65	62	60	48
Minneapolis	91	90	92	77
Phoenix	63	57	49	41

[a]Annual load is defined as the sum of the calculated heating and cooling loads.

The lowest total annual loads were obtained for active systems in which the roof absorptance, wall absorptance, and window transmittance were allowed to be either 0.8 or 0.1. At fixed resistance levels of 38/19/19, the active systems yielded energy savings of 12, 15, and 8 MBtu/yr compared to a passive system at 0.1/0.1/0.1. At resistance levels of 38/38/38, active absorptance/transmittance yielded energy savings of 11, 14, and 7 MBtu/yr over the best passive systems for the three locations (see Table 4).

Active Resistance and Absorptance/Transmittance Systems

Systems with all of the resistances and absorptances/transmittance active were examined for Lexington, Minneapolis, and Phoenix. These systems were able to have resistances for the attic/floor/walls of either 38 or 0.5 and roof absorptance/wall absorptance/window transmittance values of 0.8 or 0.1. As shown below, however, the energy savings for active resistance and absorptance/transmittance systems were only 2, 1, and 0 MBtu/yr better than structures with passive super resistance levels and active absorptance/transmittance systems.

Minimum Annual Loads,[a] MBtu/yr, for Three Systems with Passive and/or Active Components

Location	Resistance		
	Passive @ 38/38/38	Passive @ 38/38/38	Active @ 38 or 0.5
	Absorptance/Transmittance		
	Passive @ 0.1/0.1/0.1	Active @ 0.8 or 0.1	Active @ 0.8 or 0.1
Lexington	52	41	39
Minneapolis	78[b]	65	64
Phoenix	43	36	36

[a]Annual load is defined as the sum of the calculated heating and cooling loads.

[b]The absorptance/transmittance levels were 0.8/0.5/0.5 for this case.

As shown in Figures 4 through 6 and Tables 5 through 7, approximately 70% of the potential savings resulting from active absorptance/transmittance systems could be achieved with active windows only. Calculations for active windows on only one wall show equivalent potential savings for either east, south, or west walls. These orientations are about twice as effective as active windows on a north wall. Similar results may be found for individual wall absorptances, but the areas are larger and the savings smaller.

SUMMARY

The energy-saving potential for the various systems simulated are summarized in Tables 5 through 7 for Lexington, Minneapolis, and Phoenix. The systems are grouped into categories that can conserve 1-2, 2-3, 3-4 . . . MBtu/yr if incorporated into a structure that starts with attic/floor/wall resistances of 38/19/19 and roof absorptance/wall absorptance/window transmittance of 0.8/0.5/0.5 in each location.

Increasing the passive resistance levels of the floor and walls from 19 to 38 reduces the heating and cooling loads by 7-8, 12-13, and 5-6 MBtu/yr in Lexington, Minneapolis, and Phoenix, respectively. Changing the passive absorptances/transmittance of the roof/walls/windows to 0.1 will reduce the heating and cooling loads by 2-3 MBtu/yr in Lexington and 7-8 MBtu/yr in Phoenix. The most conserving passive change in Lexington and Phoenix consists of both of the previous actions: increasing the passive resistance of the floor and walls to 38 and reducing the absorptances and transmittance to 0.1. Both changes result in conservation of 10-11 MBtu/yr in Lexington and 13-14 MBtu/year in Phoenix.

Active insulation resistance systems produce very small savings above that achieved by the passive super insulation systems: approximately 4, 2, and 1 MBtu/yr in Lexington, Minneapolis, and Phoenix, respectively. Conversely, active absorptance/transmittance systems increase the conservation potentials over the best passive absorptance/transmittance cases by 12, 13, and 8 MBtu/yr in Lexington, Minneapolis, and Phoenix, respectively. Simply making the window transmittance switchable between 0.8 and 0.1 can conserve 8, 9, and 4 MBtu/yr in Lexington,

Minneapolis, and Phoenix, respectively, over that achieved by the best passive absorptance/transmittance system.

Incorporating passive resistance levels in the floor and wall of 38 with active absorptance and transmittance systems can conserve more than 20 MBtu/yr in both Lexington and Phoenix and 25 MBtu/yr in Minneapolis. Allowing the systems to be completely active, i.e., active resistances and absorptances/transmittance, produces an additional 2, 1, and 0 MBtu/yr reduction in energy consumption in Lexington, Minneapolis, and Phoenix, respectively.

FUTURE WORK

The large energy-conserving potential of active absorptance and transmittance systems should result in additional study of these systems. The very large conservation potential of active transmittance windows and their small area of 200 ft^2 in the simulated structures, as compared to the total energy-conserving potential for active roof, walls, and windows and their total area of 2880 ft^2, indicates additional studies of this type should focus on active windows. The inability of active resistance insulation systems to conserve significantly more energy than passive super insulation systems indicates that further study of these systems is not warranted.

Two additional areas that were not investigated, but which may yield significant energy conservation potential, are variable-resistance window insulation and orientation effects on the energy-conserving potential of active window transmittance systems in rectangular buildings.

