ENERGY SYSTEMS FOR MULTIFAMILY HOUSING: AN URBAN CASE STUDY

By

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ABSTRACT

Investigations into the energy needs of multi-family housing lead to the conclusion that internal gains play a significant thermal human comfort role in the cooling as well as heating seasons.

In particular, existing row-house type construction demonstrates a strong tendency to overheat in the summertime. This situation is created when an existing building undergoes "rehabilitation" where insulation is added to the weather walls and tight fitting windows are installed. In the winter internal gains generated within the apartment act as a sizeable, beneficial heat source-lessening the demand for heat from the building heating system. However, in the same space in the summertime these heat gains become excessive, uncomfortable and are often difficult to get rid of. Of particular importance are the appliance intensive areas such as the kitchen, laundry and living room.

To determine the extent of this problem, an existing building in Boston's South End was instrumented and monitored during the summer of 1978. This provided a record of temepratures, electrical usage and solar insolation, establishing a basis for extensive thermal simulations to model the potential impact of various energy conservation schemes.

The schemes include considerations of: optimum thermal mass, optimum wall insulation, glazing properties and characteristics, dynamic internal gains, compatible active and passive solar systems that provide year-round thermal benefit. Close consideration is given to a modified Trombe wall scheme where new, thermally enhanced glazing makes this scheme more efficient and feasible than it has traditionally been.

Finally, issues involved in realizing these schemes are explored and evaluated concerning cost-benefit, compatibility with existing buildings as a 'retrofit' system and visual impact.

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INTRODUCTION

This thesis incorporates a case-study with simple simulations of the thermal behavior and characteristics of existing and rehabilitated multi-fmaily urban row-house. The purpose is to determine what are the most effective measures that can be taken to conserve energy costs due to space heating and cooling and ultimately how these measures interact with regional schemes of energy conservation. The row house is characterized by a heavy masonry or brick weather wall and usually 4 to 5 families inhabit them. Being brick is a major factor in considering this type of building as a valuable prospect for rehabilitation. The massiveness of the existing monolithic brick is a significant factor in it's potential thermal value as well as an important factor for historical and architectural preservation reasons. It's value for rehabilitation is further enhanced when compared to the high cost of constructing the same buildings with today's construction prices.

The building type was chosen due to it's being typical of a massive number of similar buildings in major urban centers and the often voiced need for effective thermal design for this type of existing housing. Studying "what can be done?" in a rehabilitation context is to study one of housings most difficult physical situations where there are many constraints and building restrictions acting togehter, limiting what can be done.

Major cities of the northeast such as New York, Boston, Philadelphia and Baltimore are all having to cope with the problems of increasing average and peak electrical demand. Critical are the summer months during extreme hot weather when the demand for cooling is very high. This situation is compounded with technical questions and social opposition concerning environmental impact and health hazards of proposed power plants. Concurrently in these same urban regions the housing sector is experiencing a revitalization and up-grading of existing housing stock. This growth in demand adds additional impact to the need for careful consideration of urban housing energy strategies. Lastly, the 1976 H.U.D. Annual Housing survey[1] shows that "insufficient heat" was reported by 5% of all <u>owner</u> owned housing units in the northeast while 17% was reported in the <u>rental</u> sector. Assuming most high-rise and row house units are rental-type this is an indication of where many current hosuing energy problems lie.

3

THE NATURE OF THE PROBLEM

First, to put the row house in perspective with an analysis of the energy needs of various types of housing, several geometric characteristics must be briefly discussed to distinguish among basic types. Broadly speaking housing can be arranged into four categories: these describe the physical configuration of the dwelling in terms of its overall dimensions and surface areas exposed directly to outdoor weather conditions - known as "weather walls." Figure 1 describes them.

1

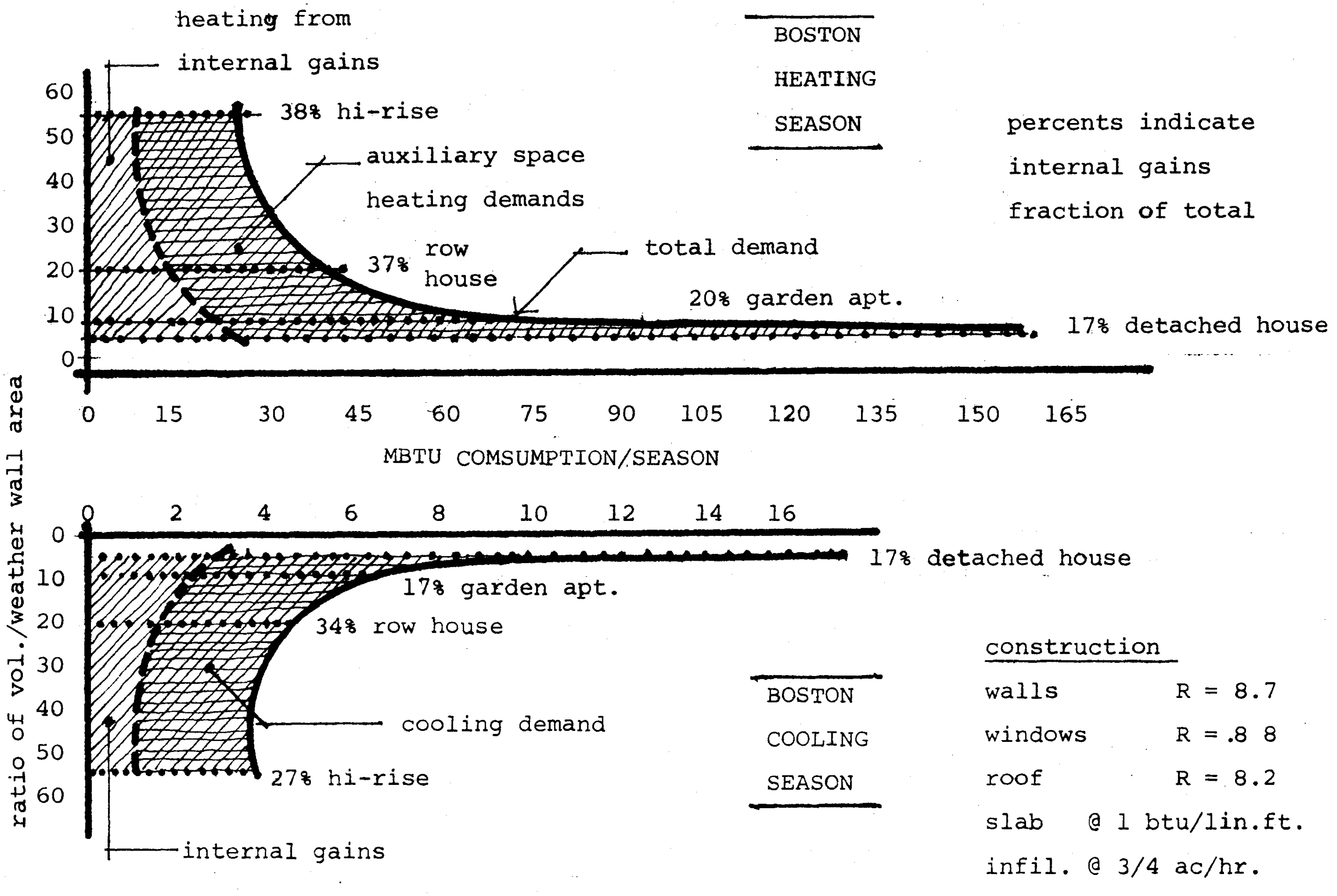
Category	Typical Example	No. of Weather Walls
Detached House	Surburban development home	4
Townhouse	Garden Apartment w/common wall construction	3
Row House	Floor through apartment	2
Hi/low Rise Apt.	Isolated aprt. in public or private housing building	1

In order to compare these types thermally, typical dimensions and assumptions can be made about them (Figure 2).

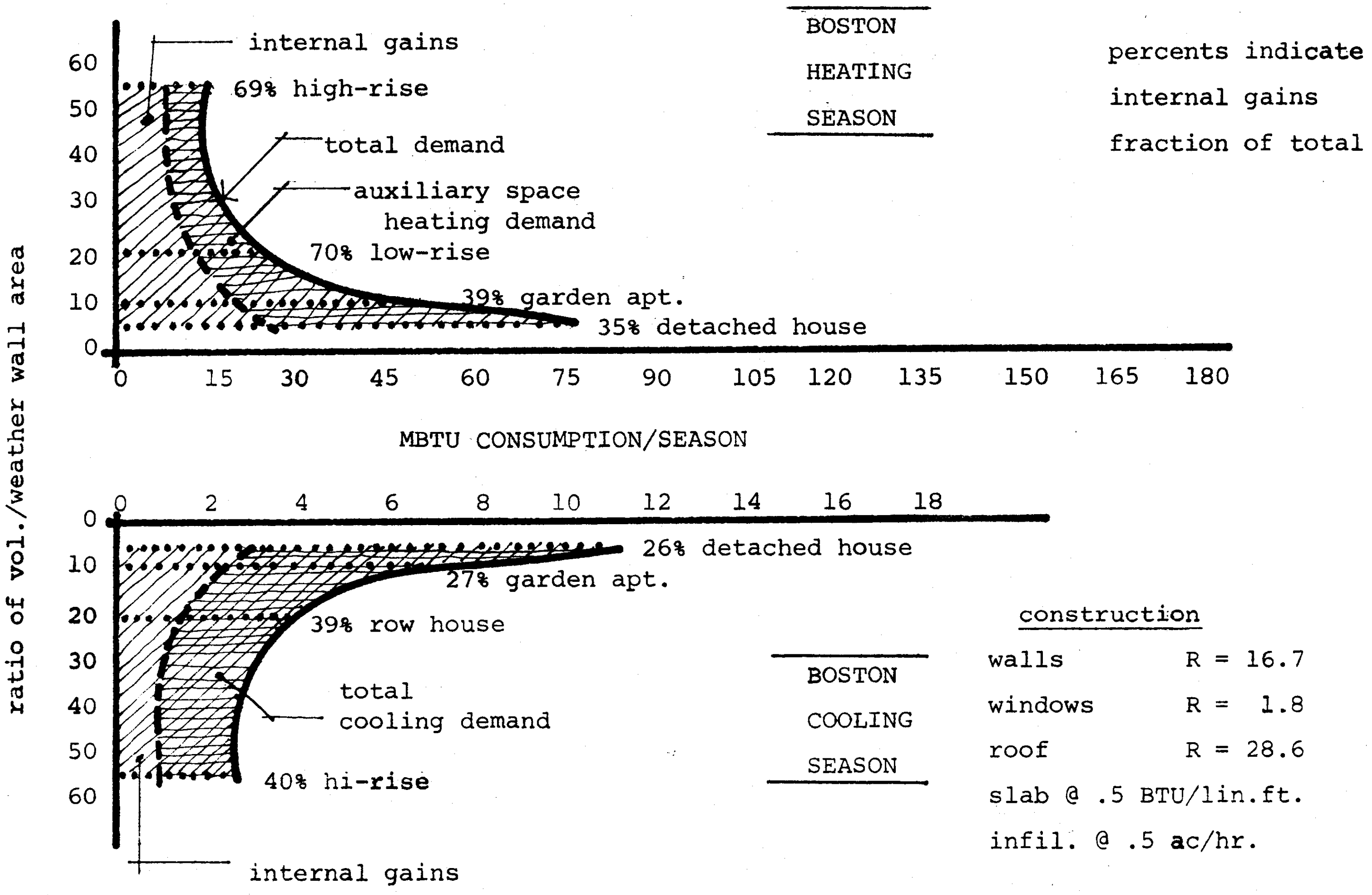
2

No. of weather walls	Slab on grade	Area (SF)	Floor to floor ht, (F)	Net Volume (CF)	Ratio of vol. to w/w surface area	(Comments)
1 high rise apt.	No	(40' x 20') 800 (SF)	10'	6400 (CF)	6400/200 = 32	Major axis of apt. lies N-S, not top floor apt.
2 Row hse.	No	(40' x 20') 800 (SF)	10'	6400 (CF)	6400/400 = 16	Major axis of apt. lies N-S, not top floor apt.
3 Garden apt.	Yes	(40' x 20') 1600 (SF)	10'	12,800 (CF)	12800/800 walls 800 roof 1600 = 8	Major axis of hse. lies N-S, 8'-0" ceiling hgts.
4 Detached hse.	Yes	(40' x 20')	10'	12,800 (CF)	12800/2000 walls + 800 roof 280 = 4.5	South facing, 8'-0" ceiling hgts.

The critical concern in analyzing the thermal dynamics of these buildings is how much livable space is enclosed and how much space is used as weather wall. This is shown as the ratio in the last column of Figure 2. The lowest ratio is the detached house; the highest is the individual high-rise apartment. A second



3 SEASONAL IMPACT OF INTERNAL GAINS ON SPACE CONDITIONING (WITH AVERAGE INSULATION)



percents indicate internal gains fraction of total

construction

walls R = 16.7
windows R = 1.8
roof R = 28.6
slab @ .5 BTU/lin.ft.
infil. @ .5 ac/hr.

4 SEASONAL IMPACT OF INTERNAL GAINS ON SPACE CONDITIONING (WITH IMPROVED INSULATION)

concern is infiltration which is a direct function of the weather wall area and it's openings. To establish the thermal value of these housing types, they can be tested for the total energy they need to remain comfortable for the heating and cooling seasons. The heating season is assumed to run from October through April while the cooling is from May through September. Boston climatological data is used for temperature and humidity profiles. The result is shown in Figures 3 and 4.

Figure 3 shows the four weather wall types - with the heating season shown on the upper portion; cooling on the lower. The graph shows the volume/ weather ratio vs. the MBTU (millions of British Thermal Units) energy demand. Internal gains are shown as a component of the total space conditioning energy needs. In the heating season the internal gains play an increasingly beneficial role for heating as the vol/w.w. ratio increases. Internal gains (by the second Law of Thermodynamics) eventually are expended as heat and are therefore a source of heat and are counted as a component of the heating needs. The cooling graph represents the total amount of electrical energy required to remove unwanted heat. These calculations are based on the Manual J Method of the National Warm Air Heating and Air Conditioning Association. As in the heating mode the internal gains increase with the larger volume surface ratio. The difference, however, is that in the summertime the internal gains are detrimental to keeping cool and this factor increases as the high-rise configuration is approached. Figure 4 is similar to 3 with the exception that insulation values of all the housing types has been increased and the air change rate slightly lowered. The differences are (see Figure 5).

5

(For Figure 3)

Insulation Values	R
Walls	8.7
Windows	.88
Roof	8.2
Slab @ 1 BTU/Lin. ft.	
Infiltration @ 3/4 A.C./hr.	

(For Figure 4)

Insulation Values	R
Walls	16.7
Windows	1.8
Roof	28.6
Slab @ .5 BTU/Lin. ft.	
Infiltration @ 1/2 A.C./hr.	

A comparison by season between the two types of construction indicates:

1. The total MBTUs required for each season by the improved building is lessened dramatically.
2. Since internal gains are constant, the lowering of total energy required raises the internal gians fraction of the whole.
3. The internal gains fraction increases as the vol/surface area increases.
4. In the heating season the impact of internal gains for the typical high rise is double that of the detached house; in the cooling season the impact is 50% greater.
5. For both seasons the row-house and high rise behave similarly and the garden apartment and detached house are similar.

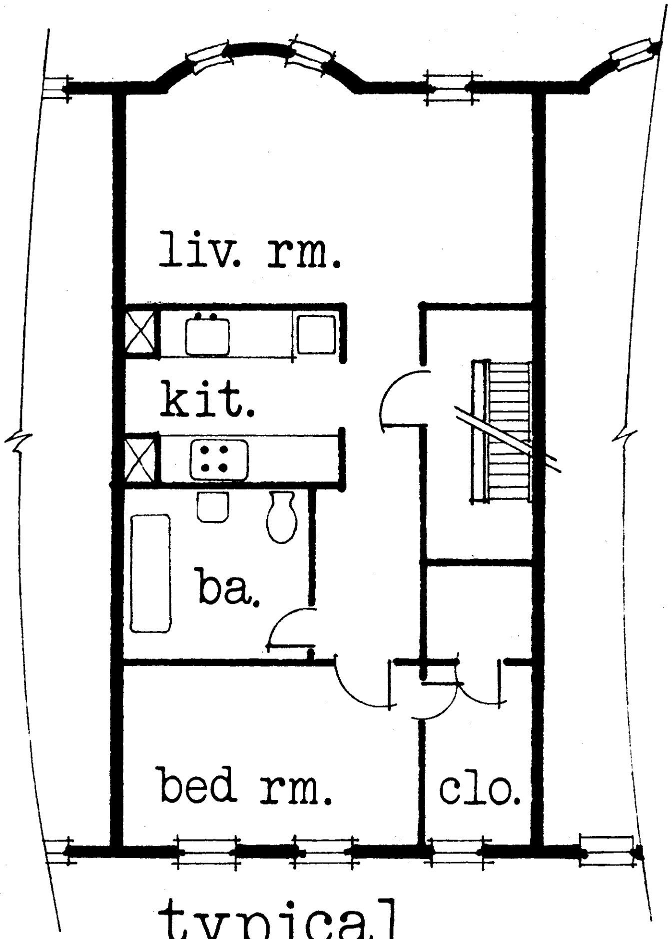
With these results in mind the significance of dealing with internal gains becomes obvious. Particularly critical are the conditions in the high-rise apartment and row house where overheating is a very likely occurence. Therefore, this is one of the main underlying phenomena to investigate.

a Monitoring

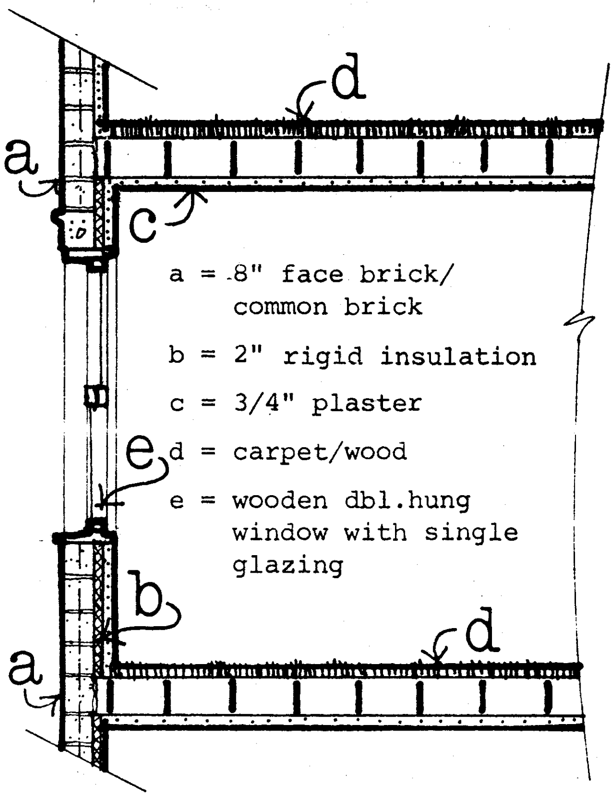
In order to establish a temperature profile for analyzing the performance of row house buildings, an existing building at 132 Chandler Street was selected (located off Columbus Avenue in the South End). The building was chosen because it met these criteria:

1. Must be an existing multifamily row house of a type of construction prevalent in major cities of the northeast.
2. The building must be in good condition - the kind considered valuable for "rehabilitation."
3. If in a historical district, it's back wall must be south-facing.
4. The south facing wall must be within 30° east or west of south and unshaded.
5. The building must have insulated weather walls and tight fitting windows of a type currently found in conventional rehab construction.

The Boston Redevelopment Authority had "rehabbed" this building in 1971, when the apartment building was taken over by a private management firm. The five floor apartment building was rented out to five individual tenants each with a floor through (full single floor) apartment. Figure 6 shows a typical apartment floor plan and vertical wall section through the south facing wall.



typical
plan



a = 8" face brick/
common brick

b = 2" rigid insulation

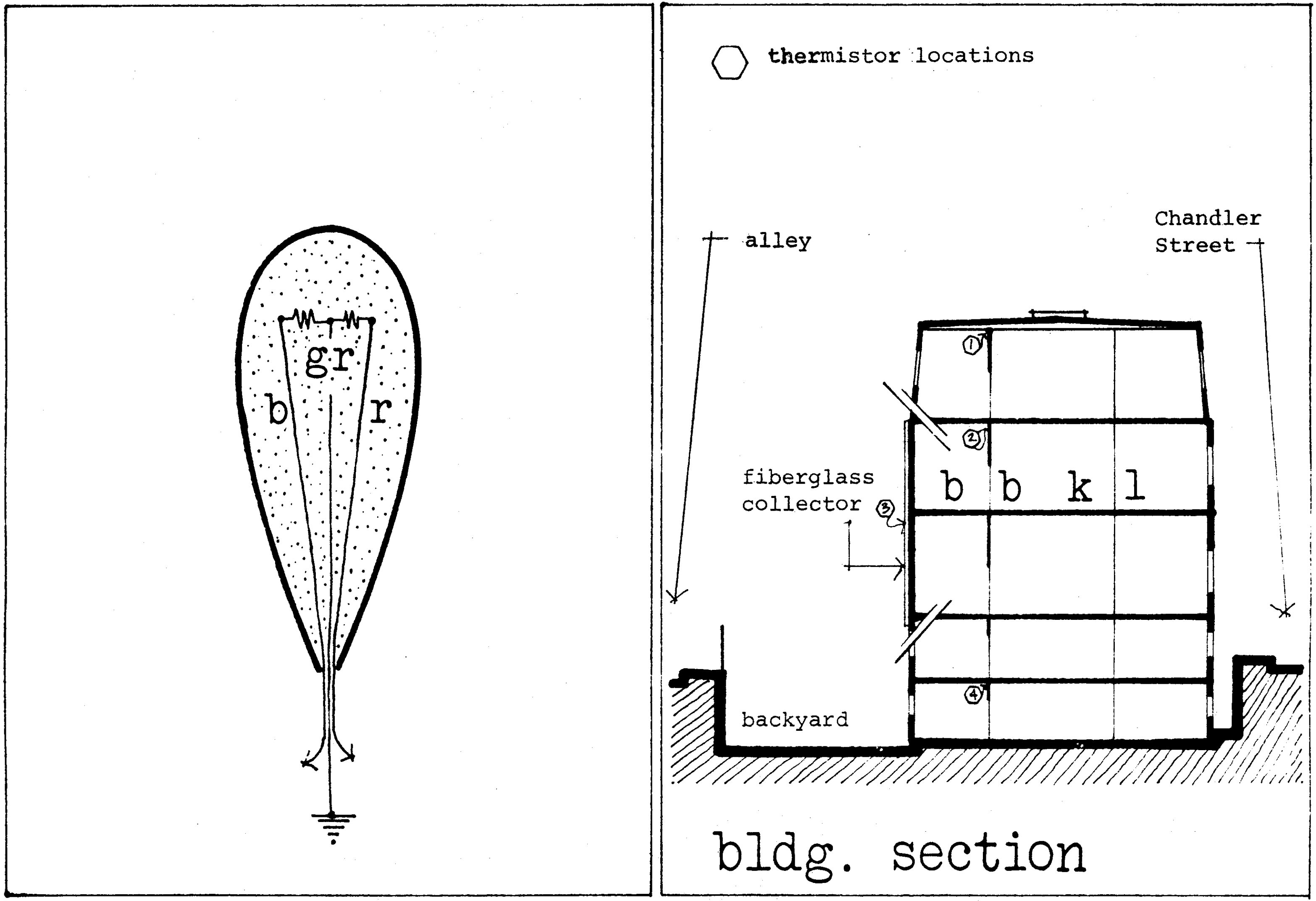
c = 3/4" plaster

d = carpet/wood

e = wooden dbl.hung
window with single
glazing

typical
wall section

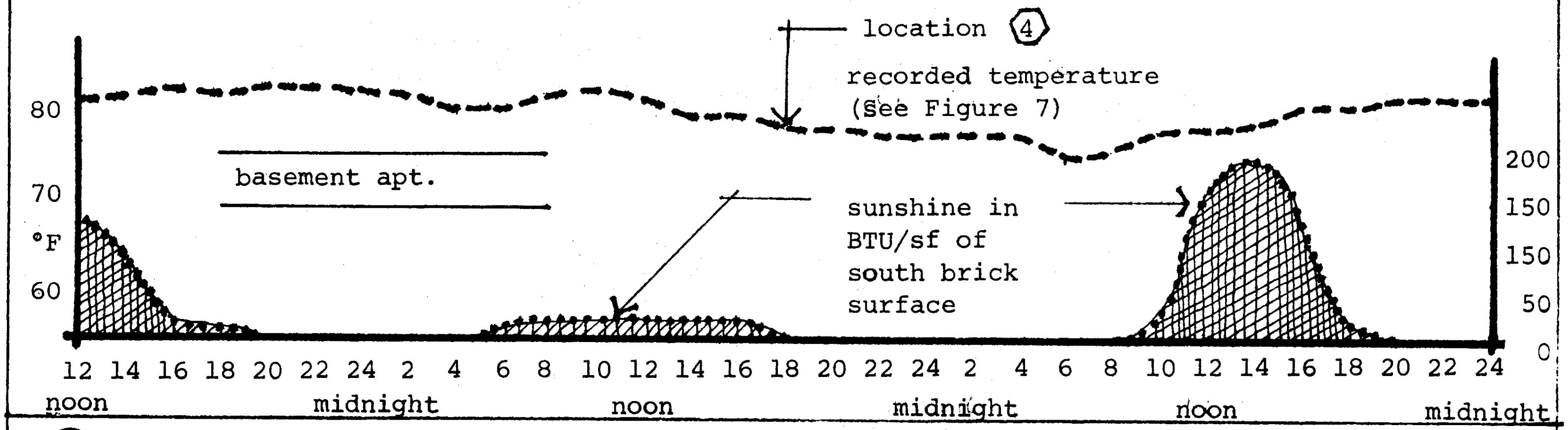
6 ROW HOUSE AT 132 CHANDLER STREET, SOUTH END, BOSTON



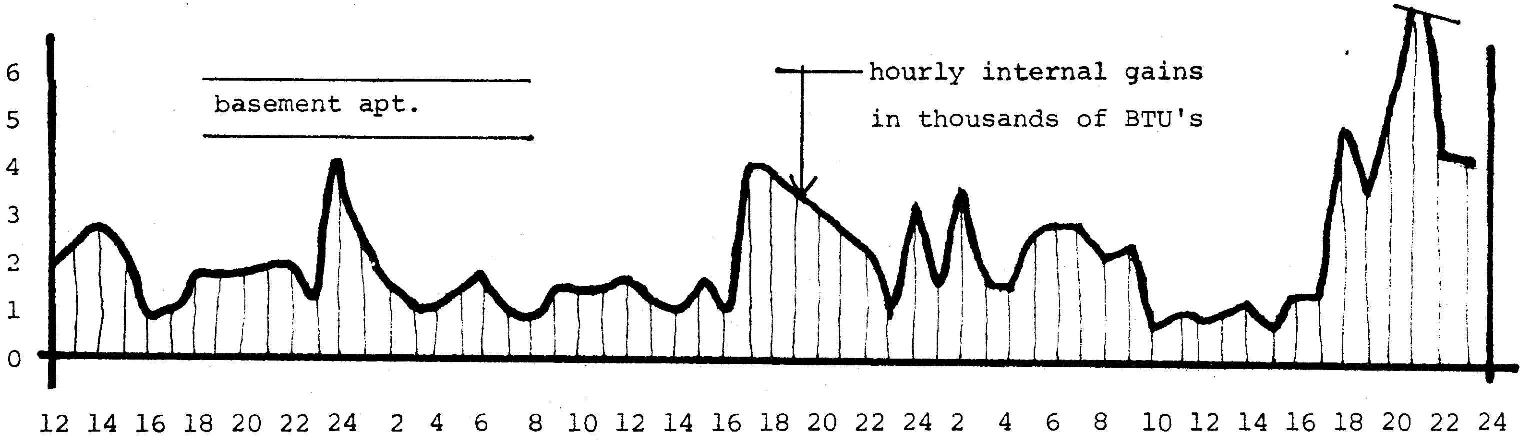
7 132 CHANDLER STREET - THERMISTOR BLOW-UP AND LOCATIONS IN MONITORED BUILDING

Instrumentation Set Up

This building was instrumented with thermistors (linear temperature sensors) which were sampled hourly by an analog multiplexer. Thermistors are the size of a hatpin and consist of a 'head' containing a sealed set of resistors (Figure 7). The system senses temperatures by placing a reference voltage across the thermistor. Since the resistance varies linearly with temperature, the current will vary linearly with temperature. Thus current is then recorded as an audio binary code on conventional tape recorder cassetts. The cassettes are then processed and a printout of binary counts is made. These hourly counts are then converted into their corresponding temperatures and this makes up the temperature graph for the particular room being monitored. Thermistors were generally located at the intersections of ceilings and walls, (primarily because this was the most unobstrusive spot to locate them and usually required the shortest wire runs.). Electrical and solar insolation data were also recorded. The electrical record was made by a recording ammeter which makes continuous readings of the amperage of selected power box wires. This record of amps usage is simply multiplied by the known voltage, to arrive at the total kwhr (x 3,410/kwhr = BTUs/hr) expended in the apartment space. Sunshine was sensed by a pyranometer. The pyranometer produces a varying voltage as the incident energy of the sun fluctuates. These fluctuations were graphed and the pyranometer was calibrated to establish BTU readings on the graphs. This data helps to determine how the direct gains through the windows combine with internal gains from appliances plus people , gains resulting in the temperautre levels recorded.



8 132 CHANDLER STREET - INDOOR AIR TEMPERATURE AND SUNSHINE RECORD



9 132 CHANDLER STREET - INTERNAL GAINS RECORD

Typical Data

Figures 8 and 9 show data gathered from a typical warm day. Measurements were taken at 3 different locations in the apartment building. With these temperature profiles recorded over runs of 10-50 hours on different summer days a good idea of how 132 Chandler Street is performing the summertime is established. The temperature graph in Graph 8 was compared with computer simulated temperatures to verify the computer model.

b

Internal Gains

An important issue in understanding the thermal needs of row house apartments is to put into perspective the quantities and nature of the internal gains generated within the apartments. As noted earlier internal gains play a beneficial or detrimental role in terms of human comfort depending on many factors particularly in different seasons.

For the year 1972 the gross national BTU consumption associated with housing was 11.6 quads[2] (Fig. 10) of measured energy (end-use) which represents a per capita consumption of 56 MBTU per year. To compare this with measured electrical consumption at 132 Chandler Street - energy for heating, cooling and hot water heating can be subtracted from this grand total (none of these took place within the monitored apartments in the summer). This yields a figure equal to 1525 $\mathrm{BTU/Hr}^{-2}$/occupant. This compares (within 13%) with a measured figure averaging 1730 BTU's at 132 over the 44 hour period shown in Figure 8. A further breakdown is shown in Fig. 10 where 3 sources provide energy consumption profiles for annual consumption. Despite the differences in geographical areas represented

	All Residential Consumption,U.S.	Lo-Rise Consumption Multifamily -Balt.- Washington Area	Lo-Rise, New England	Standard Profile
Source	%	%	%	%
Space heat	54	57	35	49
Hot water	19	15	18	17
Cooking	6	6	13	8
Dryers	4	2	8	5
Appliances/ lights/ refrig.	12	16	23	17
Air cond.	5	4	3	4
	100%	100%	100%	100%
	a	b	c	d

10 Annual Energy Profile - 3 Sources

by these profiles, the percentages are quite similar and are averaged into a standard profile - shown in the column D of Fig. 10. One assumption made at this point is that all internal gains generated within the apartment, whether the source is electricity, gas, oil kerosene, etc., will eventually be manifested as heat in the apartment space. This discounts the fact that a tiny amount of energy goes into doing work, since this is such a small percentage of the total energy expended.

One interesting way of interpreting the patterns of internal gains is to apply the seasonal consumption figures to a floor typical of the monitored building to indicate where the seasonal heat intensive areas are located. First, this is important to note because their proximity to exterior walls and windows determines how these gains will be perceived. Secondly, the thermal mass surrounding an area of

ANNUAL ENERGY REQUIREMENTS OF ELECTRIC HOUSEHOLD APPLIANCES[5]

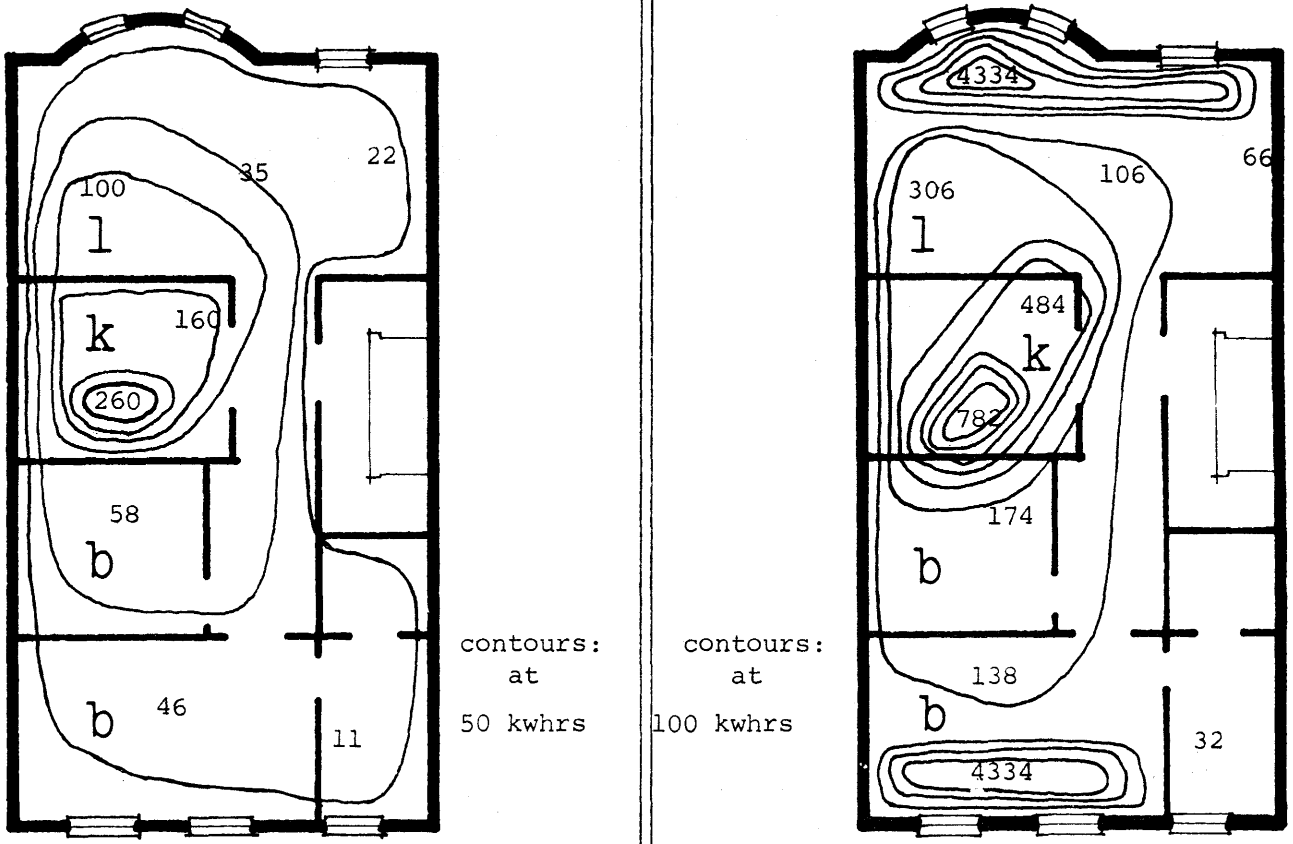
11

	average wattage	est. kwh consumed annually
Health & beauty		
Germicidal lamp	20	141
Hair Dryer	381	14
Heat Lamp (infared)	250	13
Shaver	14	1.8
Sun Lamp	279	16
Tooth brush	7	0.5
Vibrator	40	2
home entertainment		
Radio	71	86
Radio/Record player	109	109
Television		
black & white tube type	160	350
solid state	55	120
color - tube type	300	660
solid state	200	440
housewares		
Clock	2	17
Floor Polisher	305	15
Sewing Machine	75	11
Vacuum Cleaner	630	46
Food preparation		
Blender	386	15
Broiler	1,436	100
Carving Knife	92	8
Coffee Maker	894	106
Deep Fryer	1,448	83
Dishwasher	1,201	363
Egg Cooker	516	14
Frying Pan	1,196	186
Hot plate	1,257	90
Mixer	127	13
Oven, microwave (only)	1,450	190
Range with oven	12,200	1,175
with self-cleaning oven	12,200	1,205
Roaster	1,333	205
Sandwich Grill	1,161	33
Toaster	1,146	39
Trash Compactor	400	50
Waffle Iron	1,116	22
Waste Disposer	445	30

	average wattage	est. kwh consumed annually
food preservation		
Freezer (15 cu ft)	341	1,195
Freezer (Frostless 15 cu ft)	440	1,761
Refrigerator (12 cu ft)	241	728
Refrigerator (Frostless 12 cu ft)	321	1,217
Refrigerator/Freezer (14 cu ft)	326	1,137
(Frostless 14 cu ft)	615	1,829
laundry		
Clothes Dryer	4,856	993
Iron (hand)	1,008	144
Washing Machine (automatic)	512	103
Washing Machine (non-automatic)	286	76
Water Heater	2,475	4,219
(quick-recovery)	4,474	4,811
comfort conditioning		
Air cleaner	50	216
Air conditioner (room)	1,566	1,389
Bed Covering	177	147
Dehumidifier	257	377
Fan (attic)	370	291
Fan (circulating)	88	43
Fan (rollaway)	171	138
Fan (window)	200	170
Heater (portable)	1,322	176
Heating Pad	65	10
Humidifier	177	163

high internal gains can help modulate the resulting temperatures of the immediate area depending on several factors including; the heat capacity of surrounding mass, the orientation of source of heat to mass, heat transfer coefficients at surfaces, and air movement (see Chapter 10 on optimizing thermal mass). First, it is neccessary to list typical residential appliance usage in terms of BTU's consumed on a national basis per residential unit[5] (Figure 11). Applying these figures to our monitored building, appliances consumption can be estimated based on the types of appliances observed in the majority of the five apartments at 132. With these annual totals, a breakdown into heating season and cooling season can be made. This is arrived at by porportioning by season - summer is assumed to be a 4 month period with internal gains equal to 20% of the annual. Winter equals 80%. By superimposing these numbers onto a typical plan we can "map" the contours of electrical usage by season (Fig. 12). These contours show an interesting energy use pattern. The kitchen area tends to be the intensive area in the summer. In the winter, consumption is heavily weighted around the windows where the baseboard heaters are offsetting losses to outdoors while this load dwarfs the kitchen load. (Winter heating figures were derived from measured consumption during the winter of 1978-9).

The last piece of information to describe internal gains is to consider at what time of day these sources of heat are coccuring and what their magnitude is. Figure 13 is a breakdown of internal gains generation into three categories: appliance, lights and occupants. For the purpose of this study it is assumed that

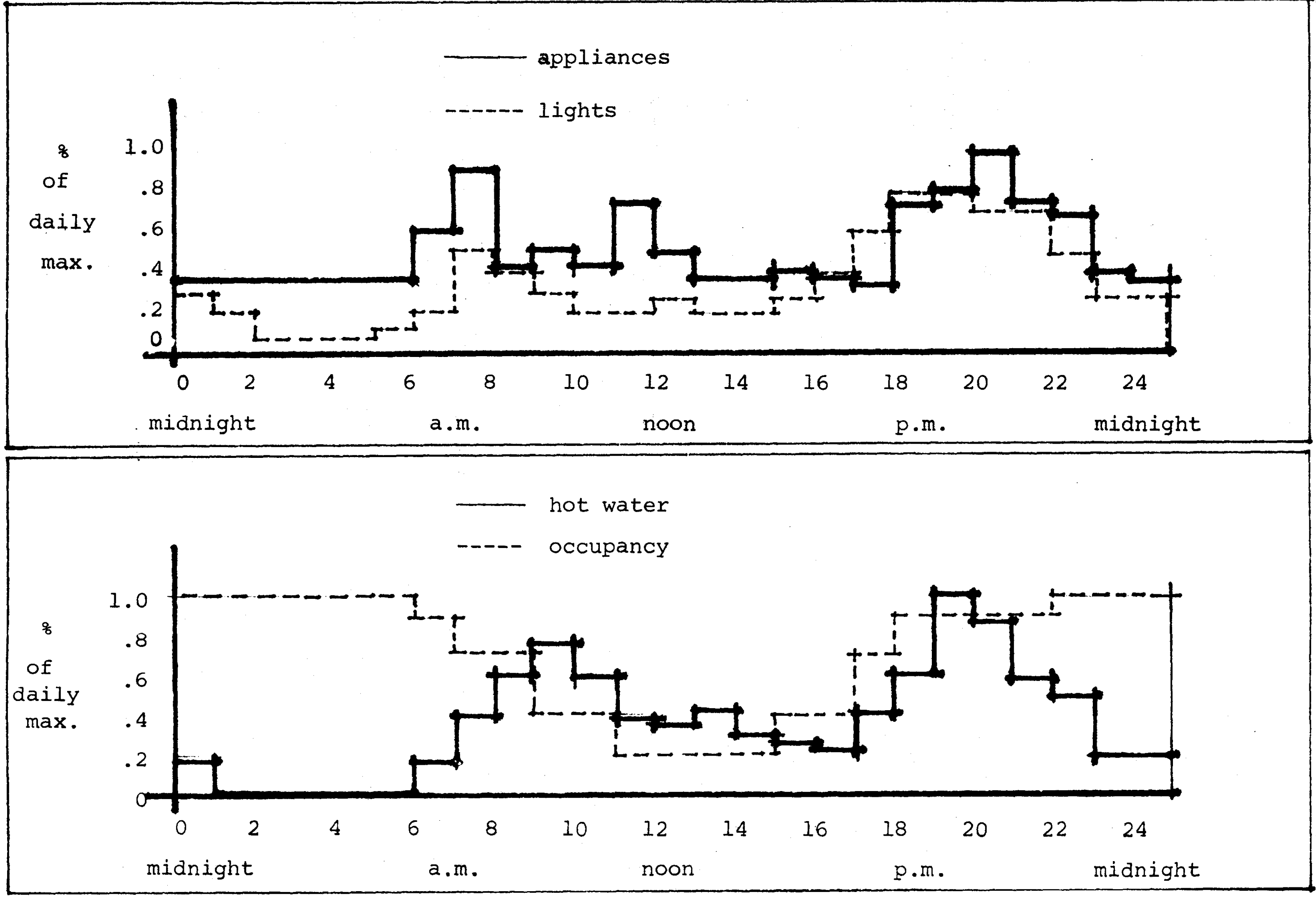

June - September

October - May

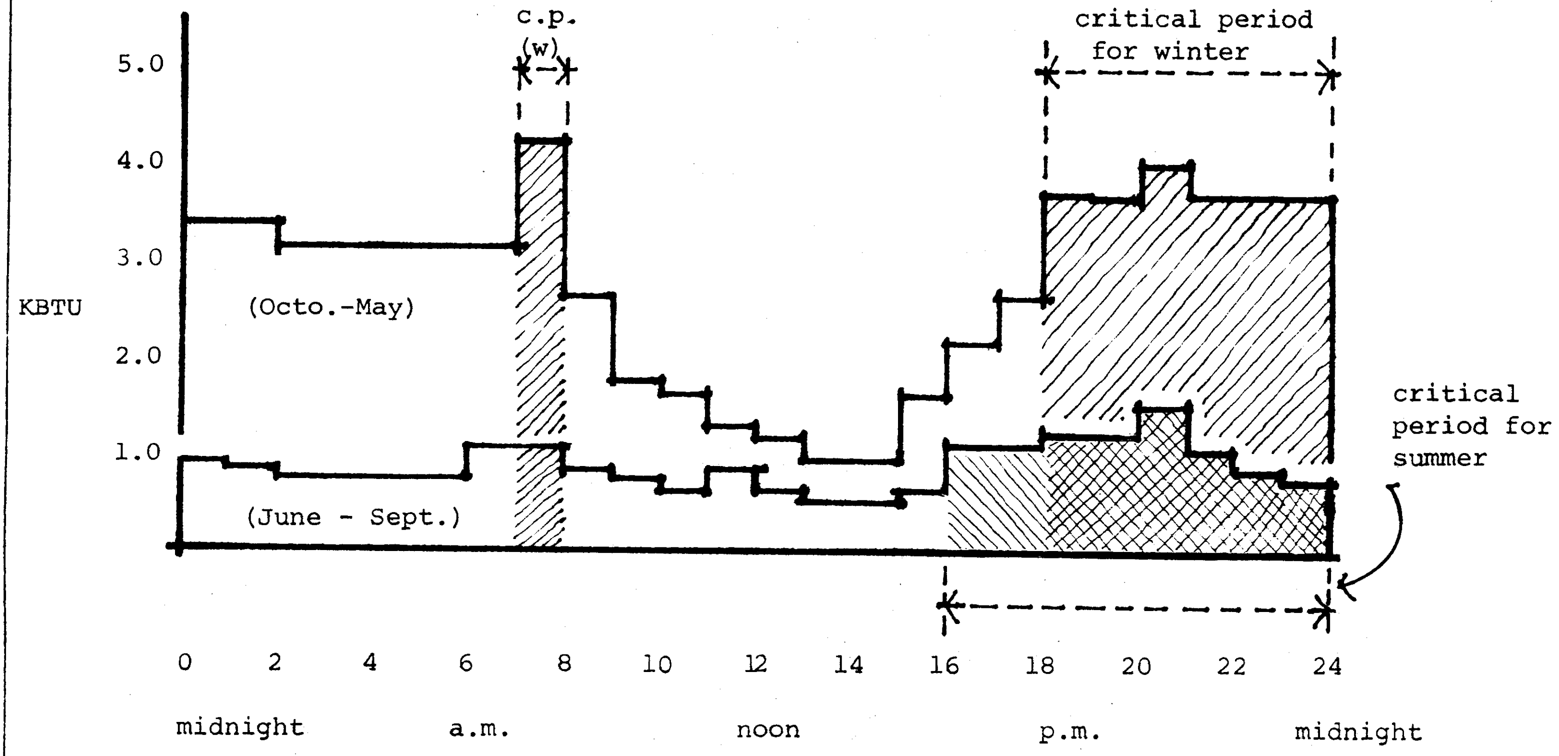
summer

winter

12 132 CHANDLER STREET - SEASONAL ELECTRICAL CONSUMPTION CONTOURS BASED ON USAGE WITHIN FLOOR PLAN



13 RESIDENTIAL DAILY INTERNAL LOAD PROFILES BY TYPE OF SOURCE[3]



14 132 CHANDLER STREET - AVERAGE INTERNAL GAINS OVER A 24 HOUR PERIOD

in the summertime those sources comprise the bulk of internal gains. (Please note that an occupancy of .2/hr is not a new breed of partial people but rather a statistical average!).

Totalling the appliance and lighting profiles of Figure 13 and then porportioning them by seasonal use (adding in an occupancy factor of 400 BTU/occupant/hr for light work) results in (theoretical typical profiles shown in Figure 14. From the two profiles it is deduced that in the winter time the hours of 6 pm-10 pm are richest in internal gains followed closely by the midnight to 7 am period. In the evening period heating accounts for 88% of the total energy use and in the early morning the average percentage is the same. In the summer it is deduced that the intensive hours are again 6 pm-10 pm with the peak at 8 pm (hour 20). This deduced profile is similar to the real measured data from 132 Chandler St. (Fig. 9).

C

Winter

1. Winter time energy intensive areas are at the windows and in the rooms bordering the weather walls. Since the heaters at Chandler Street are electric baseboard types with individual thermostats in the weather wall rooms, we can assume they are turning on to offset heat losses to the out-of-doors. Discomfort here is of the nature of the quick warm up then fast cool-down characteristic of electric convective heaters.

The summertime, while showing smaller total daily gains has a much smaller temperature difference between indoors and outdoors and the impact of these gains is therefore very significant.

d Summer

1. The critical area of overheating to investigate is the interiorized spaces such as the kitchen at the hours of 6-10 pm.

2. Of secondary importance is the area of the living room at the same time.

3. Where window management is used to control unwanted gains, the bedrooms don't appear to be overheating if proper insulation is installed in the walls discouraging any discomforting heat migration from the exterior brick.

User Responses:

With this analysis in mind the summertime is clearly a critical period for human comfort. Realistically the impact of internal gains is constantly changing in nature as is the occupants respond to those gains. Each aprtment has its own unique construction, layout and massing and makes any computer modeling extremely challenging.

The user-response to overheating is to either bring in fresh air quickly by opening windows or flipping the switch to the kitchen fan. These are often unsatisfactory measures. Opening windows cools down the local area, but not the interior areas with any efficiency. Interior walls and partitions inhibit effective cross ventilation. Furthermore, building inspections show that few vent systems work with any efficiency after several years. Roof top wind ventilators tend to get clogged and lose their suction. Vents with electric fans become inoperative due to neglect in maintenance.[6]

To find the appropriate solution to this overheating phenomena a brief look at the historical methods for determining what makes a space comfortable is next made.

4

HUMAN COMFORT

Three sources are discussed here that define fundamental criteria for human comfort with particular reference to summertime space conditioning. They are Victor Olgyay, P.O. Fanger and the A.S.H.R.A.E. Handbook of Fundamentals and Comfort Standards. Comfort is at best a difficult phenomena to establish simply due to the quantity of factors involved and the imprecise nature of comfort zone "boundaries." This is compounded by racial and cultural factors. An example of this is found in the Handbook of Fundamentals section "Physiological Principles" which has separate guidelines for high temperature radiational heating as determined by skin response. The Guidelines weigh the optical and thermal properties and necessarily distiniguish between light and dark skinned people. Broadly speaking, the definition of comfort most widely used is that "....(comfort is).... a sensation that is neither slightly warm nor slightly cool[7]... "This definition results in the many predictive charts offered to H.V.A.C. engineers to determine the climatic requirements for space conditioning.

A more interesting and esoteric definition is offered by the ASHRAE Comfort

Standard 55-74 when thermal comfort is called "...that state of mind which expresses satisfaction with the thermal environment...." this definition allows the element of changing human experience to enter into the comfort equation. This is important because more than a pre-ordained dry-bulb temperature and corresponding R.H. % are needed for comfort. Certainly a tangible vitality is experienced during transition through certain types of thermal environments. For instance, moving from a hot dry piazza in Rome to a cooler arcade is very pleasant by contrast though both environments if measured would be well beyond the "boundaries" of human comfort. The human organism thrives on constant change and finds necessary stimulation in an ongoing renewal of sensory impressions. An environment as maintained by conventional office HVAC systems may be technically adequate but lacks in providing a rich and stimulating or "delightful" thermal environment.[f]

a Victor Olgyay

With these 'other' qualities in mind Victor Olgyay narrows in on a definition of a comfort zone in 'Design with Climate',[8] but makes very clear at the outset that the comfort does not have real boundaries but rather, relative ones. His well known "Bioclimatic Chart" (see Appendix A)-also known as the Banana Chart - outlines zones that indicate a translation of the comfort zone envelope for winter and summer seasons. They also allow some latitude of interpretation between a "desirable" comfort zone and a "practical" zone. This particular chart as well as others discussed below refer to a specific set of given conditions - usually they refer to moderate climatic zones, "customary" clothing, at elevations less than 1000 ft. above sea level for activities that qualify as sedentary to light work. It's evident then, that any comfort definitions must be flexible for interpretation and easily modified to suit the specifics of a given problem. Olgyay considers the following elements to be basic elements considered in his banana graph:

1. Air movement
2. Vapor pressure
3. Heat loss through evaporation
4. Latent heat
5. Radiation and M.R.T.
6. Dry bulb temperatures and RH % as the indices of his chart.

Some interesting points about these elements include:

1. Morning air is normally perceived as follows:

Velocity	Sensation
Up to 50 F.P.M.	Not noticed
50 - 100	Pleasant
100 - 200	Causes constant awareness of air movement
200 - 300	Slightly drafty
300+	Unhealthy, requires corrective measures (winter conditions)

2. Vapor Pressure

(the pressure exerted by water vapor in the water vapor-air mixture within a space)

Amount	Sensation
Up to 15 mm Hg	Acceptable
Over 15 mm Hg	Causes a close or "depressed" feeling.

If a situation is encountered where 15 up to 23 mm Hg is present this can be balanced out by adding 88 FPM/mm of air movement. This addition is effective up to 700 FPM.

3. Evaporation and Latent Heat

By adding grains of moisture per pound of dry air to a high dry bulb air temperature the latent heat of vaporization is utilized to restore comfort.

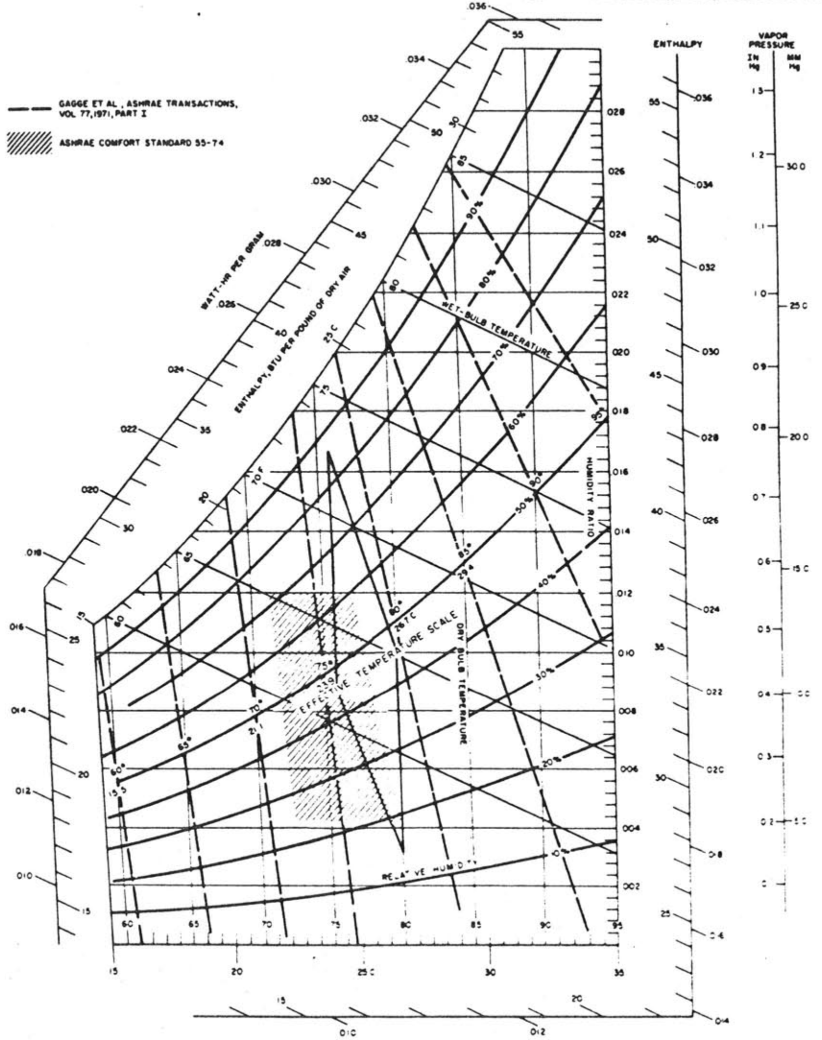
4. Radiation/M.R.T.

A certain amount of comfort compensation can be adhieved by altering the mean radiant temperature of the surrounding surfaces of a room. For example a drop of 1° F of dry bulb in temperature can be counteracted by elevating the M.R.T. by 8° , though the difference between room air and M.R.T. rarely exceeds 5° F. An effective source of direct radiation is through absorption of solar radiation. A 4° drop in dry bulb temperature can be balanced out by 50 BTUs of solar radiation warming the human body.

b A.S.H.R.A.E./P.O. Fanger

ASHRAE suggests that for normal conditions (conditions found in offices - sendentary activity, with normal clothing at low air velocities, when the space's M.R.T. equals the T° dry bulb) its comfort chart "The New Effective Temperature Scale" should (Figure 15) be used to determine the comfort envelope. This describes a narrow zone and other factors (such as when M.R.T. $\neq T_{dB}$) need to be considered.