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Table 1. Description of Test Structure

Floor Area - 1600 ft^2

Ceiling Height - 8 ft

Design - One Floor, Single Space, Crawl Space
Attic or Cathedral Ceiling

Infiltration - 1.0 ACH

Exterior Walls -
- Area - 320 ft^2/Wall
- Orientation - N, E, S, and W
- Windows - 50 ft^2/Wall
- Solar Absorptance (Absorptance) - 0.8, 0.5, or 0.1
- R-value - 38, 19, or 0.5
- Mass - 10 lb/ft^2 floor area

Attic -
- Area - 1600 ft^2
- Roof R-value - 1.2
- Roof Absorptance (Absorptance) - 0.8, 0.5, or 0.1
- Ceiling R-value - 38, 19, or 0.5
- Roof Pitch - 0.33 ft/ft
- Ventilation - 0.1 CFM/ft^2

Crawl Space -
- Area - 1600 ft^2
- Ceiling R-value - 38, 19, or 0.5
- Wall R-value - 0
- Ventilation - 0.2 CFM/ft^2

Windows -
- No. Panes - 2
- Shading (Transmittance) - 0.8, 0.5, or 0.1
- Insulation - None

Systems - Heating and Air Conditioning
- Cooling on - 5/1
- Thermostat - 76°F
- Heating on - 9/1
- Thermostat - 70°F
- Humidity Control - None

Table 2. Passive Insulation Systems Simulated

Location	Resistance (h·ft²·°F/Btu) Attic	Floor	Walls	Absorptance/Transmittance Roof	Walls	Windows
Resistance Systems (81)[a]						
Lexington, KY	[38	38	38]b	0.8	0.5	0.5
Minneapolis, MN	19	19	19			
Phoenix, AZ	0.5]	0.5	0.5]			
Absorptance/Transmittance Systems (297)[a]						
Lexington, KY	38	19	19	[0.8	0.8	0.8]b
	38	38	38	0.5	0.5	0.5
	10C[c]	19	19	0.1]	0.1]	0.1]
	19C[c]	19	19			
	38C[c]	19	19			
Minneapolis, MN	38	19	19			
	38	38	38			
	19C[c]	19	19			
Phoenix, AZ	38	19	19			
	38	38	38			
	19C[c]	19	19			
Miscellaneous Systems (52)[a]						
Other Passive Cases	22					
HVAC System Tests	18					
Infiltration Analysis	12					

[a]Number of passive systems.

[b]Brackets indicate a matrix.

[c]Structures with cathedral ceilings.

Table 3. Active Systems Simulated

Location	Active Element	Active Levels
Resistance Systems (84)[a]		
Lexington, KY	Attic (A)	38 or 19[b]
Minneapolis, MN	Floor (F)	19 or 0.5[b]
Phoenix, AZ	Walls (W)	38 or 0.5[b]
	A&F	38 or 19 or 0.5[b]
	A&W	
	F&W	
	A&F&W	
Absorptance/Transmittance Systems (84)[a]		
Lexington, KY	Roof (R)	0.8 or 0.5[c]
Minneapolis, MN	Walls (W)	0.5 or 0.1[c]
Phoenix, AZ	Windows (Wi)	0.8 or 0.1[c]
	R&W	0.8 or 0.5 or 0.1[c]
	R&Wi	
	W&Wi	
	R&W&Wi	
Resistance and Absorptance/Transmittance Systems (3)[a]		
Lexington, KY	A&F&W + R&W&Wi	38 or 0.5[b] + 0.8 or 0.1[c]
Minneapolis, MN		
Phoenix, AZ		

[a]Number of active systems.

[b]Resistance level in $h \cdot ft^2 \cdot {}^\circ F/Btu$.

[c]Absorptance/transmittance level.

Table 4. The Annual Loads (MBtu/year) for Selected Cases

Resistance Attic/Floor/Walls ($h \cdot ft^2 \cdot °F/Btu$)	Roof Absorptance/Wall Absorptance/Window Transmittance 0.8/0.8/0.8 (a)	0.8/0.5/0.5 (a)	0.1/0.1/0.1 (a)	0.8 or 0.1[d] (b)
		Lexington, KY		
0.5/0.5/0.5	182.8	182.7	181.6	
19/19/19		66.1		
38/19/19	65.1	62.3	59.7	47.9
38/38/38	57.9	54.7	51.6	40.7
10C/19/19[c]	78.6	76.3	73.6	59.8
19C/19/19[c]	70.6	67.9	65.3	52.5
38C/19/19[c]	65.7	62.9	60.2	48.1
38 or 0.5[d]		51.1[e]		39.0[f]
		Minneapolis, MN		
0.5/0.5/0.5	231.0	231.0	231.1	
19/19/19		96.3		
38/19/19	90.7	90.2	91.7	76.8
38/38/38	78.8	77.9	78.7	64.7
19C/19/19[c]	99.2	99.0	100.7	84.8
38 or 0.5[d]		75.4[e]		63.5[f]
		Phoenix, AZ		
0.5/0.5/0.5	134.0	135.2	137.7	
19/19/19		59.5		
38/19/19	63.1	56.6	48.8	40.8
38/38/38	58.1	51.4	43.2	36.4
19C/19/19[c]	67.3	61.3	52.6	43.4
38 or 0.5[d]		50.5[e]		36.3[f]

[a]Passive resistance and absorptance/transmittance case, except as noted.

[b]Passive resistance but active absorptance/transmittance case, except as noted.

[c]Structure with cathedral ceiling.