The envelope applies for lightly clothed, sedentary individuals in spaces with low air movement, where the MRT equals air temperature



15 EFFECTIVE TEMPERATURE SCALE[7]

To meet this need Fanger's General Comfort Charts are recommended.[9] Fanger's work was initiated at Kansas State University where an extensive summertime comfort study was carried out with 1700 students, and continued at the Technical University of Denmark. His main objective was to generalize the "phisiological basis of comfort so that comfort for any activity can be predicted analytically." Fanger's comfort equations are based on a heat balance equation that integrates the conditions of the body in a passive state of thermal equilifrium with empirical parameters during activity periods when comfort is expereinced. These are measured by average temperature of the skin (T_{sk}) and evaporative heat loss by regulatory sweating (E_{tsw}). His two predictive equations for a comfortable t_{sk} and E_{rsw} are:

$$t_{sk} = 35.7 - .0372\ M, \quad °C \text{ and } w/m^2 \qquad (1)$$

where:

t_{sk} = at 4 locations average of skin temp, °C

M = MET metabolic rate of particular activity

(w/m^2 of skin)

seated, quiet = 1 MET ; typing = 1.3 MET

moderate walking = 2 MET

and

$$E_{rsw} = .42\ (M - 58.2)\ , \quad w/m^2 \qquad (2)$$

E_{rsw} = evaporative heat loss at skin surface, w/m^2

m = (as above)

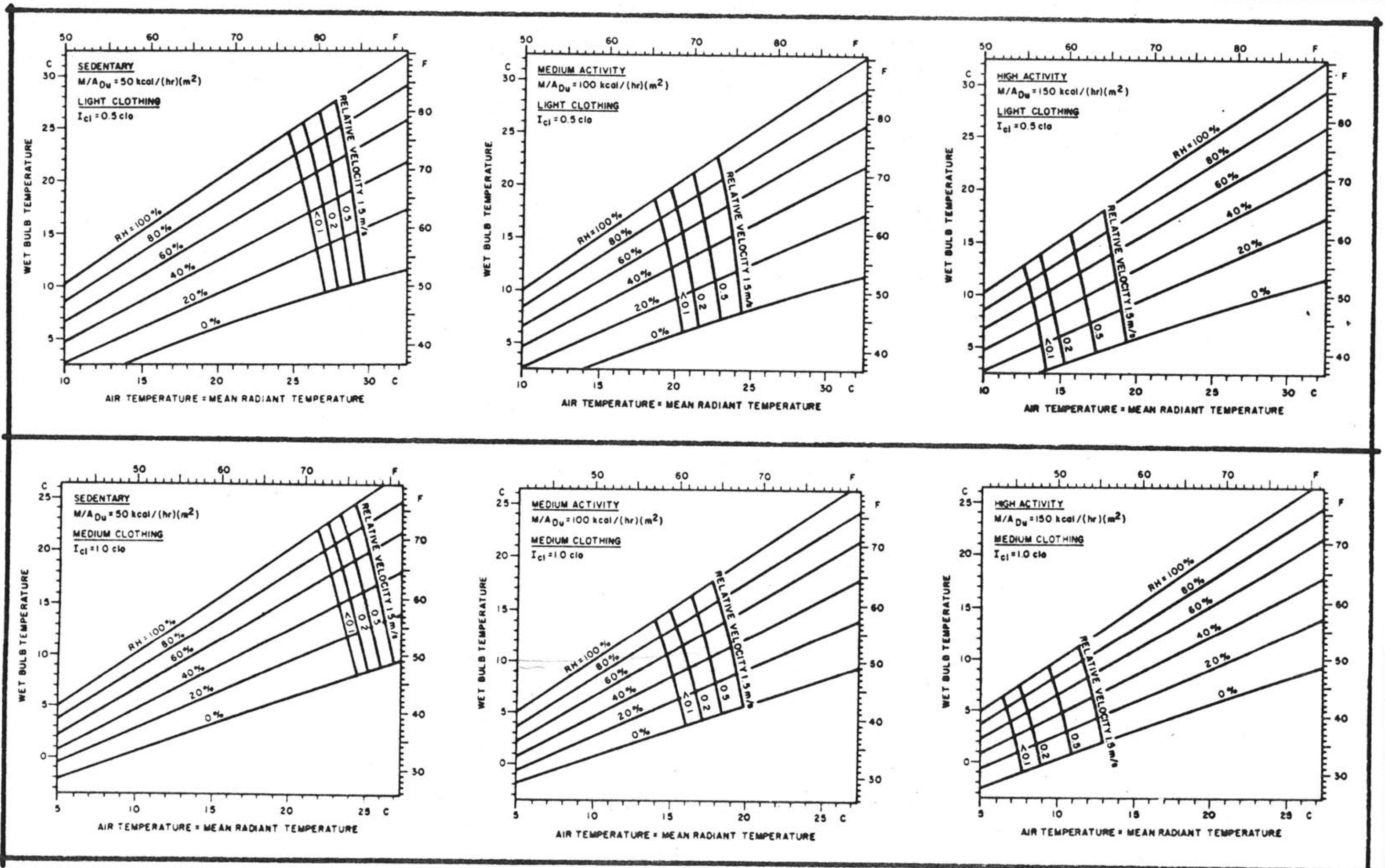
When these two equations are integrated into a long form heat balance equation for sedentary activity the result is that:

$$f(m, clo, v, MRT, t_a \text{ and } P_a) = 0 \quad (3)$$

where:

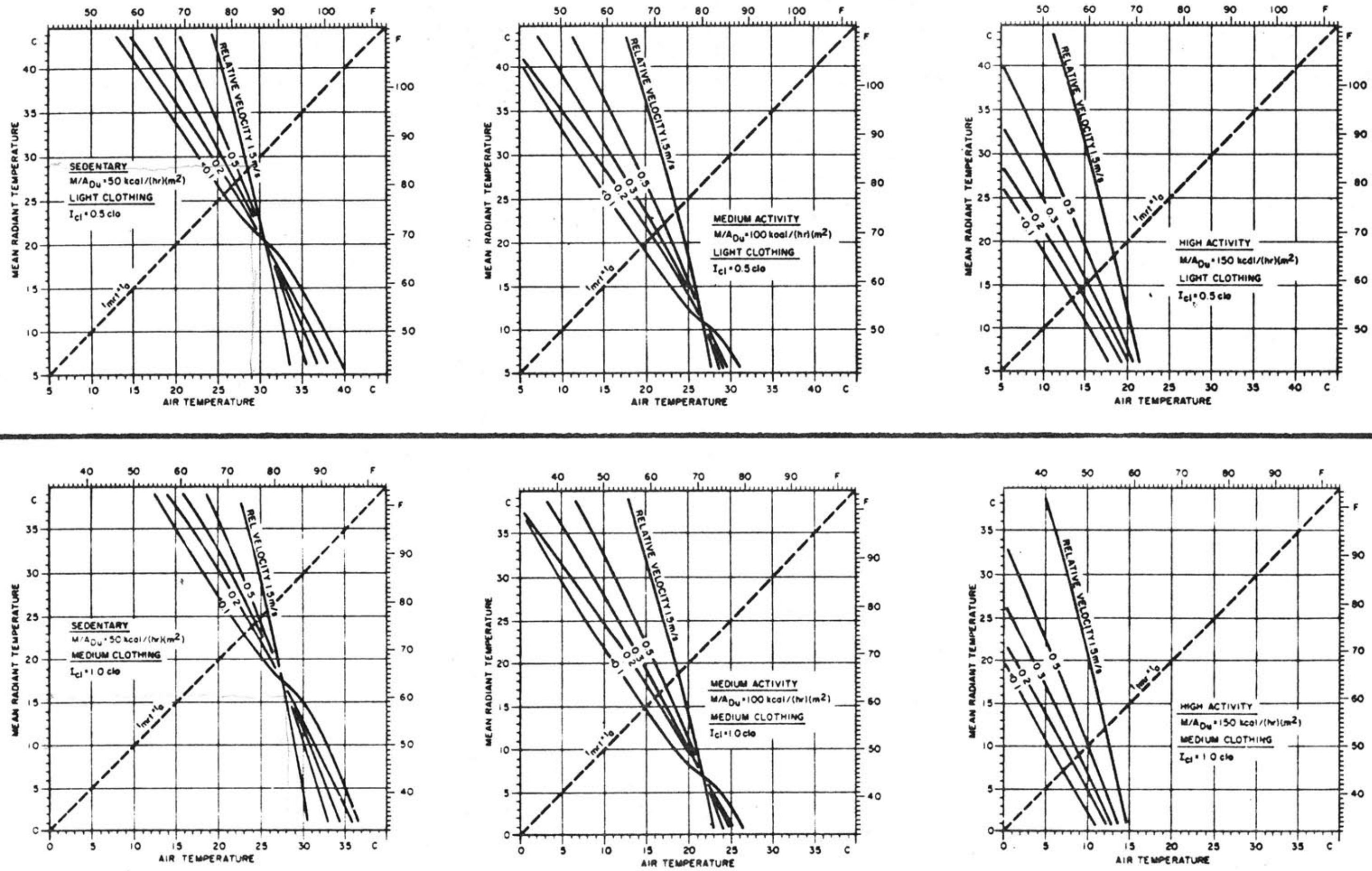
m = metabolic rate
clo = clothing type
v = velocity of air movement
MRT = mean radiant temperature
t_a = ambient air temp
P_a = saturated vapor pressure at t_a

This function describes the situation of thermal equilibrium for comfort when the variables contained balance each other out. To make these body response equations more accessible Faner's equations have been solved for comfort lines with two variables from equation (3) graphed against each other using different givens. It is worth while perusing these charts and 3 examples using them follow below. (A full set of charts is to be found in his writings[9]). To use the charts, clothing (clo) and activity (m) rates must first be established.



The comfort lines are curves through different combinations of ambient temperature and humidity which provide thermal comfort. The six charts apply to six different combinations of activity and clothing, where air temperature equals mean radiant temperature.

16 FANGER CHARTS - COMBINED INFLUENCE OF HUMIDITY AND AMBIENT TEMPERATURE



The comfort lines are curves through different combinations of mean radiant temperature and air temperature which provide thermal comfort.The six charts apply to six different combinations of activity and clothing at 50% rh.

17 FANGER CHARTS - COMBINED INFLUENCE OF M.R.T. AND AIR TEMPERATURE

. . . .

EXAMPLE 1: While driving on a thruway during March, the mean radiant temperature inside a car is 60° F. Find the air temperature necessary for comfort if the passengers are seated quietly ($m = 50$ kcal/HR/m^2) without their overcoats on (clo = 1). If a steady air movement is present (280 FPM) what should the MRT be assuming MRT = t_a for the car to be comfortable?

Solution: From the top chart (Fig. 17), air temp. is 29° C (84° F).

. . . .

EXAMPLE 2: In a solar heated classroom building at night, a dance party is going on ($m = 150$ kcal/HR/m^2) with the RH % = 50% with people lightly clothed. If a steady air movement is present (280 FPM) what should the MRT be assuming the MRT equals the air temperature for the space to remain comfortable?

Solution: From upper chart (Fig. 18) where MRT = t_a = 65° F (18.3° C).

. . . .

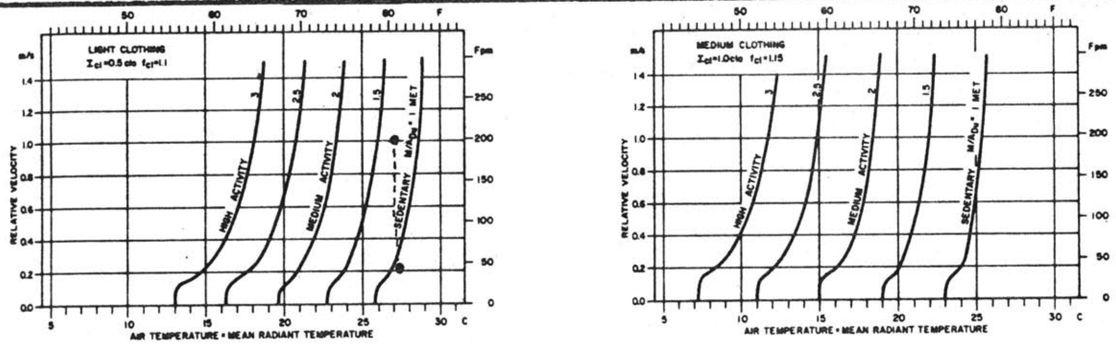
EXAMPLE 3: In the same classroom building in the summer the air temperature is recorded to be 80° (t_a = MRT). The activity involves light work and walking about (med. activity); shorts and T-shirts are the prevalent dress. If the relative humidity climbs to 80% how much air movement is required to maintain comfort?

Solution: Using the upper chart of (Fig. 16) - .35 m/s (70 FPM) is needed.

. . . .

Monitored Building

Using the Fanger Charts a farily reasonable estimate of comfort can be estimated for our building at 132 Chandler Street. Using the data collected shown in Fig. 8 , we have an average air temperature over the first 12 hours of the recorded time. The room where these measurements were made contained few appliances



The comfort lines correspond to five different activity levels are curves through different combinations of relative air velocity and ambient temperature which provide optimal thermal comfort. The two charts apply for persons wearing 0.5 and 1.0 clothing at 50% rh.

18 FANGER CHARTS - COMBINED INFLUENCE OF AIR VELOCITY AND AMBIENT TEMPERATURE

that might cause unusual internal gains and local wall plaster temperature anomolies. We can assume therefore, that MRT equals air temperature. The recorded R H % was 70%. If we assume that the rate of air change = 4/hour (windows being open on a warm summer night) we can pin down the apartments comfort status. Activity and clothing are taken to be as light for both values. Applying the t_a = MRT at 70% RH to Figure 18, left chart a V = 1.00 m/s (186 FPS),

From:

$$V = \frac{\text{A.C. rate x vol.}}{\text{clg. ht x clg. width}} / (60 \text{ sec/min x } 3.1 \text{ ft/m})$$

where V = velocity of air, m/s(x 186 = FPM)

The apartment is within the comfort zone. If the night air is still, however, and the a.c. rate = 1, the air movement falls to .25 m/s (47 FPM) which is below the air movement requirement (.35 m/s, 65 FPM). The conclusion is that the apartment is very border line and needs corrective improvements for this and any other conditions beyond the ones assumed.

C A.S.H.R.A.E. Standards

The last source referring to comfort is the A.S.H.R.A.E. Comfort Standard 55-74.[10] It is comprised of definitions and an evaluation method for testing compliance with parameters shown in Fig. 15. The essential method is outlined below. Applying this method to the monitored building, the result is that the building apartment is well outside the comfort envelope shown in Fig. 15.

ASHRAE 55-74 Comfort Evaluation Method

1. Tabulate for a given space:
    a) Dry bulb temp.
    b) Globe temp.
    c) Wet bulb or dew point temp.
    d) Air velocity

    to be taken at 5 min. intervals to determine excessive rates of change at heights 3", 30" and 72" a.f.f.

2. Determine the vapor pressure from T_{db} and T_{wb} or dew point readings using Table (A) below.
3. Calculate the MRT from the globe temperature using the equation:

$$MRT = (K\sqrt{V.P.})(T_g - T_a) + T_a \qquad (4)$$

where: $K = .157$, for T(F) and V(FPM)

4. Calculate the adjusted dry bulb temperature from

$$ADBT = \frac{DBT + MRT}{2} \tag{5}$$

5. All points that exceed 70 FPM and 5.0 mm Hg > V.P. > 14.0 mm Hg are outside the standard and are considered non-compliant.
6. Use ADBT and V.P. (from Table A) to see if measurements fall within the comfort envelope.
7. Tabulate DBT and MRT (Eq. 4) at 5 min. intervals.
8. Calculate the rate of change in DBT, MRT and V.P. for each time interval, using:

$$\frac{(x_{min} - x_{min})(60)}{\text{time period}} = {}^{\circ}F/hr \text{ or mm Hg/MR}$$

where x_{max} = maximum value of DBT, MRT or V.P.

x_{min} = minimum value of DBT, MRT or V.P.

time = in mins., interval used between x_{max} and s_{min}.

60 = conversion to hours

9. If the rate of change in DBT or MRT exceeds 4°F/hr the value of $(x_{max} - x_{min})$ must be < 2°F. If the rate of change in V.P. exceeds 4.5 mm Hg/hr the value f $(s_{max} - x_{min})$ must be < 2 mm Hg.

PB= 29.92 ,ALTITUDE= 0.

DB	WB	DP	RH	VP
70.0	70.0	70.0	100.0	18.77
70.0	69.0	68.6	95.2	17.87
70.0	68.0	67.1	90.5	16.99
70.0	67.0	65.6	85.9	16.12
70.0	66.0	64.0	81.3	15.27
70.0	65.0	62.4	76.9	14.44
70.0	64.0	60.8	72.6	13.63
70.0	63.0	59.1	68.3	12.83
70.0	62.0	57.3	64.2	12.05
70.0	61.0	55.5	60.1	11.28
70.0	60.0	53.6	56.1	10.53
70.0	59.0	51.7	52.2	9.79
70.0	58.0	49.6	48.3	9.07
70.0	57.0	47.4	44.5	8.36
70.0	56.0	45.2	40.9	7.67
70.0	55.0	42.7	37.2	6.99
70.0	54.0	40.1	33.7	6.32
70.0	53.0	37.3	30.2	5.76
70.0	52.0	34.3	26.8	5.02
70.0	51.0	31.1	23.4	4.39
70.0	50.0	27.8	20.1	3.77
72.0	72.0	72.0	100.0	20.09
72.0	71.0	70.6	95.3	19.15
72.0	70.0	69.1	90.7	18.23
72.0	69.0	67.7	86.2	17.33
72.0	68.0	66.1	81.8	16.44
72.0	67.0	64.6	77.5	15.58
72.0	66.0	63.0	73.3	14.73
72.0	65.0	61.3	69.2	13.90
72.0	64.0	59.6	65.1	13.08
72.0	63.0	57.9	61.1	12.29
72.0	62.0	56.1	57.2	11.50
72.0	61.0	54.2	53.4	10.74
72.0	60.0	52.2	49.7	9.99
72.0	59.0	50.1	46.0	9.25
72.0	58.0	48.0	42.4	8.53
72.0	57.0	45.7	38.9	7.82
72.0	56.0	43.2	35.5	7.13
72.0	55.0	40.6	32.1	6.45
72.0	54.0	37.8	28.8	5.78
72.0	53.0	34.8	25.5	5.12
72.0	52.0	31.5	22.3	44.48
72.0	51.0	28.2	19.2	3.85
72.0	50.0	24.5	16.1	3.23
74.0	74.0	74.0	100.0	21.49
74.0	73.0	72.6	95.4	20.51
74.0	72.0	71.2	91.0	19.55
74.0	71.0	69.7	86.6	18.61
74.0	70.0	68.3	82.3	17.69
74.0	69.0	66.7	78.1	16.78
74.0	68.0	65.2	74.0	15.90
74.0	67.0	63.6	69.9	15.03

PB= 29.92 ,ALTITUDE= 0.

DB	WB	DP	RH	VP
74.0	66.0	61.9	66.0	14.19
74.0	65.0	60.2	62.1	13.35
74.0	64.0	58.5	58.3	12.54
74.0	63.0	56.6	54.6	11.74
74.0	62.0	54.7	51.0	10.96
74.0	61.0	52.8	47.4	10.19
74.0	60.0	50.7	43.9	9.44
74.0	59.0	48.5	40.5	8.71
74.0	58.0	46.2	37.1	7.98
74.0	57.0	43.8	33.9	7.28
74.0	56.0	41.2	30.6	6.58
74.0	55.0	38.4	27.5	5.90
74.0	54.0	35.3	24.4	5.24
74.0	53.0	32.0	21.3	4.58
74.0	52.0	28.7	18.3	3.94
74.0	51.0	25.0	15.4	3.31
74.0	50.0	20.6	12.5	2.69
76.0	76.0	76.0	100.0	22.98
76.0	75.0	74.6	95.5	21.95
76.0	74.0	73.2	91.2	20.95
76.0	73.0	71.8	86.9	19.97
76.0	72.0	70.4	82.7	19.01
76.0	71.0	68.9	78.6	18.07
76.0	70.0	67.4	74.6	17.14
76.0	69.0	65.8	70.7	16.24
76.0	68.0	64.2	66.8	15.36
76.0	67.0	62.5	63.1	14.49
76.0	66.0	60.8	59.4	13.64
76.0	65.0	59.1	55.7	12.81
76.0	64.0	57.2	52.2	12.00
76.0	63.0	55.3	48.7	11.20
76.0	62.0	53.3	45.3	10.42
76.0	61.0	51.3	42.0	9.65
76.0	60.0	49.1	38.7	8.90
76.0	59.0	46.8	35.5	8.16
76.0	58.0	44.4	32.4	7.44
76.0	57.0	41.8	29.3	6.73
76.0	56.0	39.0	26.3	6.04
76.0	55.0	35.9	23.3	5.36
76.0	54.0	32.6	20.4	4.69
76.0	53.0	29.3	17.6	4.04
76.0	52.0	25.5	14.8	3.40
76.0	51.0	21.2	12.0	2.77
76.0	50.0	16.0	9.3	2.15
78.0	78.0	78.0	100.0	24.55
78.0	77.0	76.7	95.5	23.48
78.0	76.0	75.3	91.4	22.44
78.0	75.0	73.9	87.2	21.41
78.0	74.0	72.5	83.1	20.41
78.0	73.0	71.0	79.1	19.43
78.0	72.0	69.5	75.2	18.46
78.0	71.0	68.0	71.4	17.52

PB= 29.92 ,ALTITUDE= 0.

DB	WB	DP	RH	VP
78.0	70.0	66.4	67.6	16.60
78.0	69.0	64.8	63.9	15.70
78.0	68.0	63.2	60.3	14.81
78.0	67.0	61.4	56.8	13.95
78.0	66.0	59.7	53.3	13.10
78.0	65.0	57.9	50.0	12.27
78.0	64.0	55.9	46.6	11.45
78.0	63.0	54.0	43.4	10.66
78.0	62.0	51.9	40.2	9.87
78.0	61.0	49.7	37.1	9.11
78.0	60.0	47.4	34.0	8.36
78.0	59.0	45.0	31.0	7.62
78.0	58.0	42.4	28.1	6.90
78.0	57.0	39.6	25.2	6.19
78.0	56.0	36.6	22.4	5.50
78.0	55.0	33.2	19.6	4.82
78.0	54.0	29.9	16.9	4.15
78.0	53.0	26.2	14.2	3.50
78.0	52.0	21.9	11.6	2.85
78.0	51.0	16.7	9.1	2.22
78.0	50.0	10.1	6.5	1.61
80.0	80.0	80.0	100.0	26.22
80.0	79.0	78.7	95.7	25.10
80.0	78.0	77.3	91.6	24.01
80.0	77.0	75.9	87.5	22.94
80.0	76.0	74.5	83.5	21.89
80.0	75.0	73.1	79.6	20.87
80.0	74.0	71.7	75.8	19.87
80.0	73.0	70.2	72.0	18.88
80.0	72.0	68.6	68.4	17.92
80.0	71.0	67.1	64.8	16.98
80.0	70.0	65.5	61.2	16.06
80.0	69.0	63.8	57.8	15.15
80.0	68.0	62.1	54.4	14.27
80.0	67.0	60.3	51.1	13.40
80.0	66.0	58.5	47.9	12.56
80.0	65.0	56.6	44.7	11.72
80.0	64.0	54.6	41.6	10.91
80.0	63.0	52.5	38.6	10.11
80.0	62.0	50.4	35.6	9.33
80.0	61.0	48.1	32.7	8.56
80.0	60.0	45.6	29.8	7.81
80.0	59.0	43.0	27.0	7.08
80.0	58.0	40.3	24.2	6.36
80.0	57.0	37.3	21.5	5.65
80.0	56.0	34.0	18.9	4.96
80.0	55.0	30.5	16.3	4.27
80.0	54.0	26.8	13.8	3.61
80.0	53.0	22.6	11.3	2.95
80.0	52.0	17.5	8.8	2.31
80.0	51.0	11.0	6.4	1.68
80.0	50.0	2.0	4.1	1.06

•ALT	ALTITUDE, FT
•DB	DRY-BULB TEMPERATURE, F
•WB	THERMODYNAMIC WET-BULB TEMPERATURE, F
•DP	DEW POINT TEMPERATURE, F
•RH	RELATIVE HUMIDITY, PERCENT
•VP	VAPOR PRESSURE, MM. HG

19 TABLE A

Conclusion

These 3 guidelines are included as a standard defining the comfort envelope and to extend its evaluation to its widest applications. All methods considered, the human body remains as the definitive interpreter and last word in psychrometrics.

Housing HVAC systems in the hierarchy of different building type mechanical systems are less complex and more localized when compared with large space systems, or complex demand systems such as those found in public assembly buildings or hospitals.

Typically in Boston an apartment building's mechanical system will be comprised of a 2-pipe fan coil to deliver steam or hot water for space heating; air conditioning is achieved by through-the-wall, local electric units; corridors are maintained with a positive air pressure by a central air system; venting is accomplished with electrical fans in bathrooms and kitchens rising through a common building stack or by locating the kitchen within 12 ft of a window. This uncomplicated and localized quality is a necessity since multifamily buildings must serve a large latitude of lifestyle thermal needs with simple flexibility. This is an advantage for adoption to new definitions of comfort envelopes appropriate to new energy standards, since local control can quickly respond to local demand (where sudden high internal gains are expended, windows are opened and where great fluctutions in vapor pressure occur due to food preparation). As new energy codes for improved insulation and enhanced glazing are met, the comfort standards may also have to expand to allow for greater differences between MRT and DBT as well as acceptable rates of air movement. The final purpose of evaluating historical comfort standards is to have a reference for computer modeling of changes suggested for 132 Chandler Street including the proposed night ventilation/mass wall system.

5

URBAN SOLAR ENERGY

This chapter covers solar radiation issues that are critical to consider for urban solar applications. The discussion starts by considering the radiation available at the exterior of the earth's surface and then estimates the losses due to reflections, absorption and shading as that energy approaches its target: our solar wall.

a Atmospheric Clearness Factors

Despite the number of variables inside the atmosphere affecting the transmittance of solar energy, the "solar constant" value (429.2 BTUH/SF) is generally accepted as being the predictive value of energy available outside the atmosphere. This constant is a starting value which is then modified by scattering, absorption, diffusion and re-radiation equations. In New York, for example, the bottom line annual average percentage of radiation falling on a surface continuously normal to the sun from sunrise to sunset is only 33% of what is available outside the atmosphere. Factors that account for this loss are due to:

1. Atmospheric Dust
2. Gas molecules
3. Ozone
4. Water vapor
5. Length of air mass traveled by radiation.

Air Mass

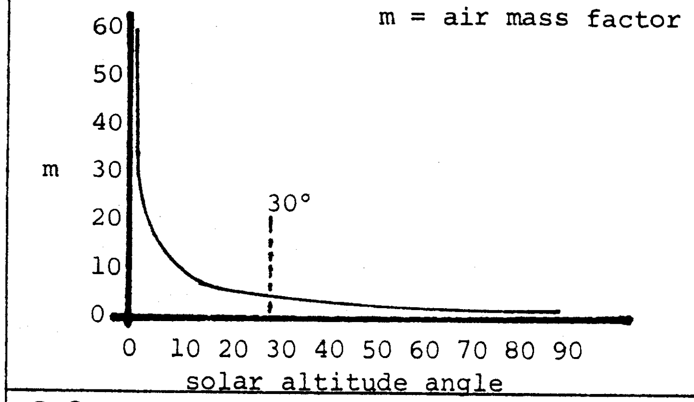
For many purposes the air mass coefficient is a factor that represents the path length and sky conditions that sunlight must travel through and is given by:

$$\text{air mass factor} = \frac{1}{\sin \alpha} \left(\frac{\text{b.p.}}{29.92}\right) \tag{6}$$

where:

α = solar attitude above horizon, °
b.p. = local barometric pressure, in Hg
29.92 = sea level b.p. in Hg

Figure 20 shows that the air mass factor becomes quite large at solar angles of 30 (m = 2) and less. This is one reason why the valuable time for solar energy collection tends to be 2-4 hours on either side of solar noon. The amount of air mass through which sunlight must travel affects not only the total percent transmitted but it also modifies the proportions of u.v., visible and i.r. energy that make up the total solar component received. Figure 21[7] contrasts transmission of air mass = 0 with air mass = 2.



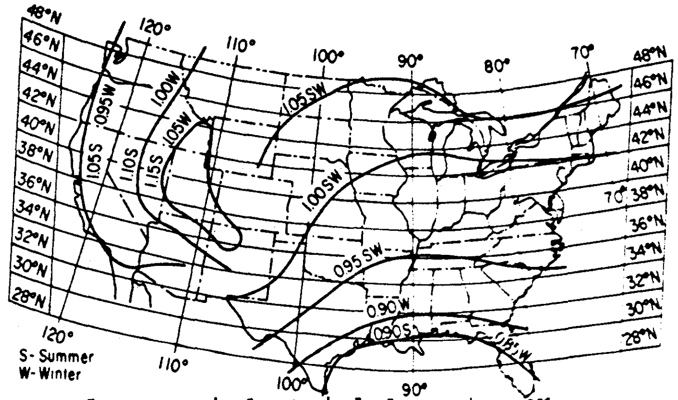
20 AIR MASS FACTOR[7]

	u.v. .29 - .4 mμ	visible .4 - .7 mμ	near i.r. .7 - 3.5 mμ
air mass = 0	9%	38%	53%
air mass = 2	3%	44%	53%

21 Solar Energy Components

The near infra-red component is unchanged while u.v. increases as the air mass factor approaches 1 at solar noon. (Experienced sunbathers confirm the benefits of this phenomena!)

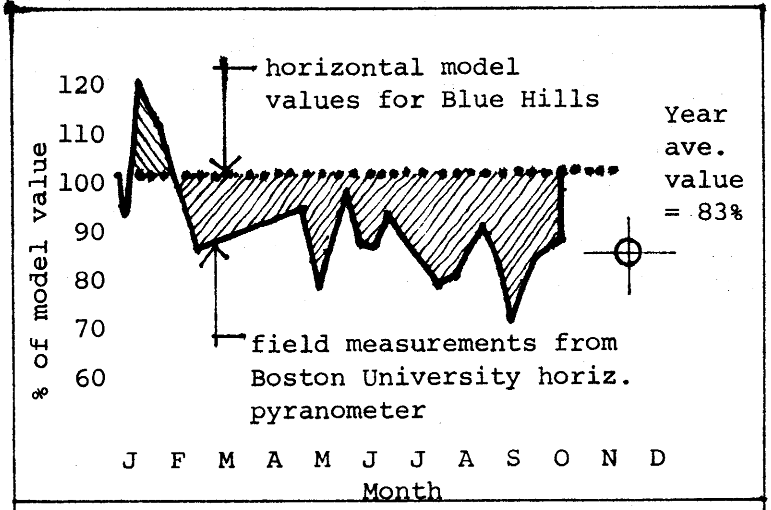
Figure 22 is an atmospheric clearness chart that maps a rough estimate of several atmospheric characteristics including the air mass factor, for non-industrial locales. If conditions are particularly moist or dirty this clear day factor can be lowered by as much as 15-30% in industrial areas. If the locale is appreciably high in elevation with a relatively dry atmosphere and clean air, the factor can be increased by as much as 15%. As shown in Figure 22 the base value for the atmospheric clearness factor is equal to 1. This is represented by the situation where



for non-industrial locations

22 STANDARD ATMOSPHERIC CLEARNESS FACTORS[7]

the sun's position is perpendicular to the earth's surface at sea level. The markings S and W refer to the summer/winter conditions. Other corrections of a more ephemeral nature also need to be considered. These are factors to compensate for air pollution or "atmospheric aerosol." To determine if this is a major effect for urban locations, clear day pyranometer data from two Boston area monitoring stations are compared in Fig. 23. The location of the stations is important to note. The weather station at Boston University (B.U.) is located on the roof of a two story building lying between the Mass. Turnpike and Commonwealth Avenue. The Turnpike is approximately 500 ft. to the south and Commonwealth a short block to the north. The clear day pyranometer readings used is Fig. 23 in the B.U. column are therefore representative of a densely populated urban environment where atmospheric turbidity and aerosol are assumed to be high. This location is within 20 blocks of 132 Chandler Street and is representative of the sunshine values used in simulations. The Blue Hills Station by contrast lies in a heavily wooded area 600 ft. above sea level. Its location is about 12 miles to the south of the Boston Univeristy station. The readings from Blue Hills are based on clear day model values for that particular station provided by the National Oceanic and Atmospheric Administration. By comparing them we can get a feeling for the effective weakening by urban pollution on available sunshine. The results of Fig. 23 indicate that the urban location readings average 17% lower annually than the suburban model value readings. Discussions with Prof. Houghton at M.I.T. Meteorology Dept. concluded with his opinion that the percentage differences are due to atmospheric differences. Differing percents in readings that might be attributed to altitude or cloud cover for the separate areas would be less than the

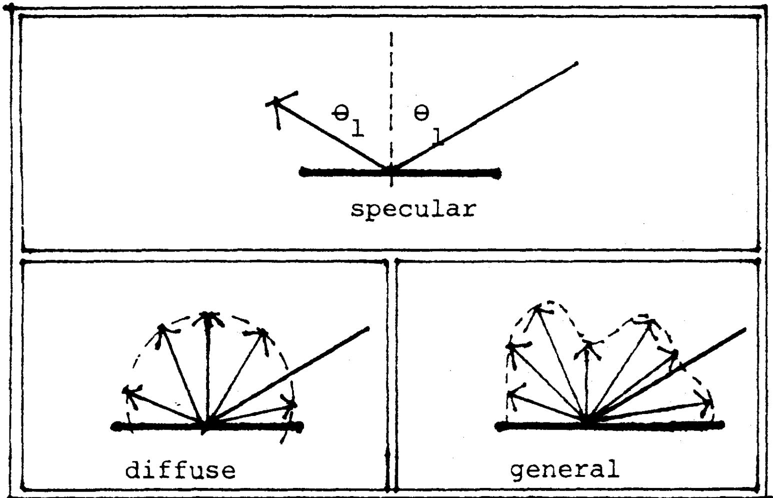


23 URBAN/MODEL **VALUE** COMPARISON OF AVAILABLE SUNSHINE

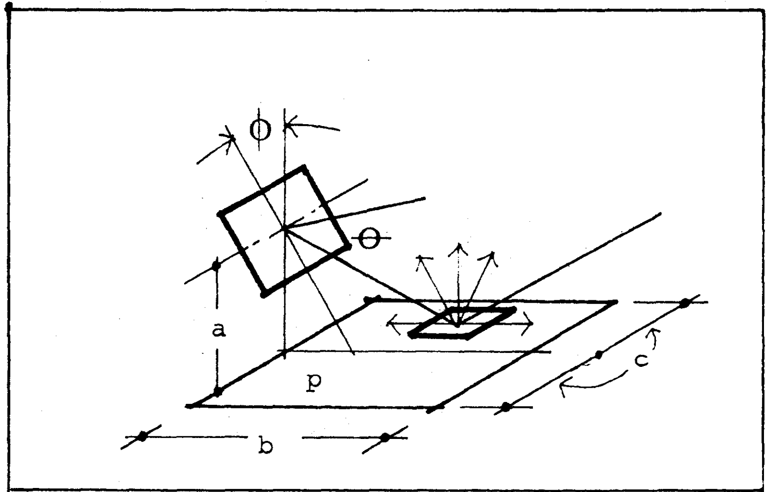
percentage of error inherent in the pyramometer readdngs themselves. Therefore a large fraction of the differences shown in the general trend are due to urban atmospheric pollution. Future research and data collection for cities is needed in this area to more accurately predict solar radiation available for urban applications.

b Reflecting Surfaces

Reflections from surfaces lying to the south of a south facing vertical wall often amounts to a significant fraction of the total solar energy available. To estimate the impact of reflections from concrete plazas, sidewalks, painted patios, etc., as well as adjoining walls and glass areas, the reflections can be considered by their distinct natures (Fig. 24). To simplify the calculation methods and examples that follow, the reflecting surfaces are assumed to be perpendicular to a vertical south wall for both ground reflections and side wall reflections. The methods given for reflections are excerpted from Thermal Environmental Engineering.[12]



24 SURFACE REFLECTIONS[11]



25 DIFFUSE GROUND REFLECTIONS

METHOD:

1. First the following data must be found:
   - a) β = solar altitude,
   - b) γ = solar azimuth, °
   - c) I_n = solar radiation incident on normal surface, BTUH/SF
   - d) I_H = solar radiation falling on horizontal surface, BTUH/SF
   - e) I_{dH} = diffuse solar radiation falling on horizontal surface, BTUH/SF
   - f) α = wall-solar azimuth angle, °
2. Find $\cos\theta$:

   when $\cos\theta = \cos\beta \cos\alpha$
3. Find I_{Dv}

   when $I_{Dv} = I_N \cos\theta$
4. Find I_{dv}:

   from Fig. 1 (Appendix A) with $\cos\theta$

   when $I_{dv}/I_{dH} \sim \cos\theta_v$
5. Find p:

   from Fig. 2 (Appendix)

   where p = surface reflectivity
6. Find F:

   when $$F = \tan^{-1}\frac{c}{a} - \frac{a}{\sqrt{a^2+b^2}}\tan^{-1}\frac{c}{\sqrt{a^2+b^2}}$$

   where a =
   b = dimension, ft. (see Fig. 25).
   c =

7. Find I_{RV}:

when $I_{RV} = \frac{PI_H F}{\pi}$

where F = geometrical factor

EXAMPLE: At 132 Chandler Street what is the average BTU quantity of diffuse reflections from new concrete; and a bright grass surface at solar noon on a mid-July day? The building is 50' high (2 x a), 20' wide (c) and 25' deep (b).

Givens are:

1. $\beta = 69$

$\gamma = 6$ w. of south

$I_{norm} = 275 \times 1.01 = 278$ BTUH/SF

$I_H = 276$ BTUH/SF

$I_{dH} = 34$ BTUH/SF

$\alpha = 6^{\circ}$

2. $= 358 \times .939 = 336$

3. $I_{dv} = .336 \times 278 = 93$ BTUH/SF

4. From (Fig. 1, App. A):

$I_{dv}/I_{dH} = .75$ and $.75 \times 34 = 26$ BTUH/SF

5. From (Fig. 2, App. A):

$P_{grass} = .31$

$P_{new\ concrete} = .26$

6. $$F = \tan - 1\ \frac{20}{25} - \frac{25}{\sqrt{625 + 625}} \tan - 1\ \frac{20}{\sqrt{625 + 625}} \doteq 1.36$$

7. $$I_{RV(c)} = \frac{.26 \times 276 \times 1.36}{\pi} = 31 \text{ BTUH/SF for new concrete}$$

$$I_{RV(g)} = \frac{.31 \times 276 \times 1.36}{\pi} = 37 \text{ BTUH/SF for bright grass.}$$

This tells us that the diffuse reflections from surfaces amount to approximately 12% of the energy available at the vertical wall element. An interesting aspect of this diffuse reflection phenomena is that the amount reflected is a function of the incident angle made betewen the ground plane and sun position.

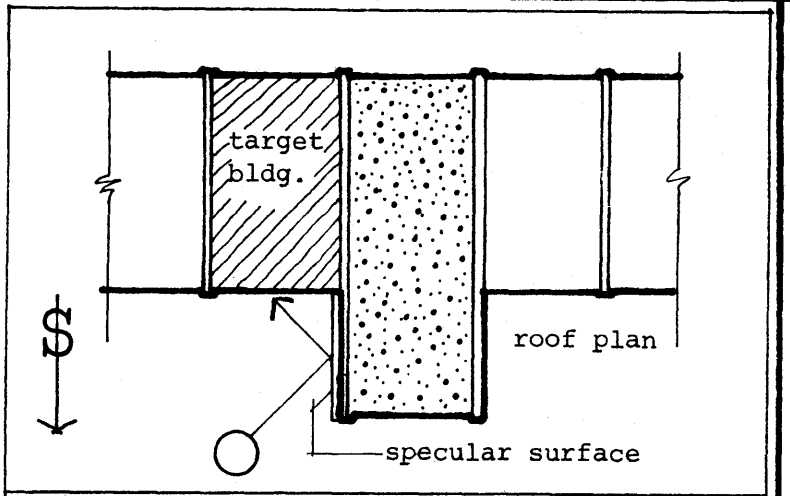
C Specular Reflections from Adjacent Surfaces

This becomes an important consideration in the often complex backyard/ front yard geometries found in housing configurations. For example (Fig. 26) is a commonly found condition where an adjacent building juts out to the south of the building being considered.

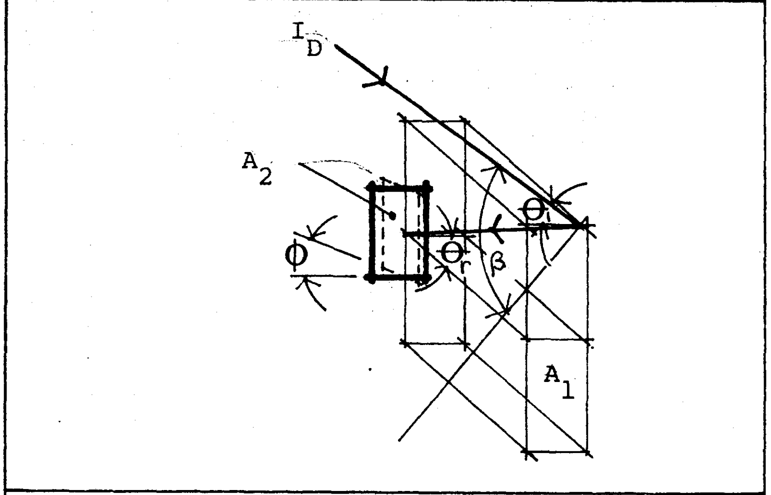
METHOD:

(8)

1. First the following data must be found:
    - a) θ_1 = sun's angle of incidence with respect to surface A_1,°
    - b) β = altitude, °
    - c) ϕ = 0° for solar-wall/reflecting wall angle = 90°
    - d) α_2 = solar wall-solar azimuth angle, °
    - e) I_D = intensity of direct solar component on surface A, BTUH/SF
    - f) p = specular reflectivity of reflective surface A_1,



26 SPECULAR REFLECTIONS ONTO SOUTH VERTICAL WALLS



27 SPECULAR WALL REFLECTIONS

2. Find θ_R: (quantity of radiation reflected) when

$$\cos\theta_R = \cos\beta\cos\alpha_2\cos\phi - \cos\theta_1\sin\phi$$

3. Find I_R: when

$$I_R = pI_D\cos\beta\cos\alpha_2$$

EXAMPLE: 132 Chandler Street is oriented 14° east of south at solar noon find the radiation being reflected to the vertical south wall (s) from the adjacent glass surface as in (Fig. 26). The beam radiation is 275 BTUH/SF and the reflectivity of the glass at the given angle of incidence is .52.

1. $\theta_1 = 80°$ $\alpha_2 = 80°$
$\beta = 27°$ $I_D = 275$ BTUs
$\phi = 0°$ $p = .52$

2. $\cos \theta_R = (.891)(.174)(1) - (.174)(0) = .15$
$\theta_R = 81°$

3. $I_R = (.52)(275)(.891)(.174) = 22$ BTUH/SF specularly reflected radiation

Thus the increase of solar energy available at our solar wall is equal to 8% of the total direct energy. Because the reflection is specular, the angle of incidence between the sun and the reflecting wall has a large impact on the quantity reflected. When incident angles are high (above 80°) the reflectivity (p) will be from 52% approaching 90% at an incident angle of 89°.[*] This means that the energy available at the solar wall nearly doubles for approximately two hours when the sun is in near alighment with the reflecting wall. If the reflecting wall being considered is a composition of glass and brick (specular and diffuse surfaces) then the contributing areas and their reflections can be calculated independently then summed together.

d Shading From Overhangs

The question of sizing effective overhangs for solar applications can be solved by several methods. They indlude three dimensional scale models mounted on a heliodon; graphic sections using a sun angle calculators; or trigonometric analysis of the first two methods. The method discussed here is a trigonometric

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[*] See Appendix B on glass transmission

method since for simple geometries sizing overhangs can be done rather quickly on a programmable hand calculator. For the mass wall system proposed here creating an overhang that might shade the south wall is highly undesirable. This is due to the fact that the mass wall is in operation both in summer and winter and the motivational force is sunshine. However, for many housing applications fire escapes, awnings, deep cornices, etc., are existing elements that ultimately affect a vertical wall's ability to receive sunshine. The first method considers the minimum dimensions for a desired overhang for summertime. The second method predicts the percentage of glass area that remains shaded at times of the year other than the summer.

Overhang Sizing Method[1.2]

METHOD (9)

1. First the following data must be found:
   - a) time and dates desired to have shade
   - b) l = local latitude,°
   - c) d = solar declination
   - d) h = sun's hour angle,° (see Fig. 3 Appendix)
2. Find β:
   when $\sin\beta = \cos l \cos h \cos d + \sin l \sin d$
3. Find γ:
   when $\cos\gamma = \sec\beta(\cos l \sin d - \cos d \sin l \cos h)$;
   γ = solar azimuth
4. Find α:
   when $\alpha = 180° - y$
   α = wall-solar angle,° azimuth angle, °

5. Find δ: δ = sun's profile angle,

when $\cot \delta = \cos \alpha / \tan \beta$

6. Find f: f = overhang width, ft.

when $f = (a + e) \cot \delta - b$

7. Then find g: g = overhang length, ft.

when $g = (f \tan \alpha)\ 2 + c$

EXAMPLE: For August 30th determine the dimensions for an overhang so that the top half of a 3' (wide) x 5' (high) window in our south wall at 132 Chandler Street will remain shaded for the hottest times of a summer day (9 am-3 pm). The building is located at latitude 42°. The overhang is located at the top of the window frame.

1. a) 9 am-3 pm
   b) $l = 42^\circ$
   c) $d = 8.33^\circ$ from (Fig. 4 - Appendix)
   d) $h = 45^\circ$ from (Fig. 3 - Appendix)
2. $\sin \beta = (.707)(.707)(.989) + (.669)(.149) = .594 \quad \beta = 36^\circ$
3. $\cos y = (1.243)\ [(.743)(.149) - (.989)(.669)(.707)] = -.444$
   $\gamma = 116^\circ$
4. $\alpha = 180 - 116 = 64^\circ$
5. $\cot \delta = (.438)/(.726) = .603 \quad \delta = 59^\circ$
6. $f = (30" + 0")\ .603 - 0 = 18"$ = overhang width
7. $g = (18 \times 2.05)\ 2 + 36 = 110" = 9' - 2"$ = overhang length

Wintertime Unshaded, Glass Areas at Noon[12]

METHOD (10)

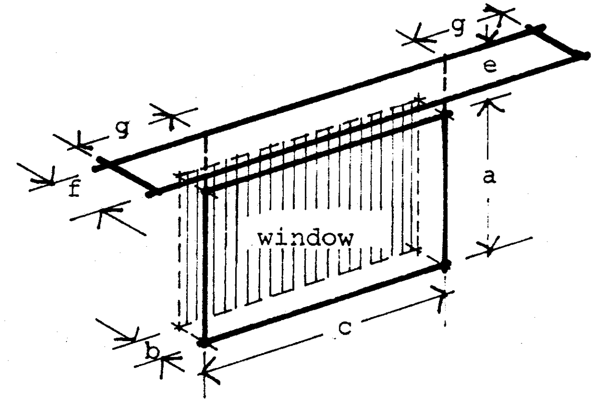
1. First the following data must be found:
   - a) d = solar declination
   - b) h = sun's hour angle,°. (See Fig. 3 Appendix)
   - c) α = wall-solar angle,°.
   - d) l = local latitude, °.
   - e) b = glass set back distance from wall plane, in.
2. Find $\sin \beta$:

   when $\sin \beta = \cos l \cos h \cos d + \sin l \sin d$
3. If $\alpha = 0$, $\delta = \beta$, find e'

   when $e' = f \tan \beta$

   e' = see diagram 28

   f = see previous method
4. If there is a setback of glazing from face of wall, $a' = b \tan \beta$



28 WINDOW SHADING GEOMETRY

EXAMPLE: The amount of the window in the previous example shaded at solar noon on Jan. 22 with a 6" set back is:

1. a) $d = -19.84°$
   b) $h = 0°$
   c) $\alpha = 0°$
   d) $l = 42°$
2. $\sin \beta = (.773)(1)(.940) + (.669)(-.339) = .471 \quad \beta = 28°$
3. $e' = 18'' (.531) = 10''$
4. $a' = 6'' (.531) = 3''$

The top 10" of the window are shaded in January which is equal to 17% of the window area. This represents the greatest amount of shading on that day. 3" of that 10" is shaded due to the set back of the glass plane.

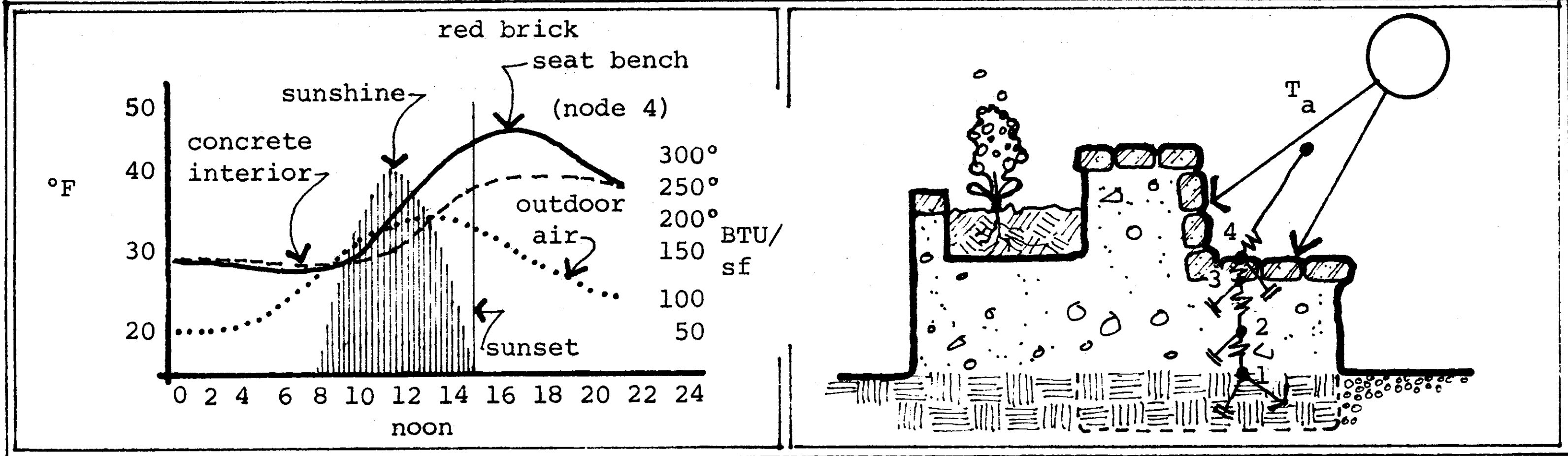
e Wind and Radiation Traps at Outdoor Areas Adjacent to a Building

The presence of radiation traps and wind baffles are significant building site elements that have the potential to alter and extend the comfort of outdoor areas. Typical considerations for a building such as 132 Chandler Street include: the absorptivity and heat capacity of the materials used in patios, walks, benches, stairs, stoops, front steps and gardens. Careful choices in planning these areas can make the "connective tissue" in multi-family housing an enriching experience ("connective tissue" is that transitional zone in housing that is neither clearly public space or private but rather a mixture of the two). Measured observations from M.I.T. classes in micro-climate commonly show that outdoor M.R.T. readings are higher than air temperautres several hours after sunset, particularly when these readings are close to (with 2-3') of a large thermal mass. Materials most commonly found in Chandler St. front and backyards include (Fig. 29).

We can see that the heat capacity of concrete is roughly half that of water and soil is about half that of concrete. To find the contribution due to re-radiation of absorbed solar heat to the surroundings, the geometry and relevant dimensions of the materials must be considered. The outgoing longwave radiation (that which we are seeking for warmth) is equal to the emissivity of the surface of the material. This governs the rate at which the absorbed energy is released. Under normal backyard conditions the largest recipient of this thermal backloss is the sky. This happens because the temperature of the sky is usually much lower than the temperature of the other surrounding surfaces. For example by simulation, a landscaped dark-red brick bench that is oriented south with good wind protection will, at its surface, run temperatures as much as 10 above the ambient air temperatures 8 hours after sunset on a sunny , cold Boston January day see (Fig. 30). Unfortunately, the effective distance of this kind of thermal landscape design becomes negligible upon moving two or three steps away from the brick bench in the example, though it is significant to the touch. A second important environmental effect is the wind effect. The impact of wind, based on calculations using average wind velocity figures, can be a considerable adverse factor on solar collector surfaces. The heat loss coefficient

MATERIAL	HEAT CAPACITY
1. Clay soil	14.0
2. Wood decking	17.0
3. Brick pavers	25.0
4. Asphalt (blacktop)	29.0
5. Concrete	31.7
6. Water	62.4

29



30 OUTDOOR TEMPERATURE SIMULATION AT BRICK BENCH ON SUNNY JANUARY DAY (AND SIMULATION NETWOK)

in (w/m^2 °C) from flat plates exposed to wind is given by McAdams[13] to be:

$$h(\text{wind}) = 5.7 + 3.8V \tag{11}$$

where V = wind speed, m/s

h = heat transfer coefficient, w/m^2 - °C

[to convert w/m^2 - °C to BTU/ft^2 - °F multipy by .176

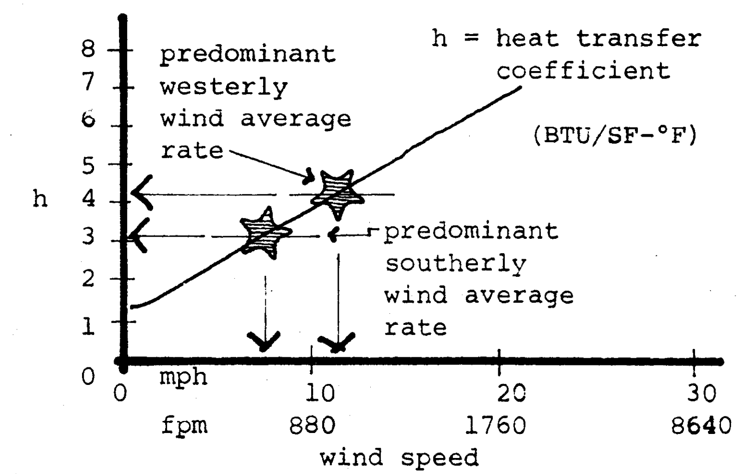
and to convert M.P.H. to m/s multiply by .447]

Computing the h values for several different wind speeds result in the following (Fig. 31). The average wind speeds for Boston are 7.3 mph for winds out of the south and 11.5 mph for winds out of the west. This corresponds to h values as shown as on (Fig. 31) of 3.2 and 4.5.

To put this into perspective the heat transfer coefficients due to radiation are shown in Fig. 8 (Appendix A). This graph shows the F_T (temperature factor) as the heat transfer coefficient between a radiating surface, F, and an absorbing surface, shown as the graphed lines. Significant to note is the fact that for most calculations involving the relatively low temperatures of popular so solar systems, the radiant heat transfer coefficient falls below 2 and the great majority below 1.4 BTUH/ft^2 F. By comparing the wind and radiation coefficients, it becomes obvious that air movement is the dominant heat robber for outdoor planar surfaces. To achieve optimum performance, urban solar applications need to respond to this in the plannig of outdoor elements adjacent to and at the solar collecting surfaces.

f Glazing Over Sun Sensitive Surfaces

An important issue to consider for urban solar applications is the type of glazing to be selected for use at the sun sensitive surfaces. In order to select the best glazing cover it is necessary to consider the fundamental optical properties of transparent media and their ability to transmit solar energy. Four importnat properties of glass and plastics to consider are their coefficients of extinction (K), their refractive indices (N), the



31 HEAT LOSS FROM OUTDOOR FLAT SURFACES DUE TO WIND[13]

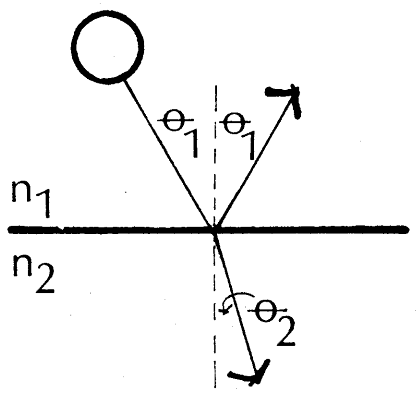
the wavelength of the incoming solar energy (λ) and its angle of incidence relative to the glazing surface. Dufie and Beckman recommend that for most solar applications (n) and (K) can be assumed to be independent of wavelength. The assumption is made here that for transparent media the sum of the quantities of energy transmitted, reflected and absorbed is equal to 1.

Transmission Through Glass After Reflections

Fresnel equations describe the relations for reflections of non-polarized radiation that passes from a medium with refractive index n, to a second medium with refractice index n_2 . Snell's Laws specify the relationship between the two mediums and their indices of refraction (bending of light path). Air has a refractive index of 1. Combining these equations into the following method provides an accurate estimate of how much energy is lost due to the incident angle and index of refraction of the glass.

. . . .

To find the amount of energy transmitted after reflections at incident angles < 90° and ≥ 0°; see Fig. 32.



32 REFLECTIONS/TRANSMISSION DUE TO DIFFERING MEDIA

METHOD

1. Find θ_2: (θ_2 = leaving angle of light path) (12)

when $\theta_2 = \text{arc sin } (\sin \theta_1/h)$

where n = the average index of refraction of n_2.

2. Find p: (p = reflected component),

when $$p = 1/2 \left[\frac{\sin^2(\theta_2 - \theta_1)}{\sin^2(\theta_2 + \theta_1)} + \frac{\tan^2(\theta_2 - \theta_1)}{\tan^2(\theta_2 + \theta_1)}\right]$$

Find T_r: T_r = fraction transmitted after reflections, %)

when $T_r = (1 - p)$

EXAMPLE

Using the best (water white) 1/8" thick regular glass with a refractive index of 1.526, establish the solar energy transmitted at both a 10° and 75° angle of incidence.

1. θ_2 at $10° = \text{arc sin } (\frac{.174}{1.526}) = \text{arc sin } .114 = 6.6°$

2. $p = 1/2 \left[(\frac{.0036}{.0811}) + (\frac{.0036}{.0883}) \right] = .0426 = 4\%$ reflected

3. $T_r = 1 - .04 = .96 = 96\%$ solar energy transmitted

and

1. θ_2 at $75° = \text{arc sin } (\frac{.966}{1.526}) = \text{arc sin } (.633) = 39.27°$

2. $p = 1/2\,[(\frac{.341}{.831}) + (\frac{.517}{4.919})] = .257 = 26\%$ reflected

3. $T_r = 1 - .26 = .74 = 74\%$ solar energy transmitted

This reduction in transmission continues until the angle of incidence approaches 90° with reflections accounting for 93% of the energy available at θ_1 equal to 89°.

Transmission Through Glass After Absorption

To find the amount of energy being transmitted after absorption the local intensity of the material through which the light must pass has to be specified. The more intense the medium and greater the path length through the medium the more energy "dies" within the glazing material itself, lost for transmission. This phenomena is described by Bouger's Law to the amount of energy absorbed in a glazing mdedium and resulting transmission the following method can be used (Fig. 33).