[d]Active system high or low levels.

[e]One active resistance case for each location.

[f]Active resistance and absorptance/transmittance case.

Table 5. Energy Conservation Potential for Test Structure in Lexington, Kentucky[a]

MBtu/year	Passive System	Passive Level	Active System	Active Level
1-2	R&W	0.1&0.1	A	38 or 0.5
	W&Wi	0.8&0.1	F	19 or 0.5
	R&W&Wi	0.5&0.8&0.1	W	0.8 or 0.5
	R&W&Wi	0.1&0.8&0.1	R&W	0.8 or 0.5
	Wi	0.1		
2-3	R&Wi	0.5&0.1	W	19 or 0.5
	R&Wi	0.1&0.1	F&W	19 or 0.5
	W&Wi	0.1&0.1	W	0.5 or 0.1
	R&W&Wi	0.5&0.1&0.1		
	R&W&Wi	0.1&0.1&0.1		
3-4	W	38	W	38 or 19
	F&W	38[b]	A&W	38 or 19
			R&W	0.5 or 0.1
			Wi	0.8 or 0.5
			W	0.8 or 0.1
			R&Wi	0.8 or 0.5
4-5	F	38	F	38 or 19
			A&F	38 or 19
			R&W	0.8 or 0.1
			W&Wi	0.8 or 0.5
			R&W&Wi	0.8 or 0.5
5-6			W	38 or 0.5
6-7			F	38 or 0.5
			A&W	38 or 0.5
			A&F	38 or 0.5
7-8	F&W	38	Wi	0.5 or 0.1
			R&Wi	0.5 or 0.1
8-9			F&W	38 or 19
			A&F&W	38 or 19
9-10			W&Wi	0.5 or 0.1
10-11	F&W + R&W&Wi	38 + 0.1	F&W	38 or 0.5
			R&W&Wi	0.5 or 0.1
			Wi	0.8 or 0.1
11-12			A&F&W	38 or 0.5
			R&Wi	0.8 or 0.1
13-14			W&Wi	0.8 or 0.1
14-15			R&W&Wi	0.8 or 0.1
21-22			F&W @38 + R&W&Wi	0.8 or 0.1
23-24			A&F&W + R&W&Wi	38 or 0.5 + 0.8 or 0.1

[a]Test structure consumes 62.3 MBtu/year with R-values of 38/19/19 and absorptance/transmittance of 0.8/0.5/0.5.

[b]Attic R-value also reduced to 19.

Table 6. Energy Conservation Potential for Test Structure in Minneapolis, Minnesota[a]

MBtu/year	Passive System	Passive Level	Active System	Active Level
1-2			W	19 or 0.5
			F	19 or 0.5
			F&W	19 or 0.5
			W	0.8 or 0.5
			R&W	0.8 or 0.5
			W	0.5 or 0.1
2-3			R&W	0.5 or 0.1
3-4			W	0.8 or 0.1
			R&W	0.8 or 0.1
4-5			Wi	0.8 or 0.5
			R&Wi	0.8 or 0.5
5-6	W	38	W	38 or 19
			A&W	38 or 19
			Wi	0.5 or 0.1
			W&Wi	0.8 or 0.5
			R&W&Wi	0.8 or 0.5
6-7	F&W	38[b]	W	38 or 0.5
	F	38	R&Wi	0.5 or 0.1
7-8			A&W	38 or 0.5
			F	38 or 19
			A&F	38 or 19
			W&Wi	0.8 or 0.5
			R&W&Wi	0.8 or 0.5
8-9			F	38 or 0.5
			A&F	38 or 0.5
9-10			Wi	0.8 or 0.1
10-11			R&Wi	0.5 or 0.1
12-13	F&W	38	F&W	38 or 19
			A&F&W	38 or 19
			W&Wi	0.8 or 0.1
13-14			R&W&Wi	0.8 or 0.1
14-15			F&W	38 or 0.5
			A&F&W	38 or 0.5
25-26			F&W @38 + R&W&Wi	0.8 or 0.1
26-27			A&F&W + R&W&Wi	38 or 0.5 + 0.8 or 0.1

[a]Test structure consumes 90.2 MBtu/year with R-values of 38/19/19 and absorptance/transmittance of 0.8/0.5/0.5.

[b]Attic R-value also reduced to 19.

Table 7. Energy Conservation Potential for Test Structure in Phoenix, Arizona[a]