METHOD:

1. First, the following data must be found (13)
   - a) K = glass coefficient of extinction usually to be found in glass manufacturer's specs.
   - b) L = path length with thickness (t), in or cm.
2. Find T_a: (T_a = fraction transmitted after absorption, %)

when $T_a = e^{-KL}$

3. Find a: (a = fraction absorbed, %)

when $a = 1 - T_a$

EXAMPLE: For the same glass as on the previous example establish the energy transmitted at 10° and 75° if the glass has a coefficient of extinction equal to .161/in.

1. a) $K = .161/\text{cm}$

b) $$L_{@10^\circ} = \frac{t}{\cos \theta_2} = \frac{.3125}{.993} = .314 \text{ cm}$$

2. $T_a = e^{-(.161)(.314)} = .89 = 89\%$ solar energy transmitted

3. $a = 1 - .89 = .11 = 11\%$ absorbed

and

1. a) $K = .161/\text{cm}$

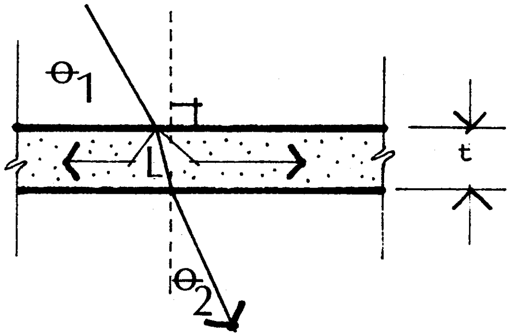
b) $L_{@75^\circ} = .3125/.774 = .304 \text{ cm}$

2. $T_a = e^{-(.161)(.304)} = .395 = 40\%$ solar energy transmitted

3. $a = 1 - .395 = .605 = 60\%$ absorbed

A.R.T. Program

The two methods given above for determining reflective and absorptive losses are summarized and integrated into a hand calculator program listed in Appendix B. The calculator program determines the final transmission at any incident angle < 90°. If the absorptance of the mass wall is known the energy finally entering the wall can also be found using a method of estimating interreflections between the glazing system and absorber surface.



33 ABSORBTION OF ENERGY IN GLAZING

6

SYSTEMS SELECTION

There are several systems that deserve consideration that can achieve the necessary cooling effect for summer conditions. Ideally an effective cooling system must meet the following criteria:

1. Must serve as a cooling source as well as have heating capacity to double up the thermal benefit and enhance the payback period.
2. Must be able to maintain comfort in apartments as well as a conventional air conditioning units or as well as conventional electric heaters.
3. Must not effect normal window usage. This means that views must be maintained and the quality and quantity of natural light must be optimized.
4. Must achieve a payback within 5-7 years. This is a target widely expected by builders, investors and homeowners.
5. Must be flexible and unobtrusive as a system - not requiring valuable floor area, and should be highly adaptable for retrofit.
6. Must have low upkeep or maintenance over it's payback period and the time beyond that period.

Potential Systems

The systems which appear feasible are:

1. Conventional A.C. Units

2. Ventilation Fans
3. Air to Air Heat Pumps
4. Active Solar Collectors (liquid or air type)
5. Stack Effect System

Conventional A.C.

The attraction of conventional air conditioning systems is four-fold. First, air conditioners for apartment construction are a consideration in that builders of apartment buildings have to provide the appropriate wall openings only. The tenant or building owner buys and installs the unit. This eliminates a sizeable cost for purchasing and installation by the contractor. Secondly, the wall or window a.c. unit gains an efficiency over a large central building system due to its being located in the immediate space it serves. By the use of multiple units for different rooms and exposures a "zoning" effect is achieved that lets the user turn on an a.c. unit only for the spaces needing it. Third, the response time is quick (units under 12,000 BTU can bring comfort within 15 mins. and this is enhanced with variable fan speeds and coolness settings). Fourth, R.H. % is lowered along with the dry bulb temperature and this double-action hastens the process of achieving comfort conditions. The biggest drawback, however, is that unit air conditioners powered by electricity add to an already critical peak electrical demand problem, unless off peak storage is implemented. This particular issue is one of the primary motivations for this thesis investigation. Other drawbacks include the fact that conventional a.c. units offer no payback on their investment - since it uses increasing expensive electricity to motivate it.
In addition, in a retrofit situation the tenant will often opt to install the unit in the existing window rather than breaking through a new hole in the existing wall.

This often renders the window unusable at times when outdoor air could be brought in to achieve cooling, necessitating an even greater use of the unit. When the a.c. unit is retrofitted into an existing window this often lessens natural lighting and blocks part of the view. Lessening daylight increases the need for artificial lighting and this generates more internal gains that must be removed.

Ventilation Fans

The cooling effect could be achieved by simply employing an 800 c.f.m. fan and running it at night when the ambient air temperature is lower than the indoor air. The initial cost for a typical apartment, the size found at 132 Chandler Street is approximately $250. The operating costs for running this system are small (less than $20. for the summer). However, this scheme is of no benefit during the heating season which eliminates it for consideration of achieving a year-round payback.

Air to Air Heat Pump[14]

In theory, the air-to-air heat pump appears to be an attractive alternative for use in both heating and cooling seasons. It has a high degree of control much the same as the unit air conditioner. In the heating season several problems occur when the outdoor air temperatures go below 40°. First the Coefficient of Performance [(C.O.P. = B.T.U. (delivered)/B.T.U. (req'd. to operate)] quickly falls from 2.5 at 40° F to approaching 1.0 around 30° F. This means that the benefit of using this method are no better than electric resistance baseboard heating. Secondly, a back-up system is needed for these colder conditions. This amounts to a minimum installation cost of $2500 for a 1,000 SF apartment in Boston for the heat pump plus the cost of the back up heating system - an expensive investment.

In the winter conditions where the humidity is high and outdoor air temperatures are below freezing, icing of the outdoor heat exchanger coils is a common problem. This hurts the performance in a condition that is already marginal at best. To avoid this the air to air heat pumps "reverse cycle" during icing and start "air conditioning" the interior. The effect of this is to warm the coils and melt the ice. The inefficiences of having to do this very often are obvious. The frequency of this "reverse cycling" should be known to best assess this problem. Third, in the summer the air to air heat pump has virtually no efficiency advantage over a conventional thru-the-wall a.c. unit. The exception would be if the conventional a.c. unit were of a low Energy Efficiency Ratio [(E.E.R. = B.T.U.(removed)/watts(req'd to operate)] then the type heat pump would prove to be superior because they tend to be expensive (of higher quality) and efficient units. If the heat pump were not an air to air type but rather a water to air, with a year-round heat source (such as deep water) the advantages would be theoretically cost effective. Finally the biggest problem implied is that the the heat pump uses the same energy to achieve cooling as the conventional a.c. unit and the heating advantage doesn't exist for the coldest winter months. This is no progress towards reducing the aggregate peak electrical demand.

<u>Solar Collectors</u> (liquid/air)

The biggest problem with active solar systems is to find a cost-effective system with reasonable payback. In general, the air type collectors are the Cadillacs of all low temperature active solar collectors. They require expensive ducting and valuable space though they are extremely desired by homeonwers, etc. due to their low maintenance factors. A hydronic system (liquid-type) represents a greater frequency-of-repair problem but is less in total cost as an installed system. In the Boston area the per foot of collector cost is rarely below $20, installed, making this system an expensive proposition.

Economizer Cycle through Stack Effect

An increasingly frequent practice in the planning of HVAC systems is to utilize the principle of using cool night time outdoor air to achieve "economizer cycle" cooling where air conditioning is a year round requirement. This can be normally employed at times of the year when the outdoor air drops to 55° or below which is 20° (summer) and 13° (winter) below the design dry bulb temp. Theoretically, outdoor air with temperatures above 55° could be introduced as pre-cooling for the chillers up to the point when outdoor air temperatures rises to inside temperatures. However, in current practice this is not done because: (1) the economizer cycle controls are normally designed to open the intakes only when the design chiller a.c. supply air temperature of (55°) equals outdoor air temperature. This provides 100% space conditioning if the R.H. % is acceptable. Being able to bring in varying amounts of outside air for those temperatures between 55°-75° (or 55°-68°) would be desirable if this were to serve spaces (such as office perimeters) that have an a.c. load that increases as ambient air temperatures increase (such as office perimeter zones) due to solar loads. To use this range of outdoor air temperatures for interior zones with constant loads yields a benefit that decreases as the outdoor air approaches the indoor air temperature.

One way to make this more feasible is to use higher volumes of air. In offices this is limited due to the noisy annoyance of high c.f.m. of air movement. When possible, using the cool, filtered air spares the use of expensive chillers, lowering the energy operating costs.

Housing, however, is a more favorable application. This is due to the fact that the distance of the windows to the innermost interior zones will rarely exceed 25 feet. This allows for a good penetration of cooler outdoor air to these zones where excessive heat generation from internal gains often occurs. High and low rise offices are often 2-3 times deeper than this dimension and 100% fresh air can rarely be achieved by simply opening windows.

Stack Effect Potential

Cooldown simulations[c] show that in our typical apartment on Chandler Street a consistent air change rate can be achieved by Stack Effect. Stack Effect is the air movement into, out of or through a building caused by thermal forces. Heat building up in particular parts of a building such as in a stairwell or vertical shaft causes a relative high pressure in the local area. The heat sources can be from internal courses such as gains from mechanical equipment or external ones such as solar radiation. As the bouyant high pressure is relieved to the out-of-doors, its exodus induces an air movement in the direction of its departure. This causes a cooler, less bouyant air to occupy the same area where it too is heated and the air movement is continued.

The required air change rate is approximately 7/hour, for average July conditions, and equals 98 f.p.m. (784 cfm moving through an 8 SF opening or 6 f.p.m. moving through the apartment. The fundamental relationship that describes stack effect is:

$$Q = 7.2\ A \sqrt{(T_s - T_a)\ h} \times (60 \times .018) \times (T_i - T_a) \qquad (14)$$

where: Q = max. B.T.U. removable from space, BTUH

A = free area of stack inlet and lutlet opening. (When these are not equal areas correct Q by factor shown in Fig.5. Appendix

h = stack height (center outlet-center inlet) height difference, Ft.

T_a = outdoor air temp., °F

T_s = stack air temp., at outlet, °F

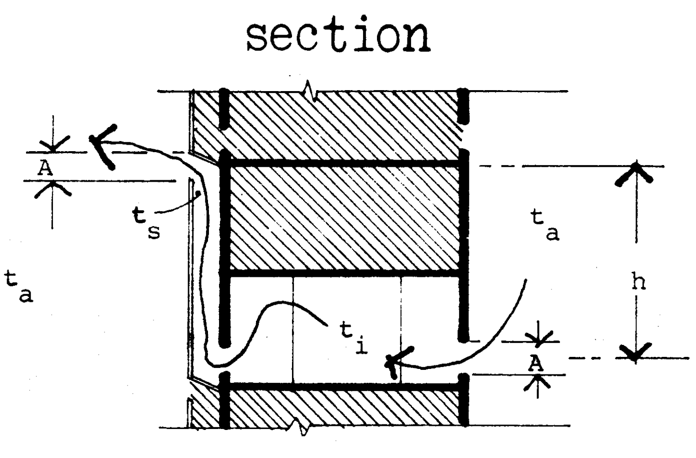
T_i = indoor air temp., °F

.018 = air heat capacity, BTUH/Ft^3 - °F

60 = conversion factor, mins./hr.

7.2 = empirical constant of proportionality for a 50% effectiveness of openings (use 9.4 for 65%)

Schematically this is represented in a section of 132 Chandler Street as:



34 STACK EFFECT SCHEMATIC

The minimum (T_s - T_a) required to remove the typical amount of BTUs due to the measured internal gains is less than 4°. [The highest recorded hourly gains were equal to 10,000 BTU (= 3 kwhr) and this would require a (T_s - T_a) of 13.4° to remove this heat. A sunny day in July provides a 17° ΔT average for the hours of 7 pm to 6 am and this is sufficient to remove even extremely large outputs of internal gains.] An average July day results in a 10°ΔT which results in an average heat removal rate of 6500 BTUH.

With this potential established several questions arise concerning cool-down of the apartment mass. Among them are:

1. In addition to removing heat generated instantaneously, how high an R.H. % can be compensated for by the predicted air movement?
2. How to maintain the effectiveness of openings to utilize stack effect through the apartment.
3. How can this stack effect be best achieved in buildings typified by 132 Chandler Street?

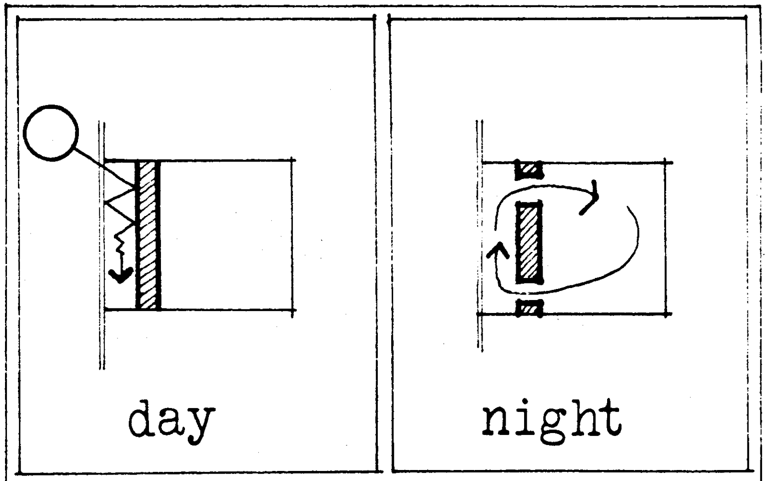
Mass Wall: Classically

A logical surface to use for stack effect is the existing brick exterior wall (see Fig. 6). Since it is existing, its inherent large thermal mass and present absorptivity (α = .6) make it a valuable solar element commonly found in existing multi-family construction. Wall orientation, surrounding reflections and shading at existing conditions are of course the cutting edge in considering the feasibility of this scheme. This brick when covered with a transparent glazing to hold heat in the wall will turn the wall into a crude solar collector and stack plenum. Traditionally the Trombe wall uses this vertical, south-facing, mass wall to collect and store solar heat for space conditioning (Fig. 35).

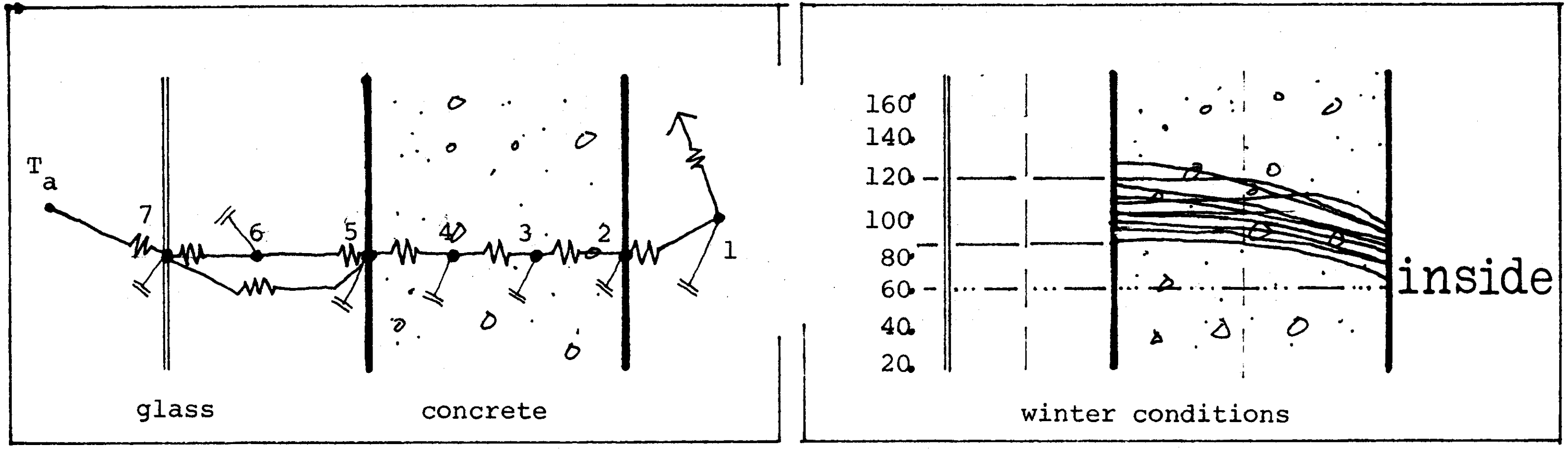
Classically, however, this system has had several problems:

1. It eliminates south views despite large south glass areas.
2. It requires an optimum thickness of 12" for the south wall. This is impractical and expensive for multi-story construction.
3. Heat migration to the interior face of the uninsulated south wall was low and solar heating fractions predictions for Boston are ≯ 57%.[15]
4. Large heating back losses out the glass cover constituteed a large part of the system inefficiency.

Typical heat migration for a Trombe wall on an average January boston day would be:(Fig. 36). Figure 36 shows the temperature profiles of each node at each hour. Each line represents the temperatures of all homes connected to gether at any given hour. The hours shown ar at 2 hour intervals for a 24 hr. period. No insulation is assumed on the inner face of the mass wall. The outside surface of the mass wall undergoes a temperature excursion of 120°-35° = 85° from just before sunrise to 4 pm, while the inside surface undergoes an excursion of 85°-60° = 25°. The principle solar engineering problem is clearly how to optimize heat retention in the wall by increasing thermal mass while maintaining a thin enough



35 MASS WALL OPERATIONAL SCHEMATIC



36 CLASSIC TROMBE WALL - TERMINAL NETWORK AND SUNNY DAY HEAT MIGRATION

section to allow the maximum amount of heat to migrate through to the inner face of the wall warming the room to within comfort boundaries. Felix Trombe suggests that for the experimental houses built in Odeillo, France the optimum thickness of concrete is 40-45 cm (16"-18").[15] Douglas Balcomb at the Los Alamos Solar Laboratories suggests (12"). With "smaller thicknesses the wall has too little heat capacity and temperature fluctuation on the inner surface are excessive. With larger thicknesses comfort and cost are increased but performance is decreased due to thermal isolation of the front portions of the wall from the building interior ...."[15]

Mass Wall: Adopted to Existing Housing

To utilize a modified Trombe wall in an existing building typified by 132 Chandler St. additional problems are posed:

1. The existing mass wall is not 12" thick monolithic concrete or solid concrete block. Commonly found in the South End are two wythes of 4" brick - one a face brick, the other common brick with no wall cavity. With the wall thickness as a given, this creates a special problem of controlling heat migration through the wall particularly in the summer when ambient air temperatures are high.

2. With less mass to hold the heat back, losses through the transparent glazing covers are increase .

3. Using this system for its stack effect in the summer as well as thermosiphon heating in the winter requires that the air movement in the apartment be relatively unobstructed by existing walls and partitions. This means effective air-passageways must be provided for retrofit applications.

4. For existing buildings window openings, bay window shapes, fire escapes, gutters, ivy, etc. must be taken into consideration as elements affecting the system performance since they occupy space or shade the mass wall. The solar heating fractions and effectiveness of stack effect are directly dependent on these characteristics of the south wall composition.

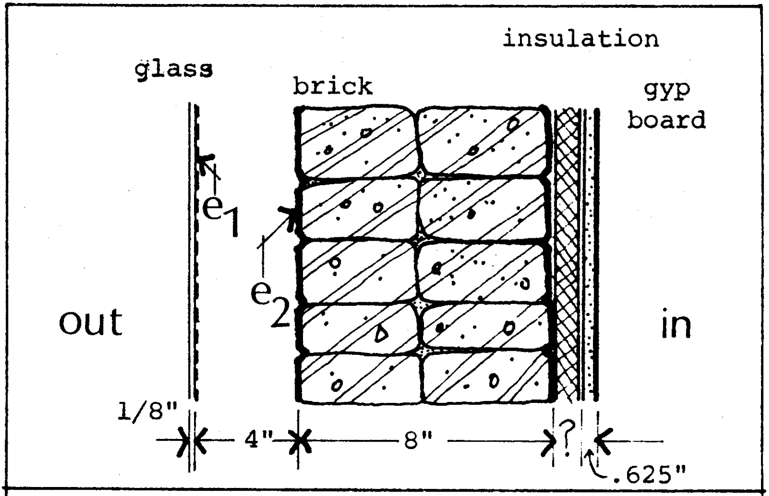
5. Cost savings can be increased for the system if the tenants participate in operating the system. The success of this is affected by their interest and the direct benefits to them, as well as their availability and the time required for its operation.

These and other problems and potential solutions are discussed in the following chapters to assess the feasibility of implementing a mass wall scheme in Boston's multifamily housing.

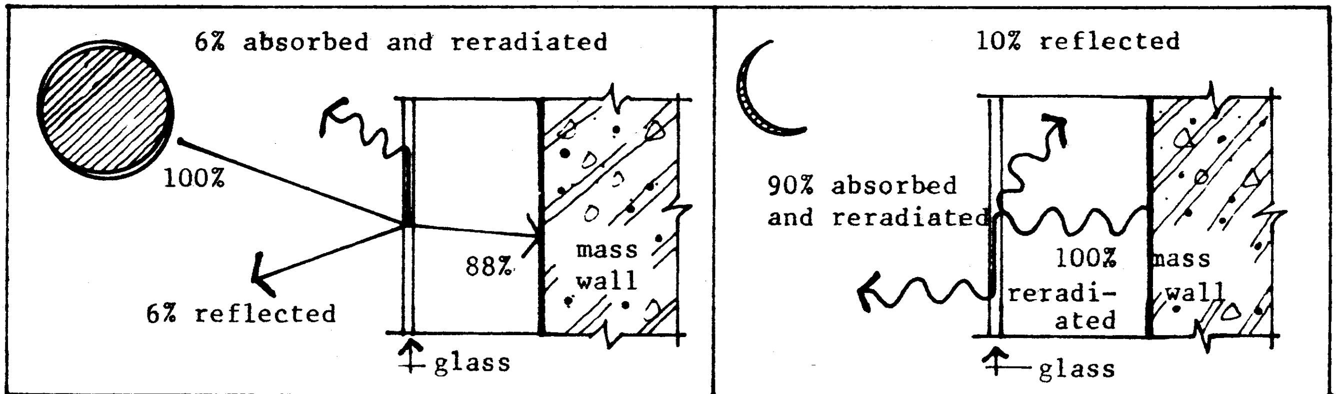
7

IMPROVED GLAZING

Figure 37 is a typical wall section of a glass covered wall as described in the previous chapter. In order to evaluate the type of glass that could be used, some interesting properties of glass are discussed at this point.



37 WALL SECTION



38a 1/8" REGULAR GLASS - TYPICAL DAY/NIGHT RADIANT HEAT BEHAVIOR

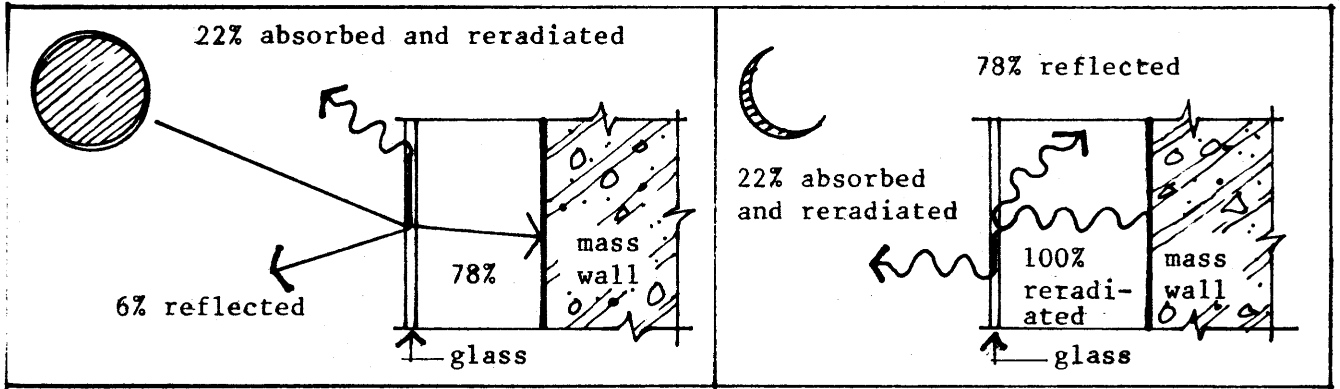
Regular glass is shown in Fig. 38a with its typical thermal behavior while being hit with solar radiation (at .4-2.2 mμ). The regular glass doesn't trap solar radiation inside the air space between the glass and brick as it is commonly thought to do. Rather at night or in cold weather it reflects a relatively small percentage of the longwave radiation from the wall and absorbs the rest. A small amount of this energy in the glass is re-radiated back to the wall but the bulk of it is re-radiated to the cool night sky or swept away by outdoor air currents. The final effect to the occupant of the solar building is that the sun energy being held in the mass wall is lost back out to the outdoors at a rate that significantly cuts down the amount of heat available to be conducted to the inside.

The most easily conceived solution to this problem is to start building up layers of glazing membranes (double, triple, etc.). This however becomes very expensive very quickly. It also causes a considerable increase in weight to support and each additional layer of glass cuts down solar transmission reaching the mass wall. An alternative is to suspend thin membranes of highly transparent material to increase the u-value of the glass by adding air gaps without sacrificing the transmission. The transmission is not appreciably lost since the membranes are of higher transmissivity than glass. Two problems arise out of this application. The first is that the additional membranes require additional stretcher frames that must be included in the glass assembly. This complicates the installation process. The second is that it is very difficult to get the plastic membranes wrinkle-free. With wrinkles (even with including a matte surface on the exterior face of the glass) the appearance from street level on a sunny day is dominated by a look of "plastic saran-wrapped brick" and is rather tacky in appearance. No matter what it's solar/thermal performance, a system that appears fragile and insubstantial will not be accepted with great public enthusiasm or confidence.

The last obvious method is to eliminate the insulation altogether on the inside face of the brick and let as much heat as possible migrate through the brick wall to the interior (Fig. 36). As previously mentioned this thermal flywheel effect has many inadequacies. (See following sections on optimization of weather wall insulation.)

A recent development in glass manufacturing has made available a selective coating for glass surfaces that circumvent nearly all of the above drawbacks. The new glass contains a heat mirror coating and lowers the thermal back-loss from mass wall re-radiation when used as the glazing cover. A 1/8" double strength heat mirror glass has properties shown in (Fig. 38b). By comparing Figure 38a with Figure 38b it is clear that the difference between the two glasses is significant in two areas:

38b



1/8" HEAT MIRROR GLASS - TYPICAL DAY/NIGHT RADIANT HEAT BEHAVIOR

1) the heat mirror glass transmits only 89% of what regular glass does. However,
2) the heat mirror glass reflects radiant heat from the wall 6 times better than regular glass.

Another way to analyze this is to compare the effective emmittance of the assembly (air space, glass and brick surfaces) (Fig. 37) by knowing the emissivity of the two surfaces facing each other across an air space. This is described by:

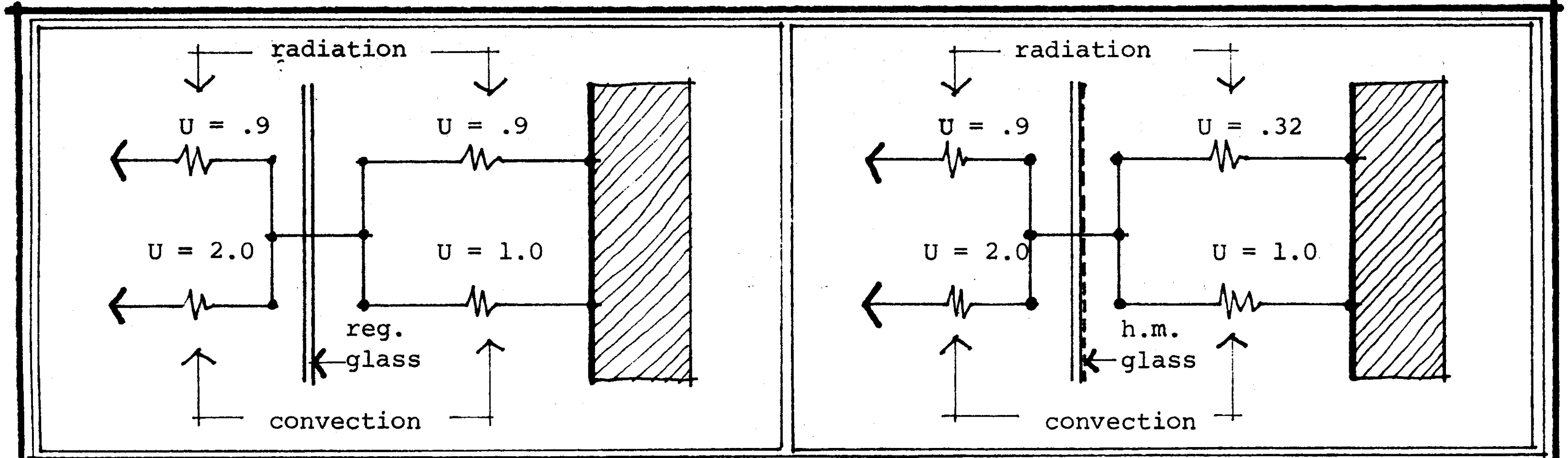
$$E = \frac{1}{1/e_1 + \frac{1}{e_2} - 1}$$

where E = the effective emmittance of the air space.
$e_1 e_2$ = emittance properties of materials.