MBtu/year	Passive System	Passive Level	Active System	Active Level
1-2	W	0.1	R	0.5 or 0.1
			R	0.8 or 0.1
			R&W	0.8 or 0.5
			Wi	0.8 or 0.5
2-3	F&W	38[b]	W	38 or 19
	W	38	A&W	38 or 19
	F	38	F	38 or 19
	R&W	0.5&0.1	A&F	38 or 19
	R&W	0.1&0.1	W	38 or 0.5
			R&Wi	0.8 or 0.5
			W&Wi	0.8 or 0.5
			W	0.5 or 0.1
			R&W&Wi	0.8 or 0.5
3-4			F	38 or 0.5
			A&F	38 or 0.5
			A&W	38 or 0.5
			W	0.8 or 0.1
4-5	W&Wi	0.8&0.1	R&W	0.5 or 0.1
	R&W&Wi	0.5&0.8&0.1	R&W	0.8 or 0.1
5-6	F&W	38	F&W	38 or 19
	R&W&Wi	0.1&0.8&0.1	A&F&W	38 or 19
	Wi	0.1	F&W	38 or 0.5
	R&Wi	0.5&0.1		
6-7	R&W&Wi	0.1&0.5&0.1	A&F&W	38 or 0.5
7-8	W&Wi	0.1&0.1		
	R&W&Wi	0.5&0.1&0.1		
	R&W&Wi	0.1&0.1&0.1		
9-10			Wi	0.5 or 0.1
10-11			R&Wi	0.5 or 0.1
11-12			Wi	0.8 or 0.1
12-13			W&Wi	0.5 or 0.1
			R&Wi	0.8 or 0.1
13-14	F&W + R&W&Wi	38 + 0.1	R&W&Wi	0.5 or 0.1
14-15			W&Wi	0.8 or 0.1
15-16			R&W&Wi	0.8 or 0.1
20-21			F&W @38 + R&W&Wi	0.8 or 0.1
			A&F&W + R&W&Wi	38 or 0.5 + 0.8 or 0.1

[a]Test structure consumes 56.6 MBtu/year with R-values of 38/19/19 and absorptance/transmittance of 0.8/0.5/0.5.

[b]Attic R-value also reduced to 19.

LIST OF FIGURES

Figure 1 Flow chart of load simulation process for buildings with passive and active insulation systems.

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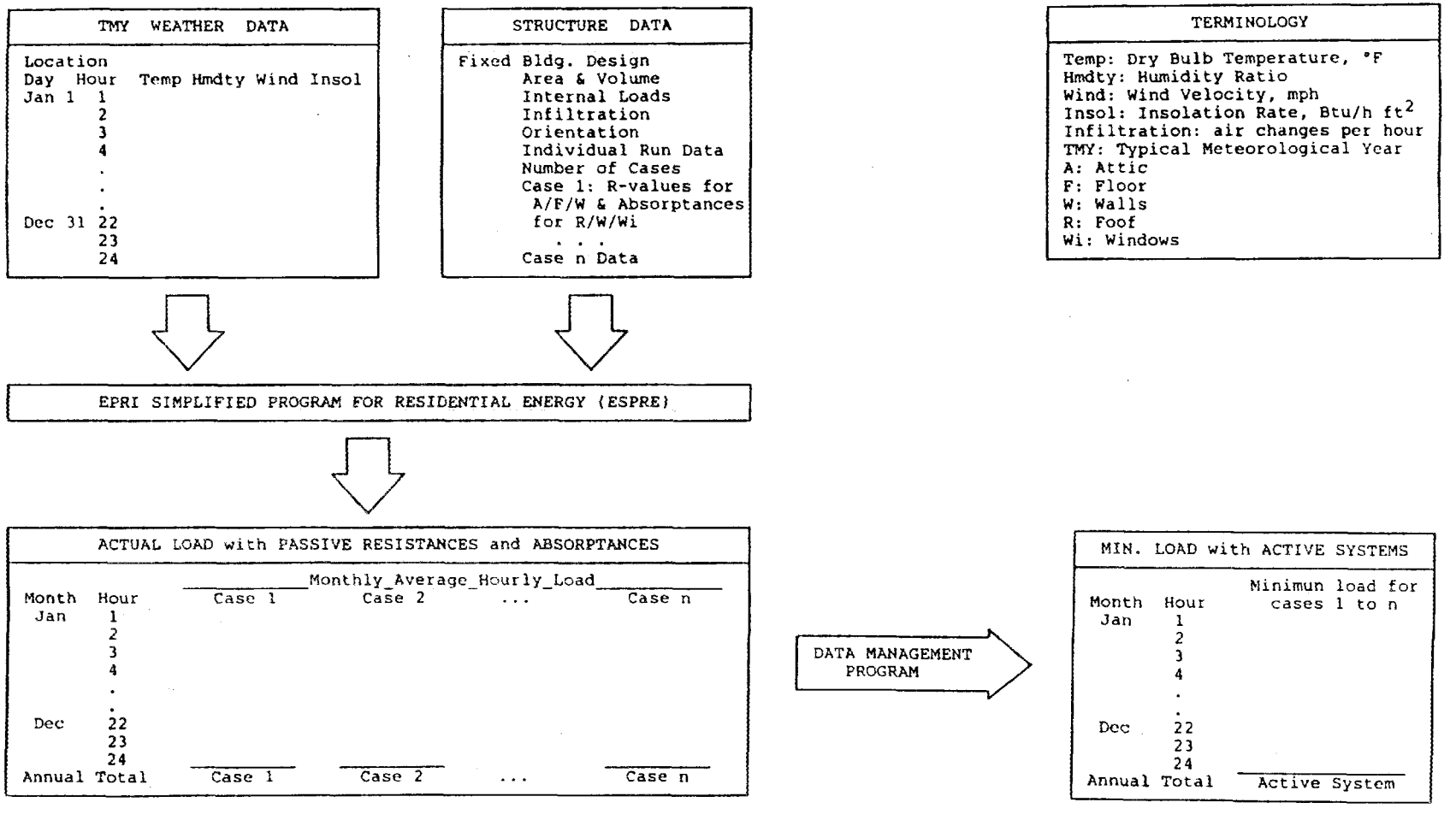