MATERIAL	e
reg. glass	.9
h.m. glass	.3
brick.	.9

Thus for the two cases we have:
E of heat mirror glass and brick = .29
and E of regular glass and brick = .82.

These effective emittance ratios are multiplied by the theoretical emissivity of a blackbody at average collector temperatures which equals 1.1 BTUH/ft^2 °F. Thus, .82 x 1.1 = .9 and .29 x 1.1 = .32 are the respective heat transfer coefficients for radiation. Diagramatically we have Figure 39 . Next, the parallel resistances and then the series resistances are solved. The resistance due to either glass material is negligible and not considered in the schematic. For regular glass we have a u = .29 in series with a u = 1.9 which when added together by taking their reciprocals, equals an R = .87 or u = 1.15. For the heat mirror glass we have a u = 2.9 in



39 U-VALUES OF GLASS ASSEMBLIES FOR REGULAR GLASS AND HEAT MIRROR GLASS

series with a u - 1.32 which equals an R of 2.20 or u = .45 BTUH/SF.°F. Therefore the ratio of the u-values of the glass is $\frac{1.15}{.45}$ = 2.6. Thus the overall conductivity of regular glass is 2.6 times greater than heat mirror glass in this particular assembly. Simulation 82 (Fig. 45) is a graph of Figure 37 comparing the heat glass to regular glass for a sunny day in January at our Chandler Street south wall. The significant differences in temperature can clearly be seen for the two glazings and their corresponding air spaces and brick walls. Important to note is that for the hours after sunset the temperature differences maintain a constant relationship even as they cool down; and the heat mirror scheme runs 10° warmer in the air space.

8

(2) SOLAR SYSTEM SCHEMATICS

Figures 40 and 41 are operational schematics of the indirect gain mass wall scheme and the direct gain system used in the modeling of the apartments.

a Indirect Gain Mass Wall Scheme

The mass wall works in both summer and winter. In the summer, the wall creates a chimney effect that draws cooling air through the apartments at night. In the winter, the mass wall has small vents that are opened to allow solar heated hot air directly into the apartments by thermo-siphon effect, and a small duct and drafless fan circulate heat to the north rooms.

Details of Operation:

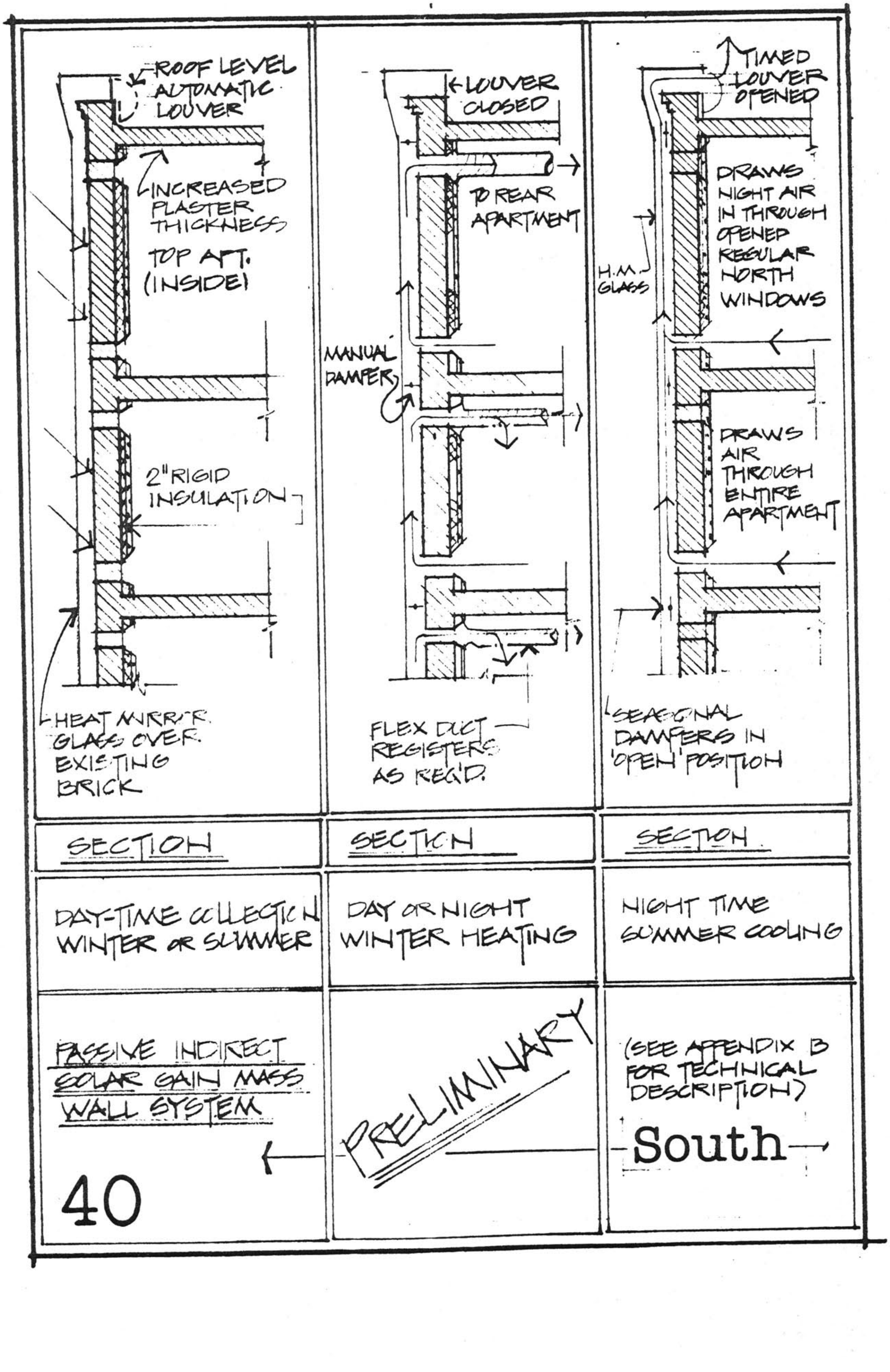
Summertime Cooling: The summertime cooling scenario is this: between the hours of 9:00 am to 7:00 pm the solar plenum (between the glass cover and brick wall) is closed with a cabinet-type door and sunshine builds up heat within the brick wall during the day. Temperatures peak on a sunny day at the brick surface at 146° and at 90° on a cloudy day (based on simulations). In the evening, in order to benefit from the stack effect cooling with night air, the tenant opens his regular north windows. Then he opens the cabinet type door at the opposite end (South end) of his apartment which opens into the solar plenum. This is the extent of the tenant's involvement. The next morning he reverses this. (The solar wall cabinet doors are in addition to his regular windows and do not affect view or normal window operation.) The tenant pre-cools the apartment with night air letting the apartment mass soak up heat during the day. The tenant can always override the system by opening the regular windows.

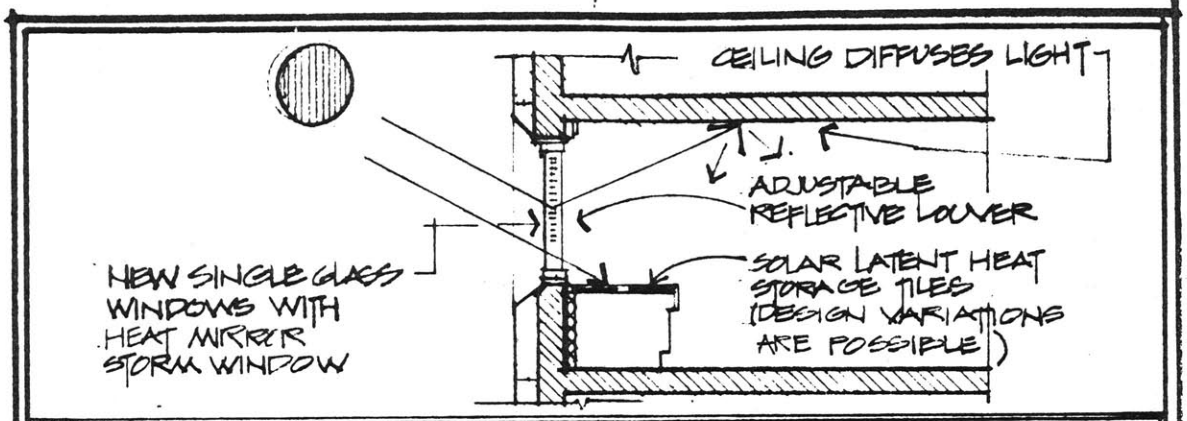
Window Heating: When the seasons change and the apartment needs to change from cooling to heating a thin plenum damper is manually turned by each tenant to portion off the solar plenum that corresponds to his area of the south wall. The wintertime heating scenario is this: in the morning the tenant opens the same solar plenum door used for cooling and a second solar plenum door both of which allow for thermosiphoning as supply and return openings. (A low-draft fan and small insulated duct is added to insure good mixing of heat throughout the apartment to the north rooms.) At night these doors are closed.

b

1(b) Passive Direct Gain System

A second system is included that utilizes the solar energy available at the window areas. This system is represented schematically in Figure 41. Sunlight is reflected to the ceiling with thin light modulating reflective window louvers. These louvers can be lowered or completely raised by the tenant. The window glass will be made up of heat mirror glass to slow thermal losses through these glass areas. Solar energy will be reflected to the ceiling where it will be diffused from a light colored ceiling onto thickened wall/ceiling surfaces of good thermal mass. Solar tile window seats will be used in the existing bay window areas. This system is attractive since it utilizes the existing bay windows by improving the glass U-value and simply adding reflective louvers to the inside of the window assembly. The vertical glass is particularly good at selectively admitting solar energy at low winter angles and reflecting solar energy due to large angles of incidence in the summer. The estimated heating bill savings is equal to 28% annually,

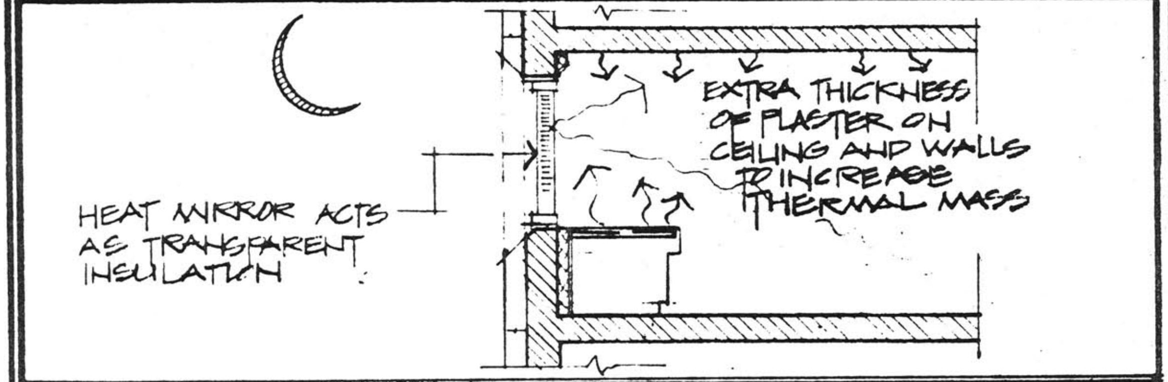

ROOF LEVEL AUTOMATIC LOUVER
INCREASED PLASTER THICKNESS
TOP APT. (INSIDE)
2" RIGID INSULATION
HEAT MIRROR GLASS OVER EXISTING BRICK
LOUVER CLOSED
TO REAR APARTMENT
MANUAL DAMPER
FLEX DUCT REGISTERS AS REQ'D.
TIMED LOUVER OPENED
DRAWS NIGHT AIR IN THROUGH OPENED REGULAR NORTH WINDOWS
H.M. GLASS
DRAWS AIR THROUGH ENTIRE APARTMENT
SEASONAL DAMPERS IN 'OPEN' POSITION
SECTION
SECTION
SECTION
DAY-TIME COLLECTION WINTER OR SUMMER
DAY OR NIGHT WINTER HEATING
NIGHT TIME SUMMER COOLING
PASSIVE INDIRECT SOLAR GAIN MASS WALL SYSTEM
PRELIMINARY
(SEE APPENDIX B FOR TECHNICAL DESCRIPTION)
South
40



SECTION

DAY COLLECTION IN WINTER
LOUVERS DIFFUSE SUNLIGHT ONTO CEILING

(TYPICAL FOR ALL SOUTH FACING WINDOWS)

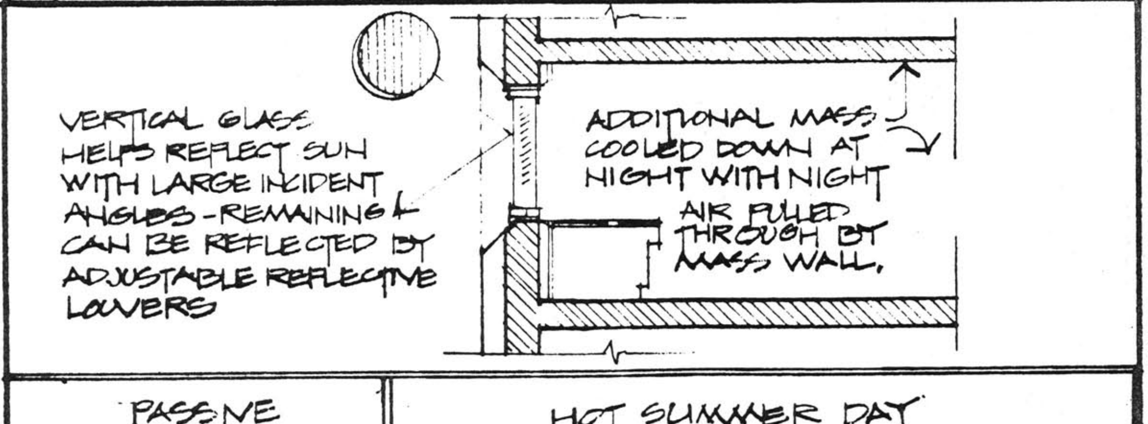


SECTION

WINTER HEATING AT NIGHT OR CLOUDY DAY

PRELIMINARY

(SEE APPENDIX B FOR TECHNICAL DESCRIPTION)



41 PASSIVE DIRECT GAIN SYSTEM

HOT SUMMER DAY

← South

above the indirect system mentioned previously. The heat mirror glass, louvers and storage system will only be used in the rooms facing south. Since the heat mirror is an effective heat barrier for any glazing opening this should also be used at north facing windows as well.

9

PROGRAM MODELLING

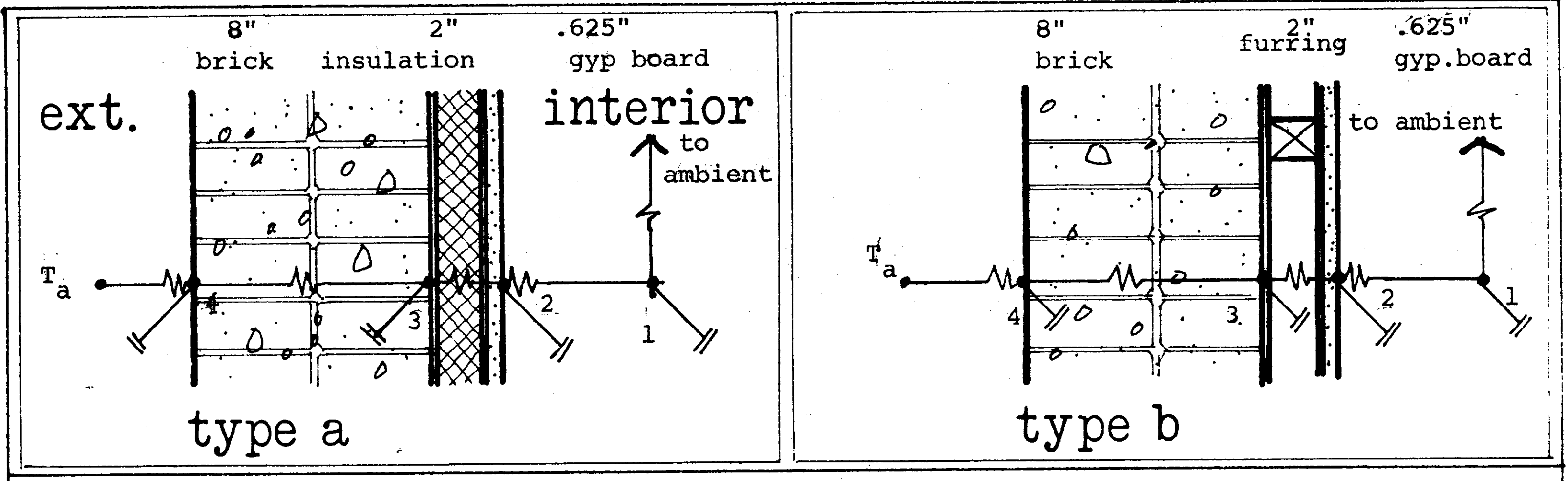
The modelling of heat transfer in the mass wall scheme and conventional schemes is done with a numerical thermal network algorithm. This algorithm is published as a hand calculator version, called TEANET. [c]

The program consists of a matrix comprised of a maximum of seven nodes. A node is a location at the interface between two different materials or at selected intervals within a single material. These nodes are connected together by a thermal conductance in such a way that the heat flow between them is linear with temperature. In addition, each node has a particular capacitance associated with it.

The program starts by using a set of assigned temperatures for each node. Then, outdoor air, losses to outdoors from indoors, sunshine and all intra-nodal computations are made. The result of the program is an hourly report of each nodal temperature plus environmental conditions and any auxiliary heating/cooling required to maintain a specific node at a pre-selected temperature. The program is particularly valuable due to the fact that heat transfer coefficients for radiation, conduction and convection can be discretely specified in the setup of the numerical matrix.

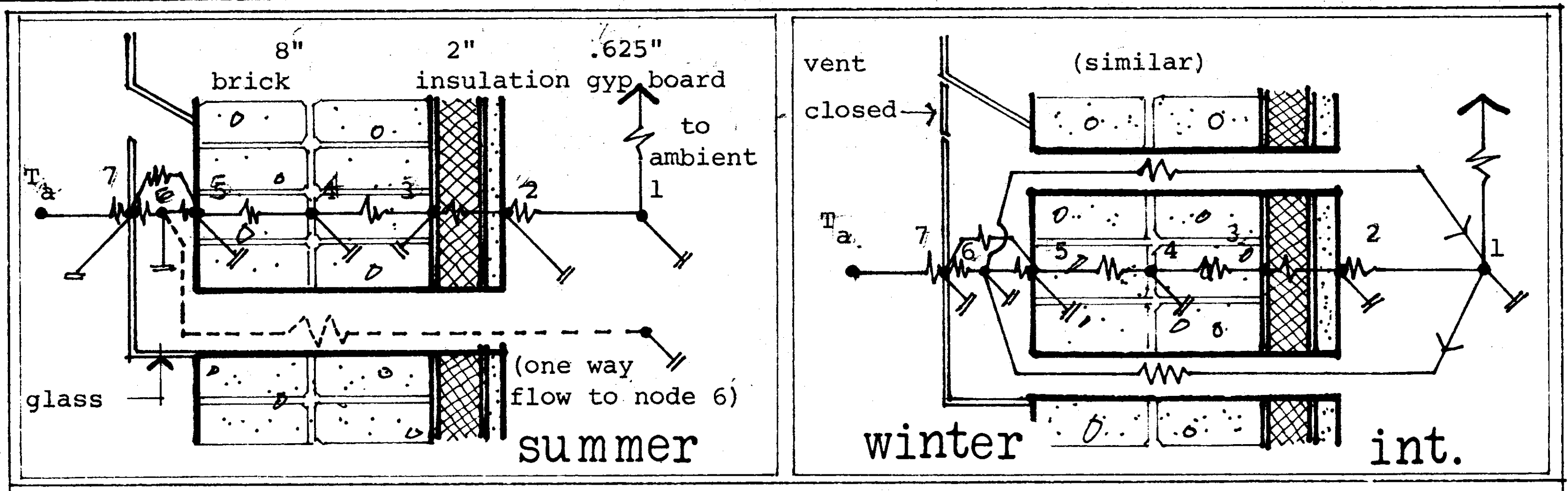
a Specific Networks used in Theoretical Modelling of the Mass Wall Scheme

The fundamental networks used in the apartment modelling are diagrammed in Figure 42 . This is based on the weather wall construction found at 132 Chandler



42 SCHEMATIC NETWORKS FOR (2) CONVENTIONAL CONSTRUCTION TYPES

Street. This particular example is also referred to as Scheme B in the next chapter. A thermally superior type of construction is diagrammed below and is later referred to as construction type C. Figure 43 represents the networks that model the glass-covered mass wall scheme. In hot weather the capacitance of node 1 is determined by the total mass of wall and ceiling plaster in the entire apartment. The other nodes are self-evident except node 6. [Since the stack effect induces a one way flow of cool night air through the apartment the node at the air space (between the glass and brick) can not be connected directly to the indoor air node. This is due to the fact that the simulation balances the heat flow between the nodes, which raises the indoor air unrealistically. To skirt around this problem, a spare node is used to feed into the stack air node. On an hourly basis it is corrected with a temperature equal to the previous hours indoor air temperature. The



43 SCHEMATIC NETWORKS FOR type c SIMULATION: HOT DAY (LEFT) AND COLD DAY (RIGHT)

resulting simulation provides results that are intuitively expected.] The winter network (Figure 43) is simpler. The collector air is assumed to exchange freely with the indoor apartment air as motivated by the thermosiphon effect.

This happens in the model when the temperature at node 5 is at least 5° higher than node 1. When it is lower the free exchange is stopped and stagnation is simulated. This parallels real usage when, for instance there is no more heat to be brought into the apartment from the solar wall and the solar wall openings are closed.

Modelling of 132 Chandler Street

Binary temperature records made at 132 during the summer of '78 make it possible to match simulations with real temperature data. This was done and several interesting phenomena were learned:

1) The air change rates during an extremely warm period were either .5 or 4.0 per hour. The 4/hr. rate was normally at hours when the sun was not shining. This indicates that the people in the apartment are opening and closing the windows to keep it comfortable. With the simulation and real records the pattern of hourly usage was established. The proposed system requires the occupants to open and close the system twice a day at similar times as records show normal windows were being opened and closed.

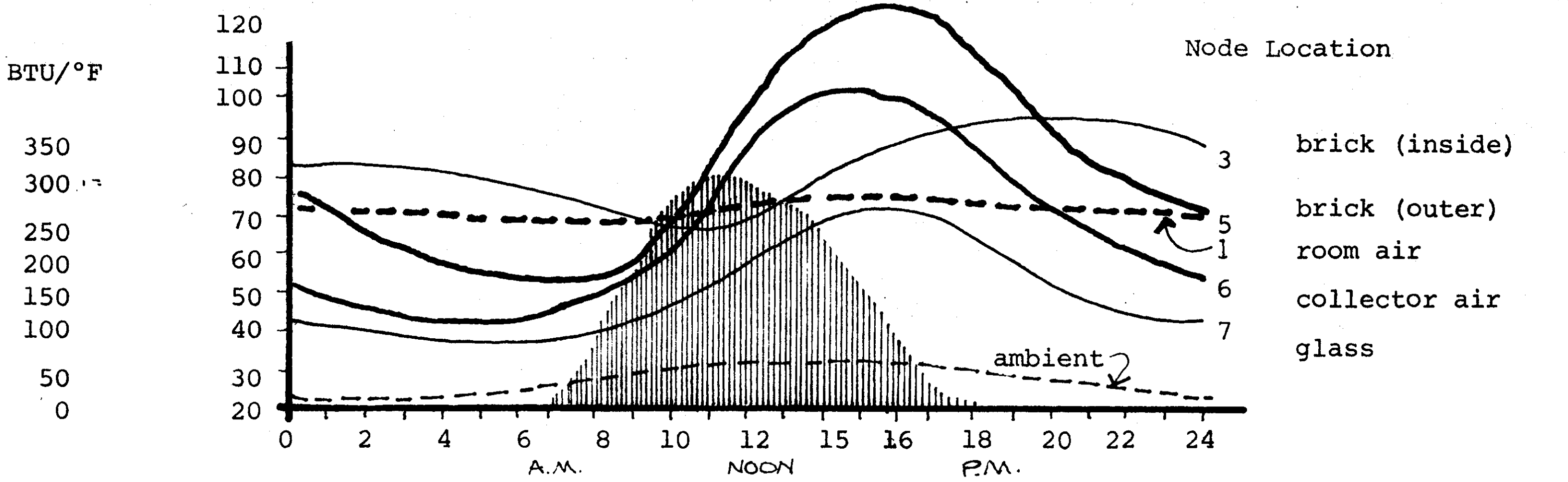
2) According to the simulation, the brick building wasn't doing a very good job of keeping the apartment cool. The large amount of thermal mass available in the common walls was apparently insulated from plaster walls. (This probably happened because an air space was created by furring strips used to nail the plaster backing board to.) Simulations show that this small amount of plaster when modeled would produce results similar to those recorded.

3) Apparently mechanical ventilation in the kitchen area was not used, and gains from the kitchen and other heat intensive areas could also account for the high temperature profiles.

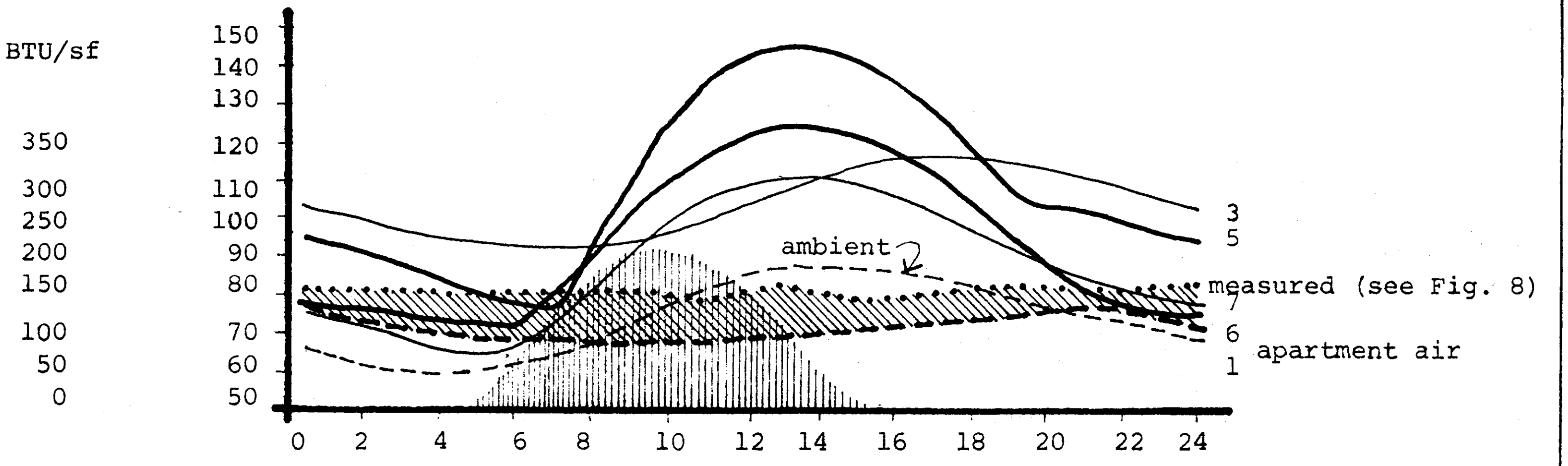
b Simulations of Interest

Figure 44a is the winter simulation similar to Figure 44b the summer. These two represent typical 7-node conditions for their respective seasons and indoor air temperatures are interesting to note. (Both simulations use regular glass as the mass wall glazing.)

As previously mentioned the mass wall scheme achieves an average 4.5° temperature reduction compared to what 132 Chandler Street was recording in the summer bringing it back inside the comfort zone (see Figure 15). In the winter the collector air temperature and brick surface temperature are significant. The



44a PROPOSED MASS WALL SCHEME C: WINTER SUNNY DAY SIMULATION



44b PROPOSED MASS WALL SCHEME C: SUMMER SUNNY DAY temperatures reflect winter conditions on a sunny day. This results in the highest temperatures. In reality cloudy and partly cloudy days must be accounted for. Start-up temperatures must also reflect whether the previous day was cloudy or sunny. The performance estimates outlined in Chapter 11 weighted these last two factors and integrated them into the conclusions of performance.