VAR-R #4/ESFIG1.D4

Fig. 1

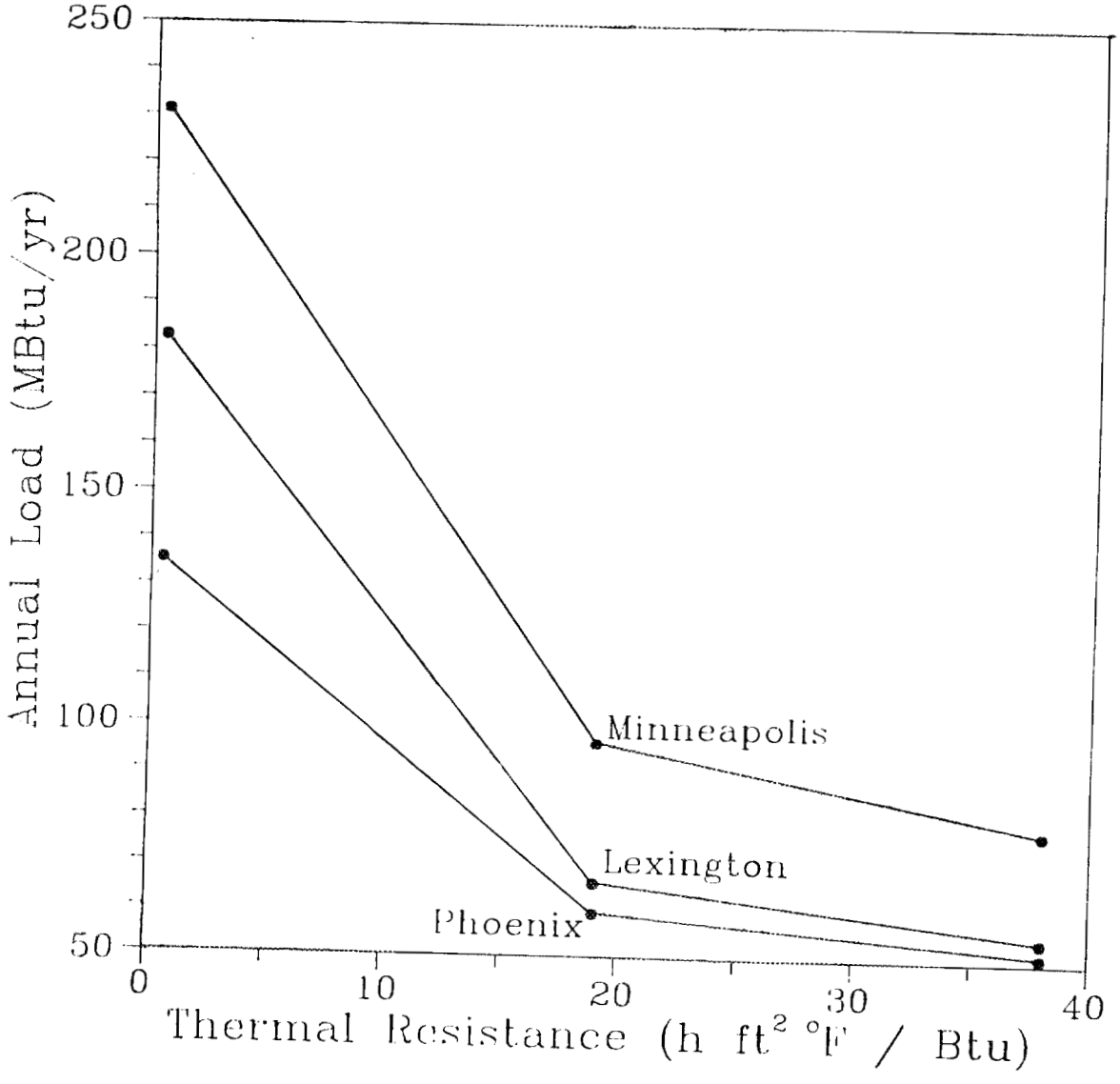
250
200
150
100
50
Annual Load (MBtu/yr)
Minneapolis
Lexington
Phoenix
0
10
20
30
40
Thermal Resistance (h ft² °F / Btu)

Fig. 2

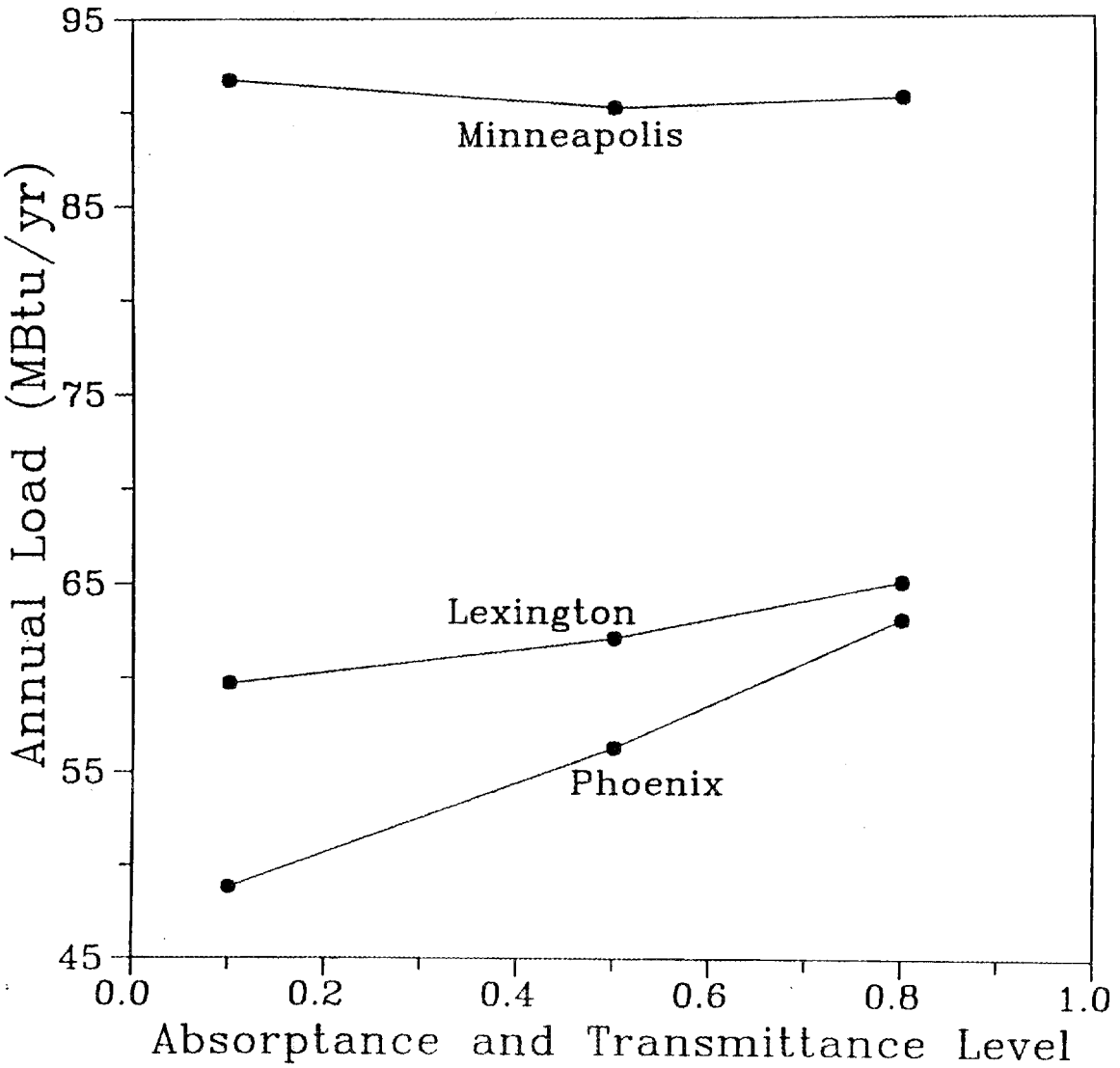
95
85
75
65
55
45
Annual Load (MBtu/yr)
Minneapolis
Lexington
Phoenix
0.0
0.2
0.4
0.6
0.8
1.0
Absorptance and Transmittance Level

Fig. 3

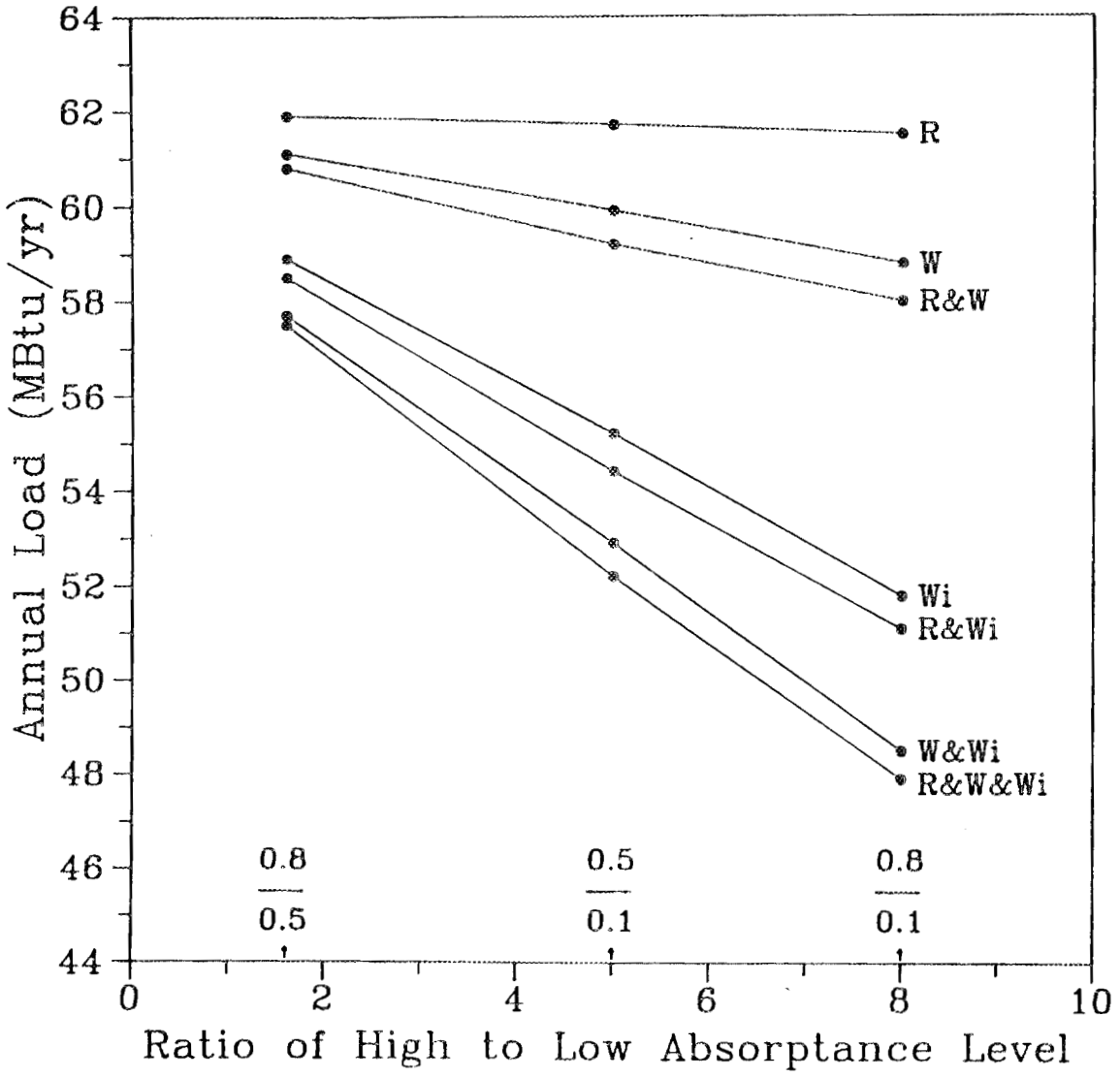
64
62
60
58
56
54
52
50
48
46
44
Annual Load (MBtu/yr)
R
W
R&W
Wi
R&Wi
W&Wi
R&W&Wi
0.8
0.5
0.5
0.1
0.8
0.1
0
2
4
6
8
10
Ratio of High to Low Absorptance Level