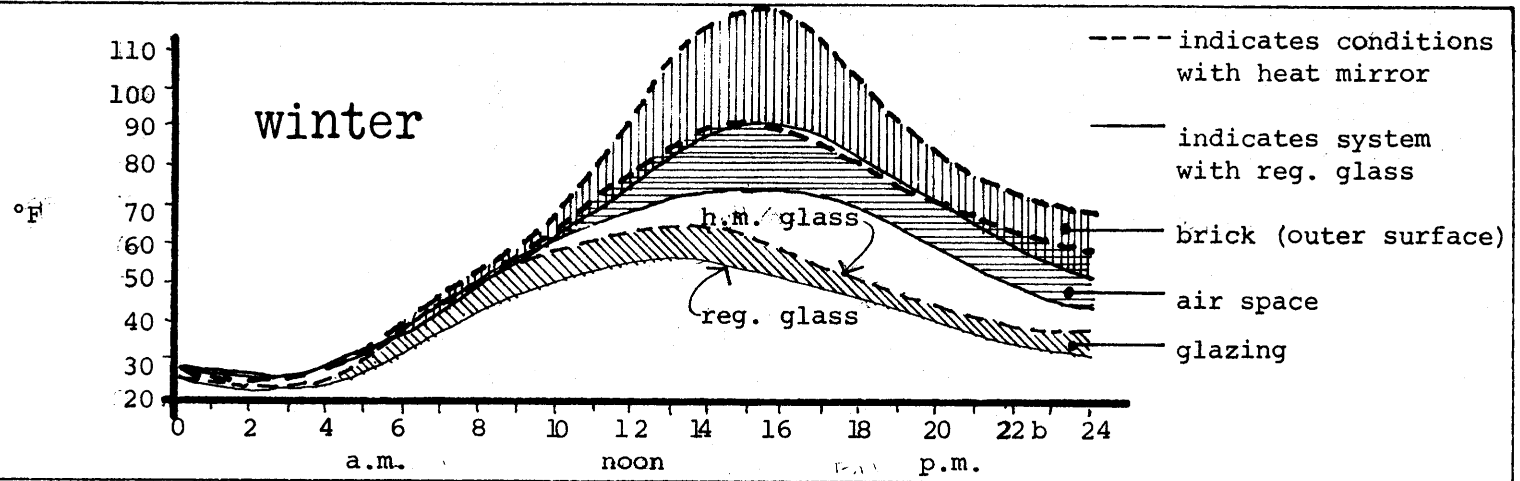
Performance of Heat Mirror Glazing vs. Regular Glazing

Figure 45 is a comparison of the glass, collector air space and brick temperatures of regular 1/8" double strength glass with 1/8" double strength heat mirror glass under stagnation conditions.

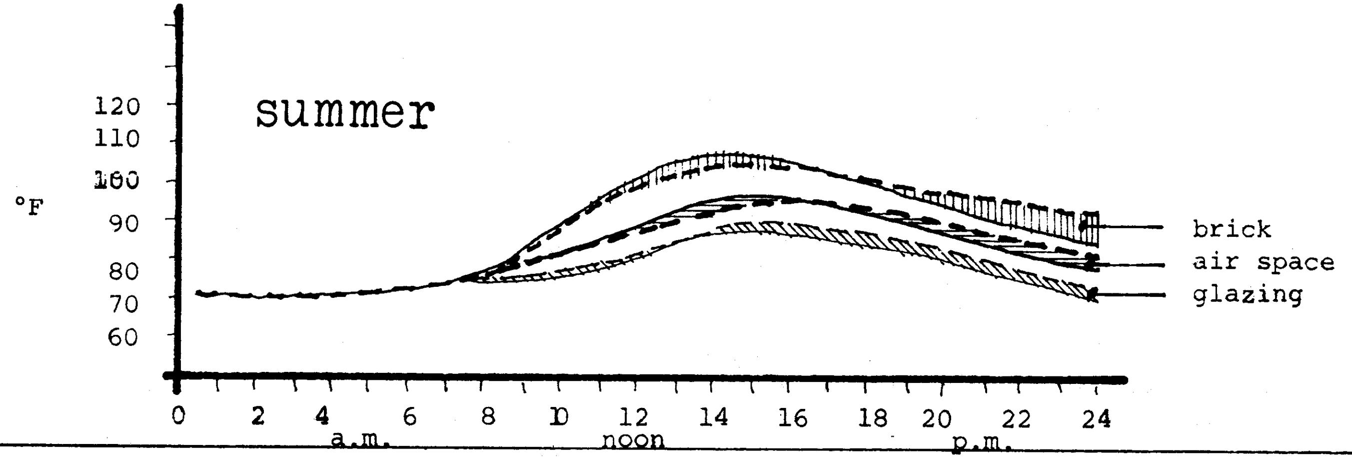
The beneficial effects of heat mirror can be clearly seen particularly in its ability to slow heat losses from the brick mass at the hours beyond 15 (3 pm).

Stack Effect

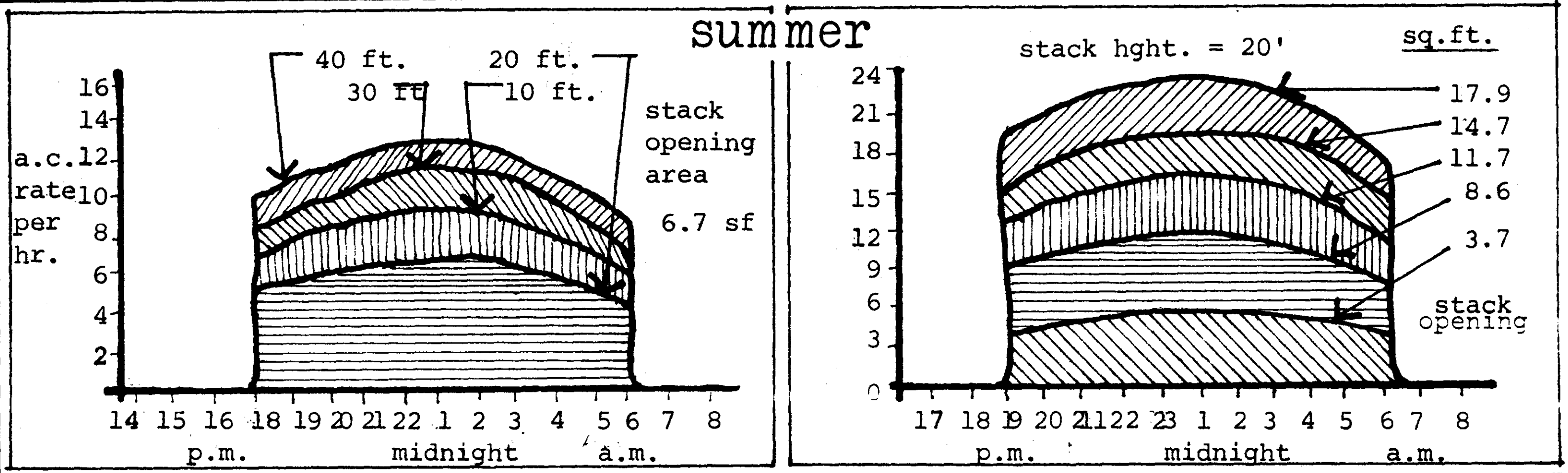
Referring to the schematic in Figure 34 and Equation (6) it is apparent that the A (area of openings) and h (height differential) can be sized to provide an air rate as required by the amount of internal gains to be removed. Figure 46 is a graph of the resulting air change rates. This chart can be used for sizing based on an apartment volume of 6720 ft^3. As is obvious from the equation, changing the inlet/outlet area has a bigger impact on the rate of BTU removal than changing the stack height.



45a REGULAR GLASS VERSUS HEAT MIRROR GLASS AS A VERTICAL GLASS COVER WITH CLEAR SKY CONDITIONS



45b SIMILAR



46 STACK EFFECT VARIABLES AND IMPACT UPON A.C. RATE (SUMMER)

10

OPTIMIZING APARTMENT INSULATION AND MASS

a Optimizing Insulation at Weather Walls

Summer

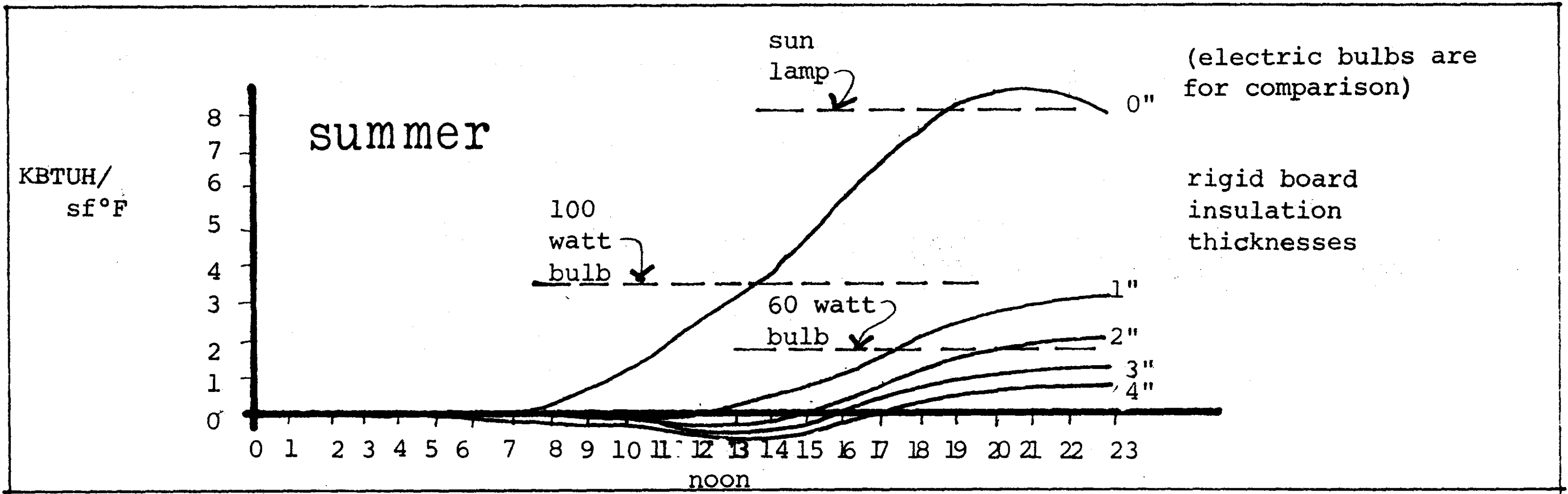
The selection of optimum insulation at the weather walls must be analyzed with respect to two (2) conditions: average hot day and average cold day for the Boston climate. To analyze the summer problem, simulations were run for 0", 1", 2", 3" and 4" of rigid insulation at the location designated ? in Figure 37. The purpose of the simulation is to see how much unwanted heat is added to the room by the heat's migration through the mass wall and plaster. See Figure 47 for a summer day when the temperature averages 75° with a temperature amplitutude of 14° for the 24-hour period.

Clearly if an overheating problem is present in these apartments the heat migration must be kept as low as possible. Any insulation less than 2" is clearly unacceptable and the difference between 3" and 4" is not significant. Therefore 3" would be an ideal amount for critical summer periods.

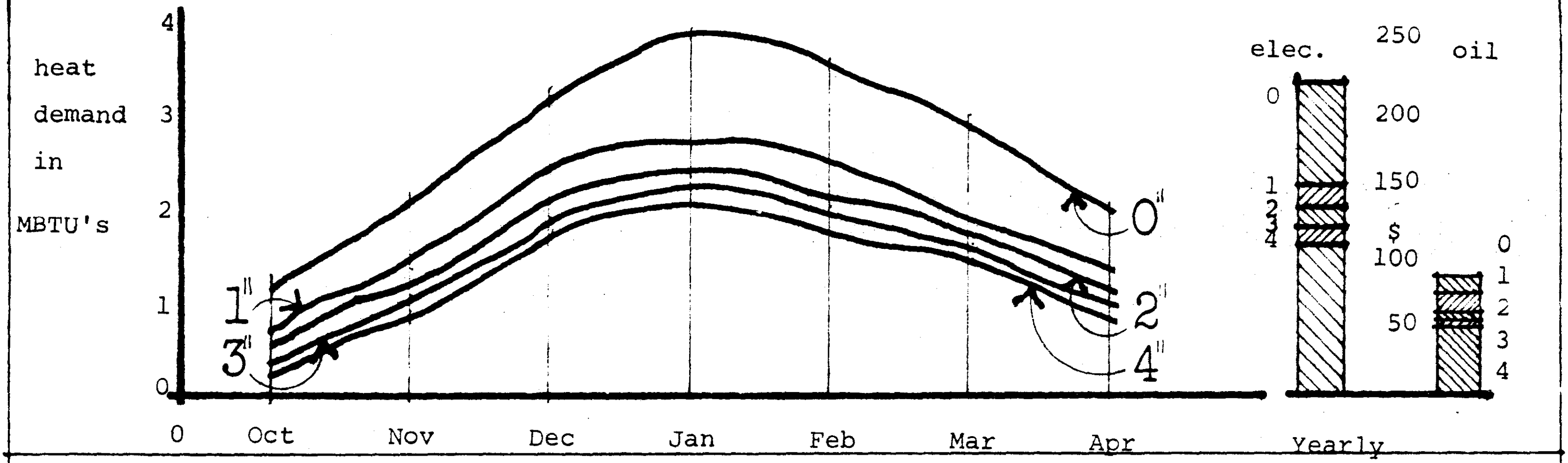
Winter

Winter is a more difficult period to evaluate since the question of infiltration and south wall galss u-values are constantly varying. For calculation purposes one can assume that the values in Figure 48 are typical.

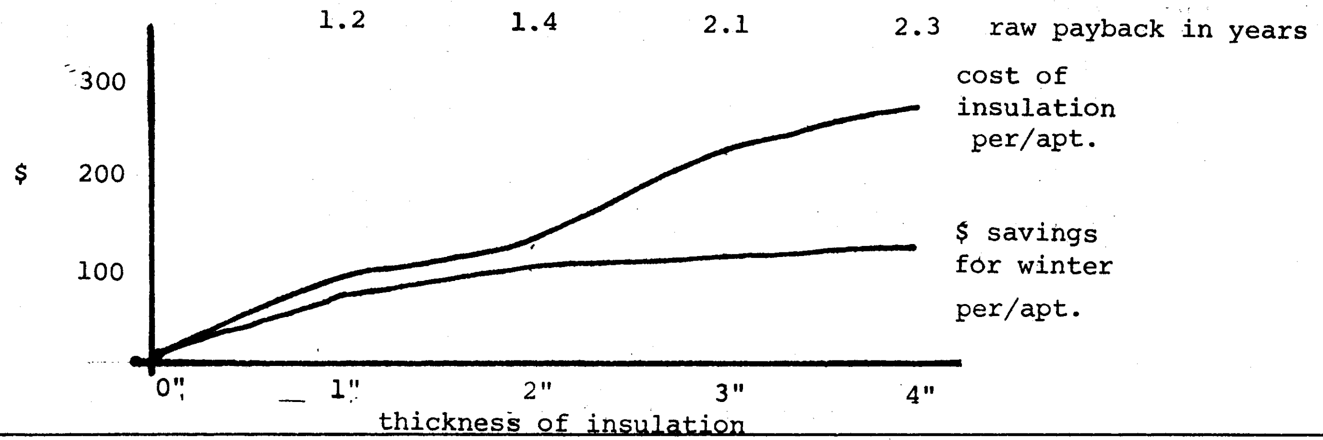
The conclusion to be drawn is that wall insulation of the thicknesses modelled is an excellent investment for any thickness from 1" to 4" since all achieve



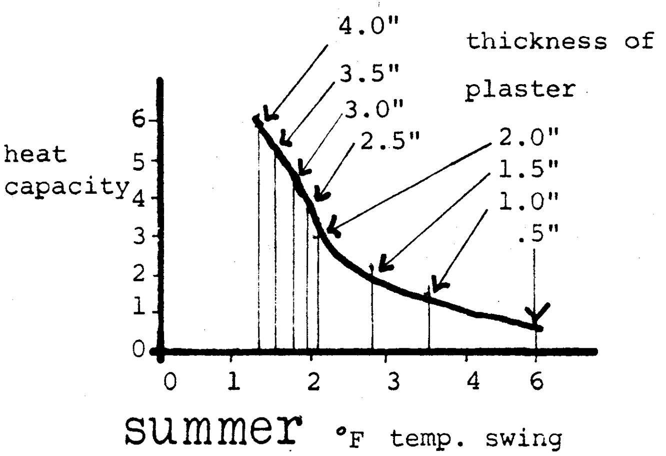
47 HEAT MIGRATION THROUGH APARTMENT SOUTH WALL ON JULY DAY



48 MONTHLY AND ANNUAL HEATING BILLS DUE TO VARIOUS THICKNESSES OF INSULATION IN ROW HOUSE APARTMENTS (PER APARTMENT)



49 INSULATION OPTIMIZATION



50 FULL APARTMENT MASS OPTIMIZATION

payback in less than 2.3 years (Figure 49). Two inches is the minimum effective amount and 3" is preferred.

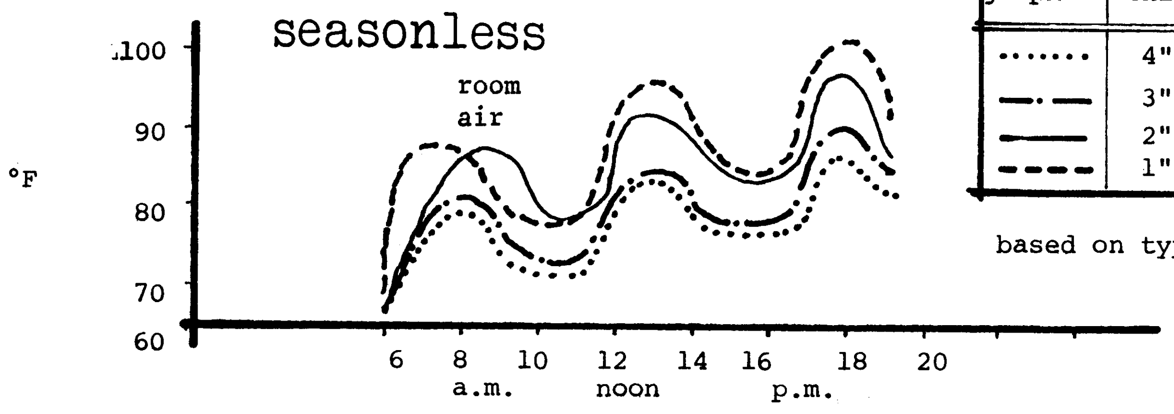
b Optimizing Thermal Mass for the Full Extent of Apartment Surfaces

Summer

The next consideration is to achieve effective cool-down of the apartments with night-time air to establish what thicknesses, types of materials for internal finishes and where to add thicker layers of internal mass where this is appropriate. This is necessary because the proposed solar mass wall scheme flushes out the apartment at night with cool air and is then buttoned up for the daytime hours. Figure 50 is a comparison of various thicknesses of plaster wall and ceiling finishes distributed throughout an apartment with wall and ceiling areas equal to what exists at 132 Chandler Street. The air change rate is equal to 4/hour, corresponding to the air change rates measured during the monitoring period. The values used for the plaster are:

Thickness	Heat Capacity/In.	Thickness	Heat Capacity
.5"	.73	2.5"	3.65
1.0"	1.47	3.0"	4.38
1.5"	2.2	3.5"	5.11
2.0"	2.93	4.0"	5.84

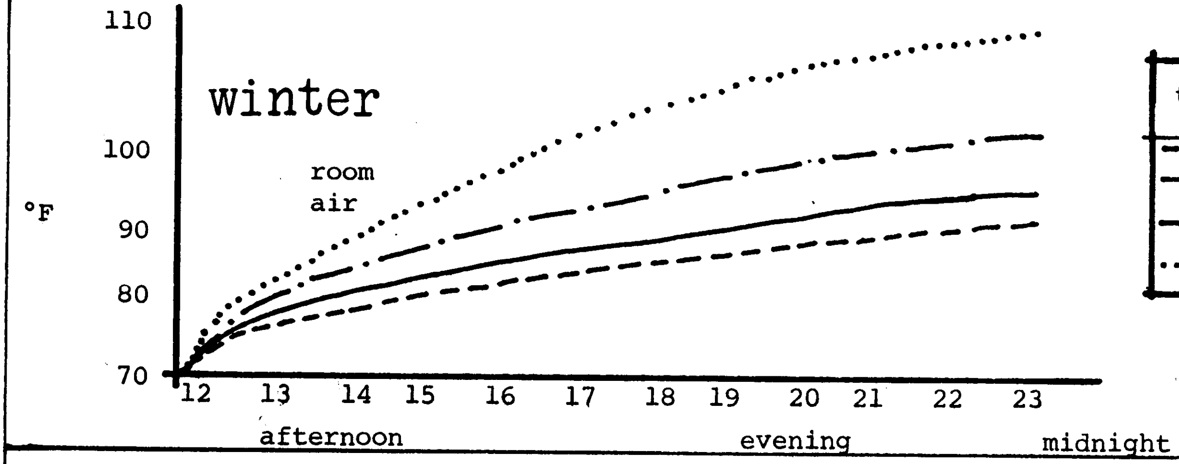
(These values are based on a plaster density of 80 lbs/of and a specific heat of .22 BTUH/CF-°F.) The results (Figure 50) indicate that for the entire apartment surfaces of 2864 SF the optimum amount of temperature saving is acheived through using 2" of plaster mass.



graph	thick.	total swing
·······	4"	21
—·—	3"	24
——	2"	31
- - -	1"	35

based on typicl internal gains

51 KITCHEN CEILING MASS OPTIMIZATION (THICKNESS OF PLASTER)



	thick.	total swing
- - -	4"	17
——	3"	19
—·—	2"	24
······	1"	32

52 LIVING ROOM CEILING PLASTER THICKNESS OPTIMIZATION

Temperature swings are determined using environmental conditions of the outdoors with the average solar or heat gains against fabric losses including opaque and transparent barriers as well as infiltration. The final output of the computation is a maximum and minimum temperature swing for the 24-hour period. It should be noted that due to the many modelling variables, trends indicated here are probably more significant then the actual savings indicated. Starting at 1/2" of plaster and travelling up towards 4" a change in trend is indicated at the point of 2" thickness. For thicknesses greater, the slope of the line becomes linear indicating that extra mass little additional effect. Thus to optimize the cool-down effect for our 'economizer cycle' cooling 2" of plaster provides the optimum comfortable conditions. Any greater thicknesses have little effect.

Heat Intensive Areas Winter

As mentioned in the section on Internal gains the heat intensive areas in the apartement are in the kitchen in the summer and areas around the back-up heat source (cast iron radiators or electric baseboard neaters) in the winter. By using an average hourly electric comsumption figure for these two areas from the data in Figure 8, the room temperatures generated from these sources can be computer simulated. Applying kitchen and living room geometries found at 132 Chandler Street (Figure 12) several valuable pieces of information become evident for apartment construction (see Figures 50, 51 and 52). Soaking up internal gains with mass is important since overheating in the winter is usually alleviated by opening a window and wasting the heat to the out-of-doors. If enough mass is present in the vicinity of the heat source, excess heat will be soaked up and held within the structure. This heat is then released when the room cools down, saving the cost of adding auxiliary heat.

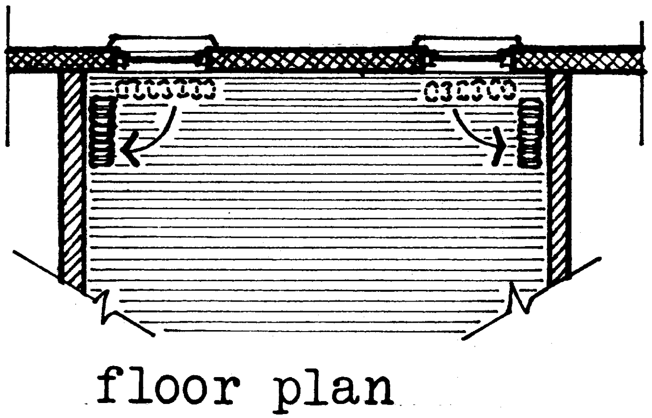
Kitchen - Summer

Since typically the primary target surface that the range and refrigerator see is the ceiling at the Chandler Street apartments, that surface area is used as the surface to optimize for controlling temperature savings. The assumption is made here that the dominant means of heat transfer will be by convention rather than radiation. This is because under normal use the stove's heating elements are normally covered and the heat transfer from boiling, frying baking and roasting implements are assumed to be greatly affected by convection. The result of this assumption is more conservative than if radiation were to dominate; however the trend is similar. The result is that 2-3" of plaster is preferred since after 3" the impact on savings is negligible. This is an attractive and feasible possibility since kitchen area ceilings are often small and can easily sustain the extra weight of plaster or it's thermal mass equivalent.

Living Room (Bedroom) - Winter Time

The primary source of BTU's in these areas is by space heaters as illustrated in Figure 9. Two distinct types of heat sources are modelled here: radiant cast iron heaters and large size connective baseboard heaters. Both are assumed to have an effective area of 12 SF. Two conditions of heaters must be studied. One is the extent of mass directly behind the radiator. The other is the amount of mass in the vicinity or corner of the room close to the heat source. For the second case (Figure 52) the amount of mass for the walls and ceilings meeds to be 3" for both types of heaters. This is a large amount of additional plaster thickness to add but alternatives exist. One is to expose the brick common wall and if necessary skim coat it with plaster. Thus a monolithic mass is achieved on both sides of the apartment for its full height and length. Another way to take advantage of this last possibility is to locate the radiator against the mass wall rather than directly under the windows (which are being tightened in an energy rehab.). A compromise might be to locate the radiator in the vicinity of the corner somewhat close to windows (Figure 53).

The other consideration is the wall directly behind the radiator which receives a large amount of direct radiation particularly when cast iron radiators are used. Again even 6" would be good to soak up the heat. Another approach is more effective, however. Instead of trying to soak up the heat a thin foil faced section of insulation the full area of the radiator, should be located behind the radiator. No heat can migrate to the wall (where it is useless) and the foil (low absorptsity, high emissivity) keeps reflecting long-wave radiation back into and through the heater, to get the heat out into the room.



53 TYPICAL ROW HOUSE

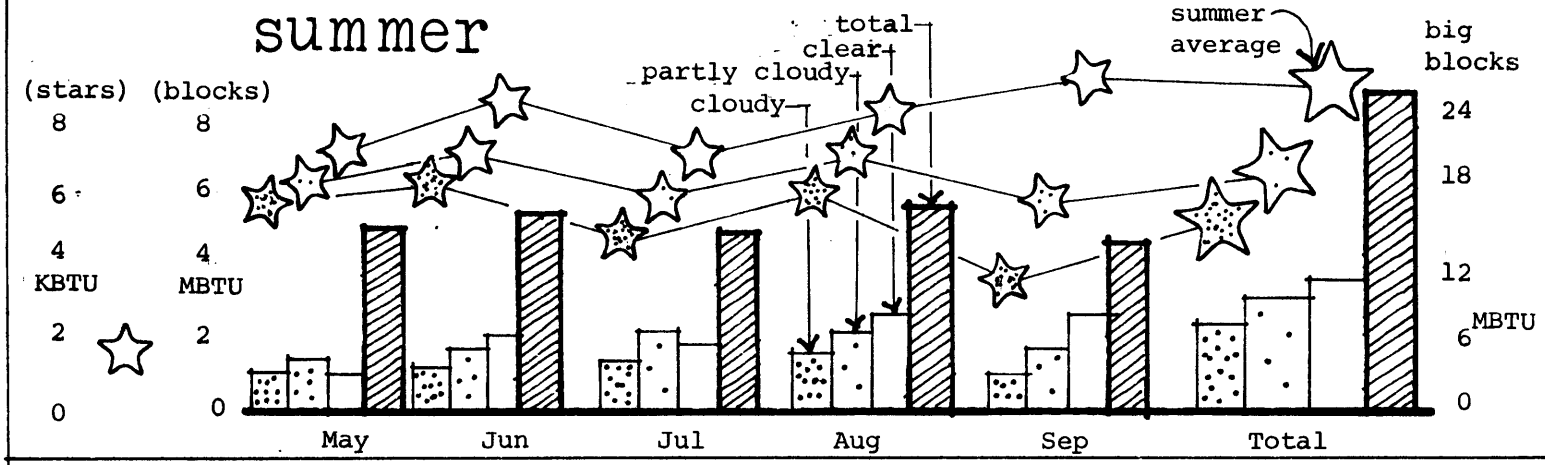
11

SEASONAL PERFORMANCE AND COST BENEFIT ANALYSIS

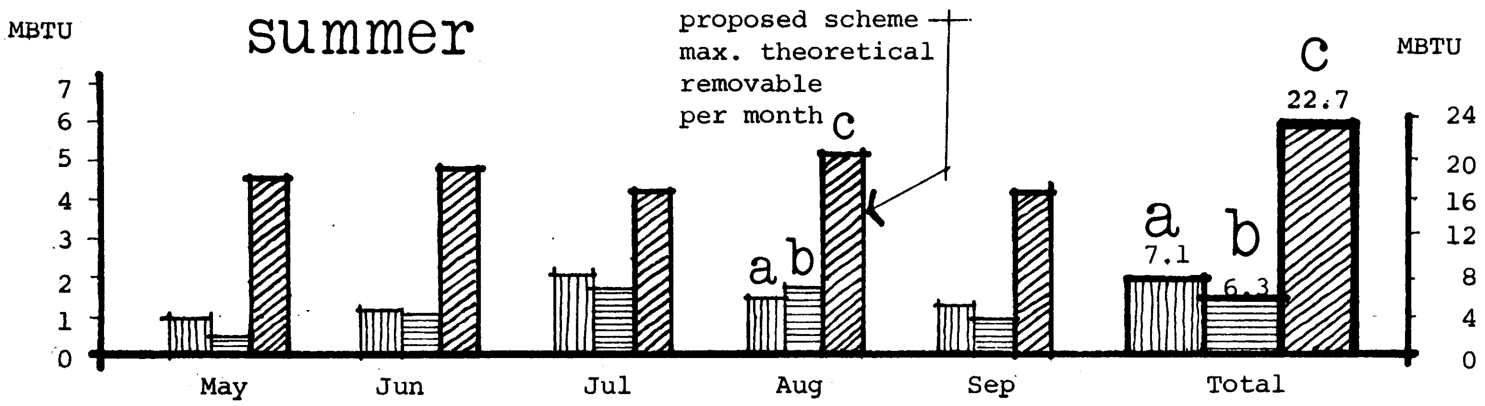
To simplify the process of understanding the performance of the solar mass-wall scheme the performance and cost-benefit studies are divided into two sections: summer and winter. This is followed by their total, the annual benefit.