Fig. 4

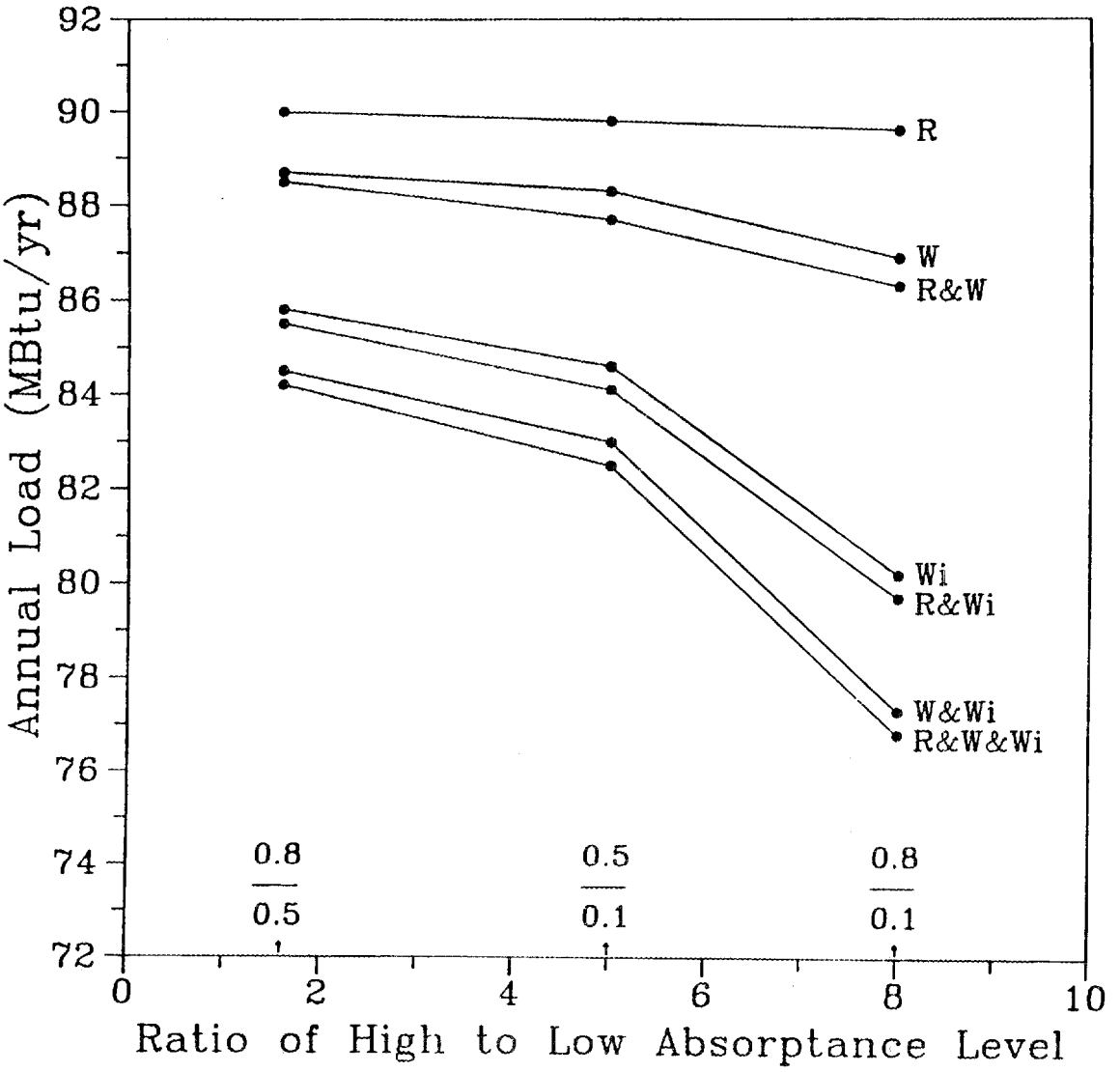
92
90
88
86
84
82
80
78
76
74
72
Annual Load (MBtu/yr)
R
W
R&W
Wi
R&Wi
W&Wi
R&W&Wi
0.8
0.5
0.5
0.1
0.8
0.1
0
2
4
6
8
10
Ratio of High to Low Absorptance Level

Fig. 5

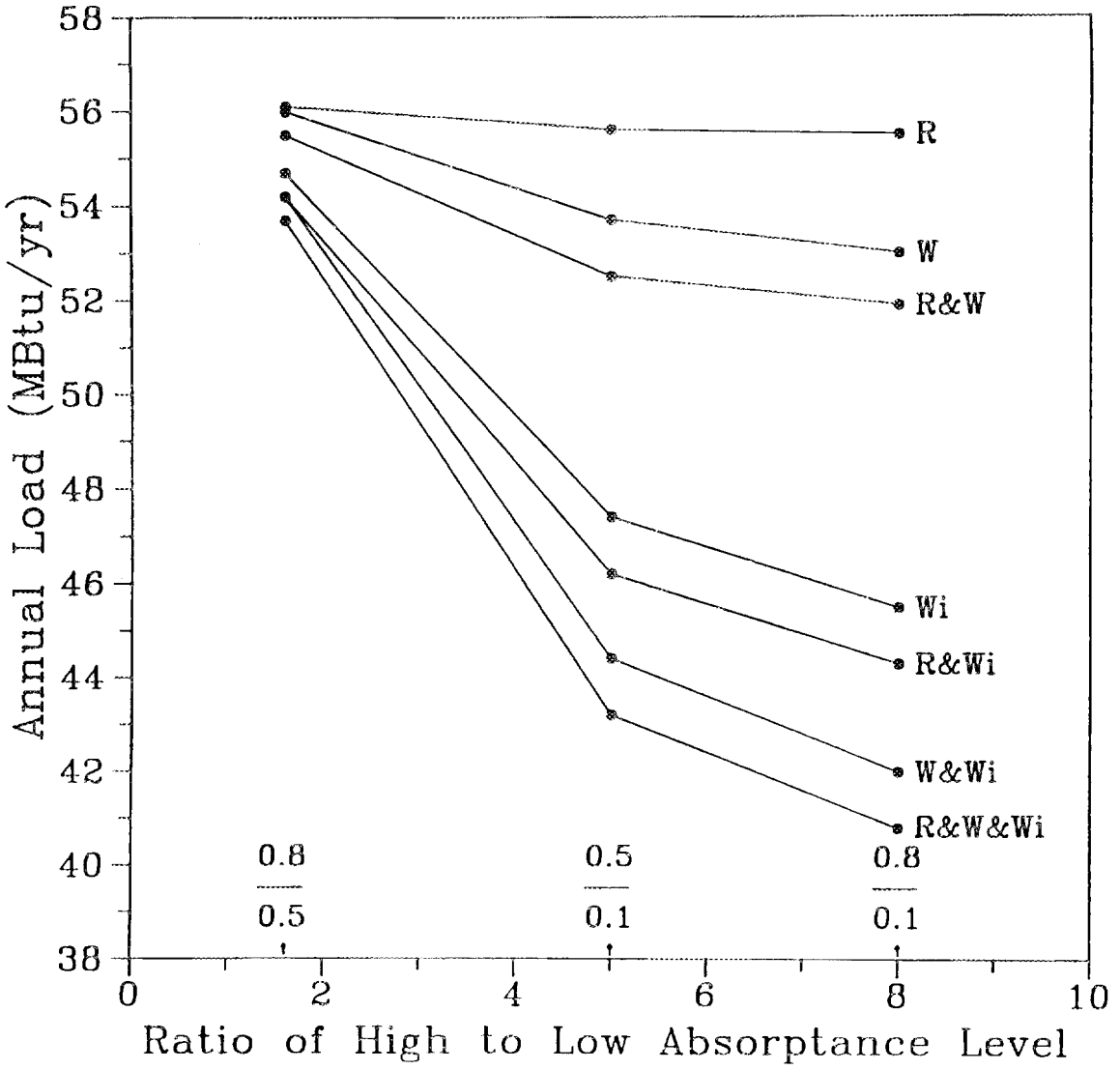
58
56
54
52
50
48
46
44
42
40
38
Annual Load (MBtu/yr)
R
W
R&W
Wi
R&Wi
W&Wi
R&W&Wi
0.8
0.5
0.5
0.1
0.8
0.1
0
2
4
6
8
10
Ratio of High to Low Absorptance Level

Fig. 6

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