Construction types A B C are used in the modelling of the performance for both seasons and are made up of the following:

TYPE	C	B	A
Weather walls	1/8" glass skin	8" brick (monolithic)	8" brick with
at 240 SF.	4" air space	1.5" rigid insulation	1 1/2" air space
	8" brick (monolithic)		
	2" rigid insulation		
	3/4" plaster	3/4" plaster	3/4" plaster
Glazing	u = .118 u.A = 28	u = .139 u.A = 33	u = .71 u.A = 171
at	Dble H.M. glass	Dble glass	single glass
80 SF.	u = .24 u.A = 19	u = .56 u.A = 45	u = 1.13 u.A = 91
Infiltration	5 A.C./HR.	.5	1.1
rate at 6720	u.A = 60	u.A = 60	u.A = 133
uA TOTAL	107	138	395



54 MONTHLY BTU MAXIMUM REMOVABLE BY STACK EFFECT AND BREAKDOWN BY TYPE OF DAY; HOURLY BTU REMOVAL RATE (☆)



55 AIR CONDITIONING COMPARISON - 2 CONVENTIONAL CONSTRUCTIONS WITH PROPOSED SCHEME: a/b INDICATES REQUIRED QUANTITIES OF A.C. TO ACHIEVE COMFORT; c INDICATES MAX. BTU REMOVABLE

Summer

The objective of the first set of simulations (Figure 54) is to see in detail how type **C** construction performs in cloudy, partly cloudy and clear weather with the mass wall chimney effect pulling night air through the apartments. The results are shown in Figure 54. Several things are interesting to note. The total amount of BTU's removable per month is a very consistent quantity, averaging 4.3 MBTU/month. The system achieves cooling despite cloudy and partly cloudy weather though the performance is significantly less than a clear day. Two reasons account for this. This wall does respond to and collect diffuse radiation on a cloudy day. Usually the BTU content is 1/7 to 1/10 of what a clear day provides. The other factor is that cloudy days are more often preceded by clear or partly cloudy days than cloudy days and this leaves a residue of heat stored in the mass wall, providing a modified chimney effect. The stars indicate the hourly rates of BTU's removable. The total average is around 6000/hour. This contrasts with our measured and average hourly figures from internal gains of 15 - 1700 and this is easily removed. The dollar figures indicate what the cost is of removing the same amount of BTU's with a conventional wall unit air conditioner. The unit is assumed to be a high efficiency type (EER = 8) and the average cost of residential electricity is $.04/ K.WHR. These totals are then re-entered on a comparative graph (Figure 55).

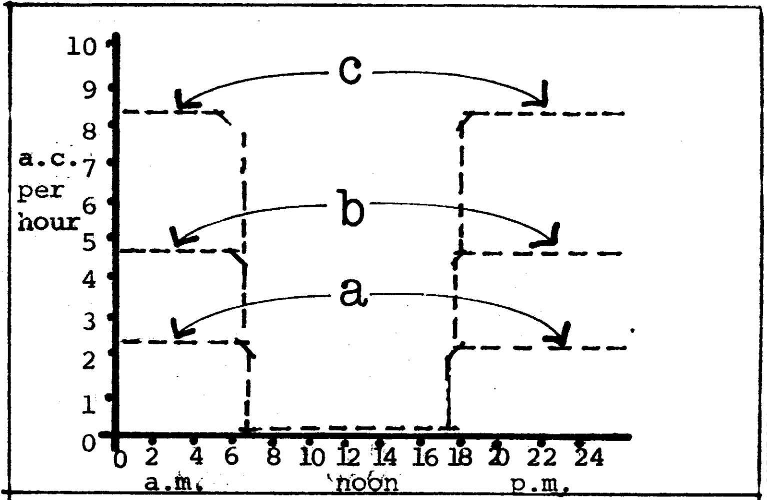
First to analyze Figure 55 the air change rates used in modelling should be mentioned for each type of apartment construction (Figure 56).

The blocks labeled **A** and B in Figure 55 represent the monthly amounts of MBTU's that must be removed from these apartments in order to maintain them at 76° or lower with average internal gains and air change rates as indicated. An unexpected thing happened. The worst constructed apartment needs less air conditioning than the better constructed apartment. This is due to the fact that the nighttime air change rate is higher (4.0 - actually measured at 132) and that the retention of internal gains heat is less with no wall insulation.

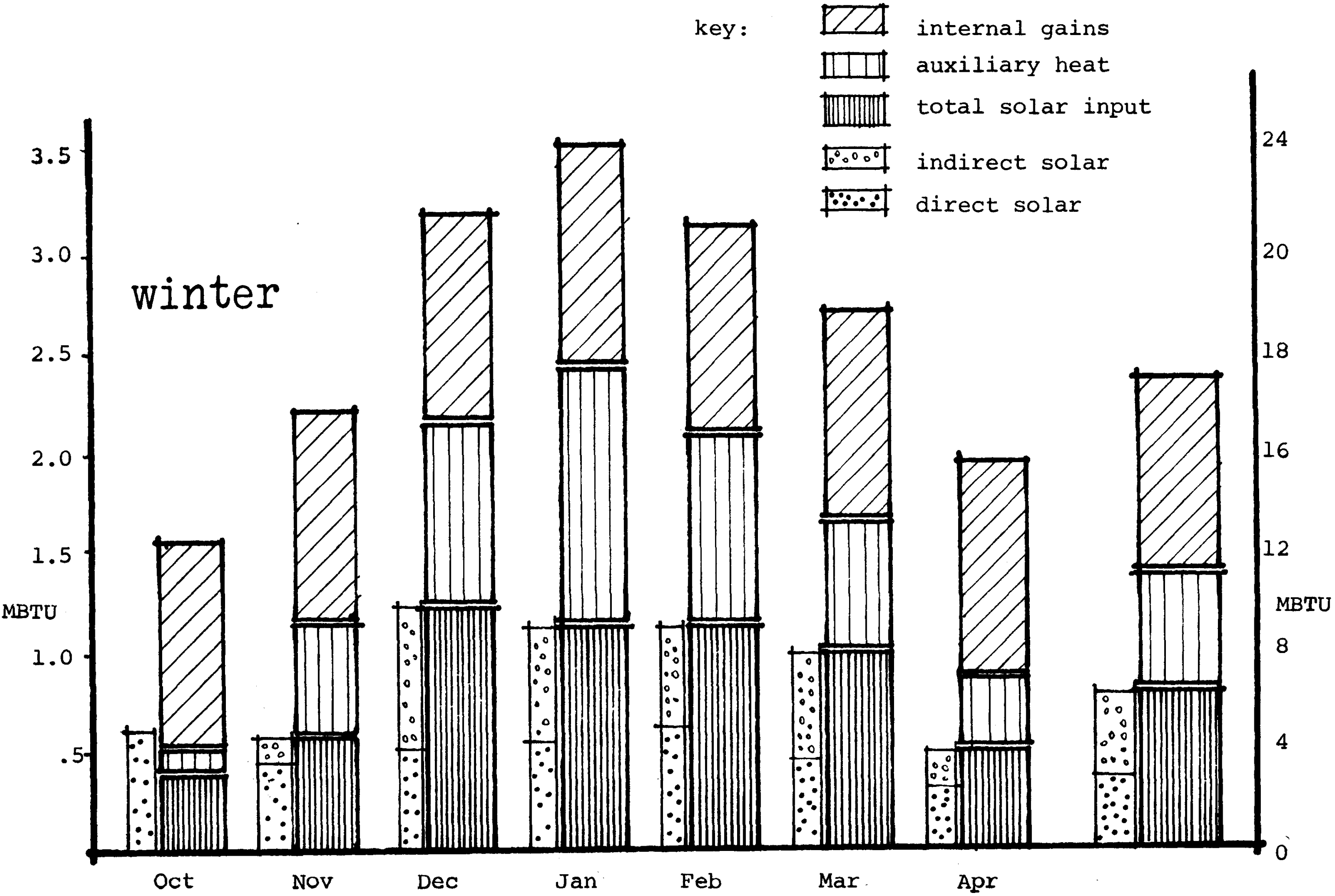
The summertime bottom line on the proposed system is that it can remove almost $100 worth of heat. Moreover typical apartments in Boston would require only $32 - $36 worth of air conditioning for an average summer and for cost-benefit purposes it is assumed that the solar mass wall saves $34 per summer in peak electrical consumption.

Winter

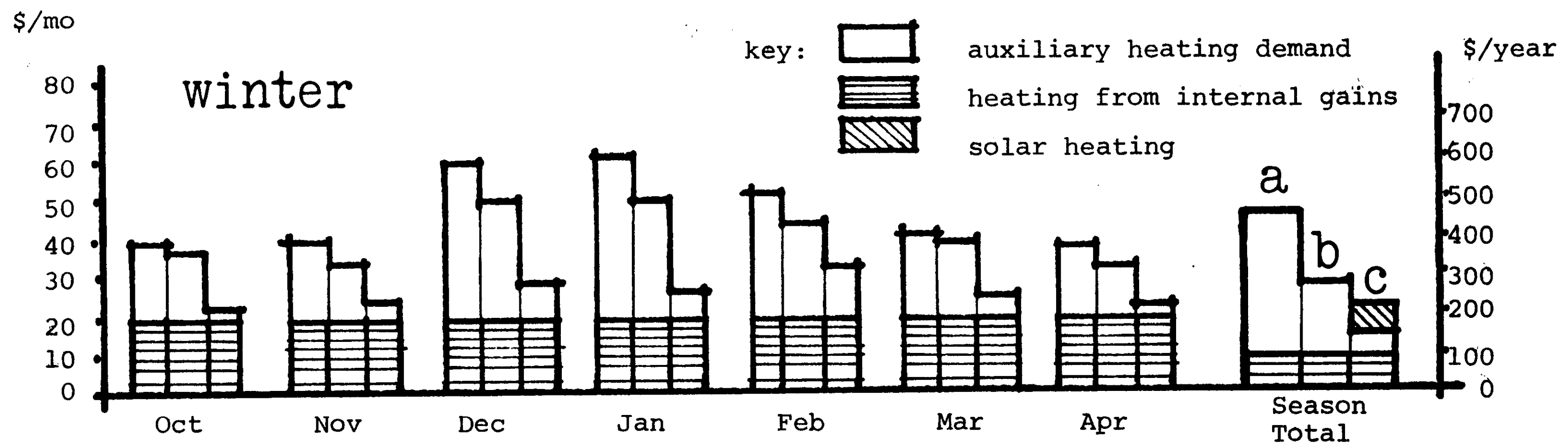
The heating season in Boston is considered to run from mid-October through mid-April. Figure 57 is a monthly analysis of the elements that contribute to the required heating of the proposed mass wall scheme with construction type C. The large part of the monthly block is made up of the particular proportions of internal gains, solar plus auxiliary that provide the total amount of heat necessary. Internal gains though not intended to be used as heating, serve this purpose in a tight, well insulated apartment. Therefore internal gains contribute the largest part of the annual heating demand. The thin block to the left is how the solar energy is received inside the apartment. This is by opening up the mass wall plenum or through



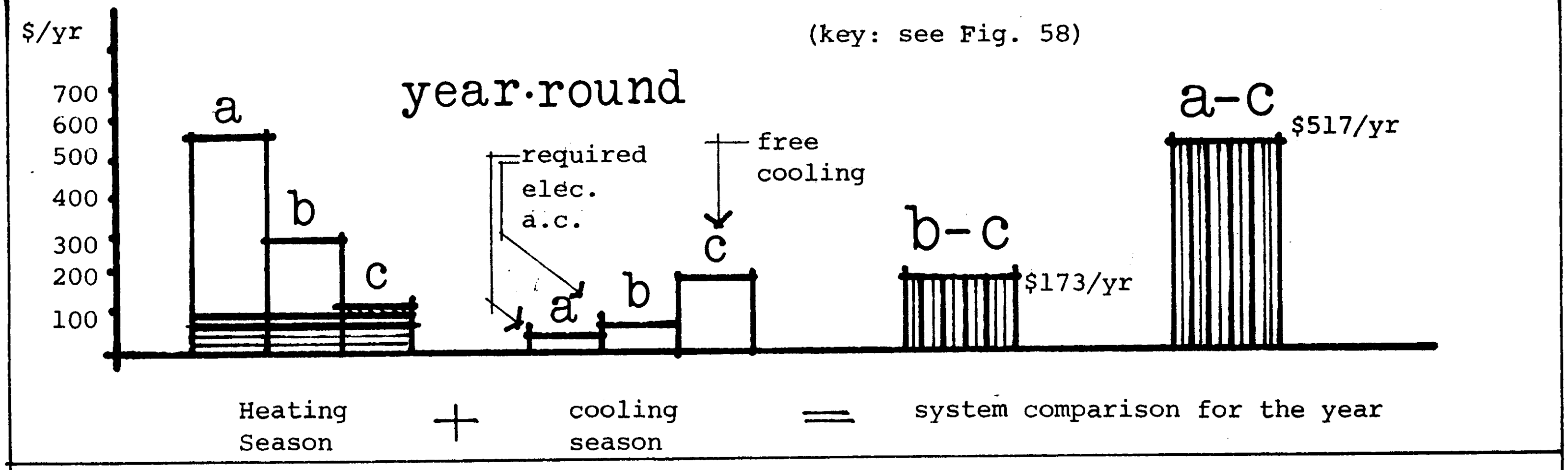
56 AIR CHANGE RATES BY CONSTRUCTION TYPE



57 WINTER PERFORMANCE WITH SOURCE OF HEATING FOR PROPOSED MASS WALL SYSTEM BY MONTHS



58 WINTER PERFORMANCE COMPARISON BETWEEN CONVENTIONAL CONSTRUCTION (a&b) AND PROPOSED SCHEME (c)



59 ANNUAL TOTAL SPACE CONDITIONING COST FOR 3 SCHEMES: A COMPARISON

direct gain of solar energy through south facing windows.

The totals provide some suprising results. Internal gains account for 42% of the heating followed by solar energy at 33% and auxiliary heating at 25%. The solar component is made up of 53% thermo-siphon heat off the mass wall and 47% direct gain through the windows. These winter simulations were done assuming a 3/4" plaster finish throughout the apartment. A greater mass would tend to lower the total auxiliary requirement by holding more heat in the apartment structure longer into the coldest hours of early morning.

The wintertime bottom line on the proposed system is that it uses $191 - $63 = $128 worth of heat per winter to heat an apartment identical to 132. This includes the cost of electricity for internal gains which also provide the benefit of performing the need they are originally demanded for. To see what kind of savings this is we can compare it to construction types A and B on a monthly basis - Figure 58. The monthly totals can be readily understood; the lower portion of the graph is the internal gains. Type B costs $271 per winter to heat. This construction type was chosen because it typifies what is considered a good energy rehab by current standards. Type **A** represents the predominant type of construction carried out by the B.R.A. in the 60's and early 70's. 132 is probably of this type. Annual winter heating costs amount to $561.

If we compare the proposed scheme to either of these last two schemes we can judge its cost benefit. Compared to Type B it represents a savings of ($271 - $128) = $143 and compared to Type A a savings of ($561 - $128) = $433 per winter.

Conclusion

Thus, we can now assign an annual savings due to solar improvements Figure 59. By combining winter (left most column) with cooling (center) the result is a total savings (right-hand) of $173 when compared to Type B and $517 compared to Type A per year. These annual savings clearly indicate that simple mass wall solar schemes are viable passive solar systems for well oriented existing brick buildings in urban locales. Important is the year round benefit of glazing the south facing brick walls: the stack effect which is created in the summer to rid the apartments of unwanted internal gains can remove far beyond the gains normally generated in an average apartment. In the winter indirect and direct passive heating easily accomplishes a significant solar heating fraction for these multifamily units.

The preceeding simulations indicate that human comfort can be maintained to rigorous conventional H.V.A.C. standards, in both summer as well as winter. The overall passive scheme studied here is a simple and direct system that is easily conceinved, constructed and run by the occupant-tenant. Its potential success is tremendously enhanced by the development of heat mirror glass. Simulations verify that this additional heat mirror coating has an architectural and thermal impact that will significantly effect all solar glazing applications. The proposed scheme can achieve a sunshine motivated cooling heat removal rate of 270% of what is necessary in multifamily housing to maintain summertime comfort. In the winter time it acheives 76% of its heating from internal and solar sources. This indicates that movable insulation is largely unnecessary as the selective heat mirror coating acts as a one-way transmitter of solar energy, curbing re-radiant heat loss.

Preliminary estimates of the additional cost due to heat mirror glazing indicate that it will run between $.80-1.25 extra per sq. foot of glass. Integrating this with with conventional glazing support systems show that the raw payback can be achieved within the prescribed period of 5-7 years.

Thus, the potential savings are extremely attractive and applications of this scheme will have an enormous benefit on multifamily housing.

FOOTNOTES

A. A.S.H.R.A.E. Handbook of Fundamentals 1977 -- Equation 29.

B. See Chapter 7 on Improved Glazing.

C. TEANET Simulations, from Teanet Calculator Program, Kohler and Sullivan, Harrisville, N.H., 1978.

D. Based on various conversations with visitors to M.I.T. Solar 5 Building, 1978-9.

E. A Hand Calculator Program for the method is included in Appendix B.

F. Lisa Heschong, M.I.T. M.Arch. Thesis, Department of Architecture, 1978.

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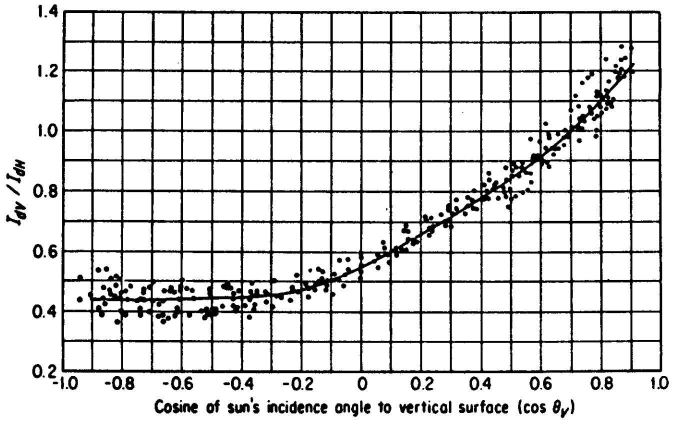
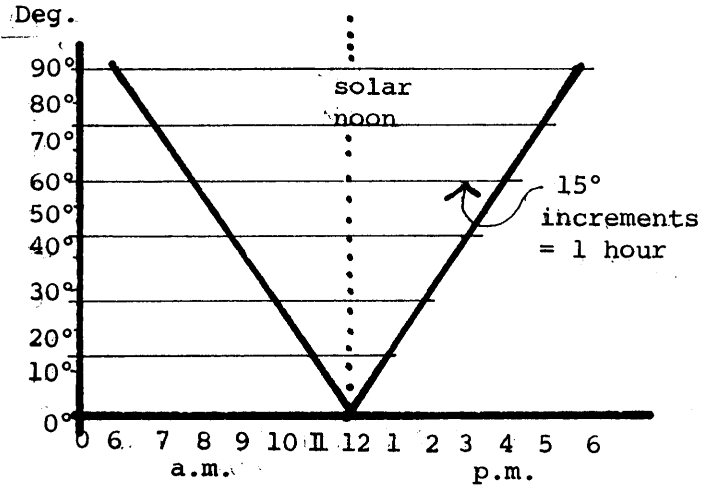
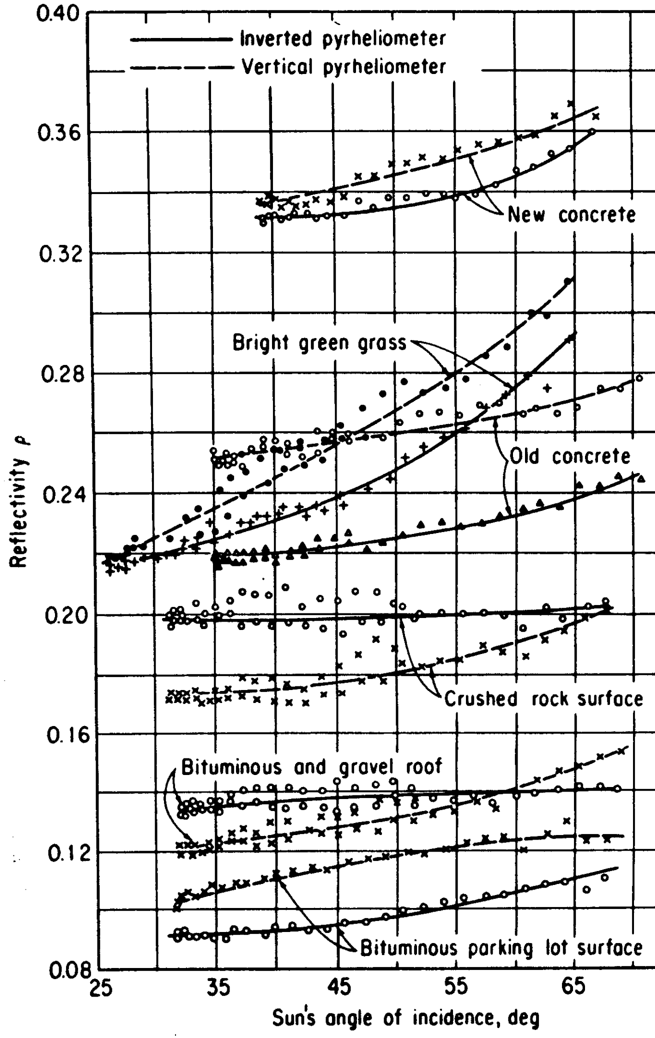
APPENDIX A



1 RATIO OF DIFFUSE RADIATION INCIDENT UPON A VERTICAL SURFACE TO THAT INCIDENT UPON A HORIZONTAL SURFACE DURING A CLEAR DAY



3 HALF ANGLE CORRECTION



2 SOLAR REFLECTIVITY FOR GROUND SURFACES[12]

THE SUN'S DECLINATION AND EQUATION OF TIME

Day →	1		8		15		22	
Month	Dec. Deg: Min	Eq. of Time Min: Sec	Dec. Deg: Min	Eq. of Time Min: Sec	Dec. Deg: Min	Eq. of Time Min: Sec	Dec. Deg: Min	Eq. of Time Min: Sec
January	−(23:08)	− (3:16)	−(22:20)	− (6:26)	−(21:15)	− (9:12)	−(19:50)	−(11:27)
February	−(17:18)	−(13:34)	−(15:13)	−(14:14)	−(12:55)	−(14:15)	−(10:27)	−(13:41)
March	−(7:51)	−(12:36)	− (5:10)	−(11:04)	− (2:25)	− (9:14)	0:21	− (7:12)
April	4:16	− (4:11)	6:56	− (2:07)	9:30	− (0:15)	11:57	1:19
May	14:51	2:50	16:53	3:31	18:41	3:44	20:14	3:30
June	21:57	2:25	22:47	1:15	23:17	− (0:09)	23:27	− (1:40)
July	23:10	− (3:33)	22:34	− (4:48)	21:39	− (5:45)	20:25	− (6:19)
August	18:12	− (6:17)	16:21	− (5:40)	14:17	− (4:35)	12:02	− (3:04)
September	8:33	− (0:15)	5:58	2:03	3:19	4:29	0:36	6:58
October	− (2:54)	10:02	− (5:36)	12:11	− (8:15)	13:59	−(10:48)	15:20
November	−(14:12)	16:20	−(16:22)	16:16	−(18:18)	15:29	−(19:59)	14:02
December	−(21:41)	11:14	−(22:38)	8:26	−(23:14)	5:13	−(23:27)	1:47

4

SUN CHART[12]

STACK EFFECT[7]

5

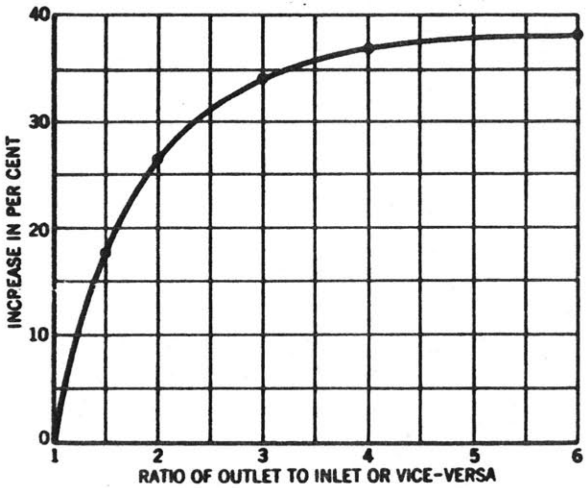


Fig. 12 Increase in Flow Caused by Excess of One Opening Over Another

SOLAR RADIATION[7]

6

Extraterrestrial Solar Radiation Intensity ($Btuh/ft^2$) and Related Data for Twenty-First Day of Each Month, Base Year 1964

	I_o Btuh/ft²	Equation of Time, min.	Declination, deg	A Btuh/ft²	B (Dimensionless Ratios)	C
Jan	442.7	−11.2	−20.0	390	0.142	0.058
Feb	439.1	−13.9	−10.8	385	0.144	0.060
Mar	432.5	− 7.5	0.0	376	0.156	0.071
Apr	425.3	+ 1.1	+11.6	360	0.180	0.097
May	418.9	+ 3.3	+20.0	350	0.196	0.121
June	415.5	− 1.4	+23.45	345	0.205	0.134
July	415.9	− 6.2	+20.6	344	0.207	0.136
Aug	420.0	− 2.4	+12.3	351	0.201	0.122
Sep	426.5	+ 7.5	0.0	365	0.177	0.092
Oct	433.6	+15.4	−10.5	378	0.160	0.073
Nov	440.2	+13.8	−19.8	387	0.149	0.063
Dec	443.6	+ 1.6	−23.45	391	0.142	0.057

Solar Reflectances of Various Foreground Surfaces

Foreground Surface	Incident Angle, deg 20	30	40	50	60	70
New Concrete	0.31	0.31	0.32	0.32	0.33	0.34
Old Concrete	0.22	0.22	0.22	0.23	0.23	0.25
Bright Green Grass	0.21	0.22	0.23	0.25	0.28	0.31
Crushed Rock	0.20	0.20	0.20	0.20	0.20	0.20
Bitumen and Gravel Roof	0.14	0.14	0.14	0.14	0.14	0.14
Bituminous Parking Lot	0.09	0.09	0.10	0.10	0.11	0.12

7 REFLECTANCE TABLE[7]

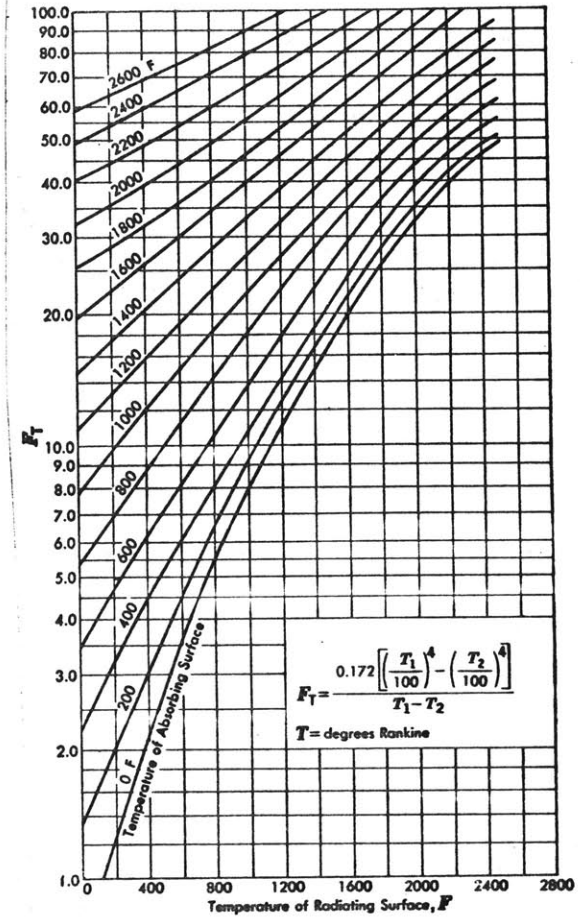
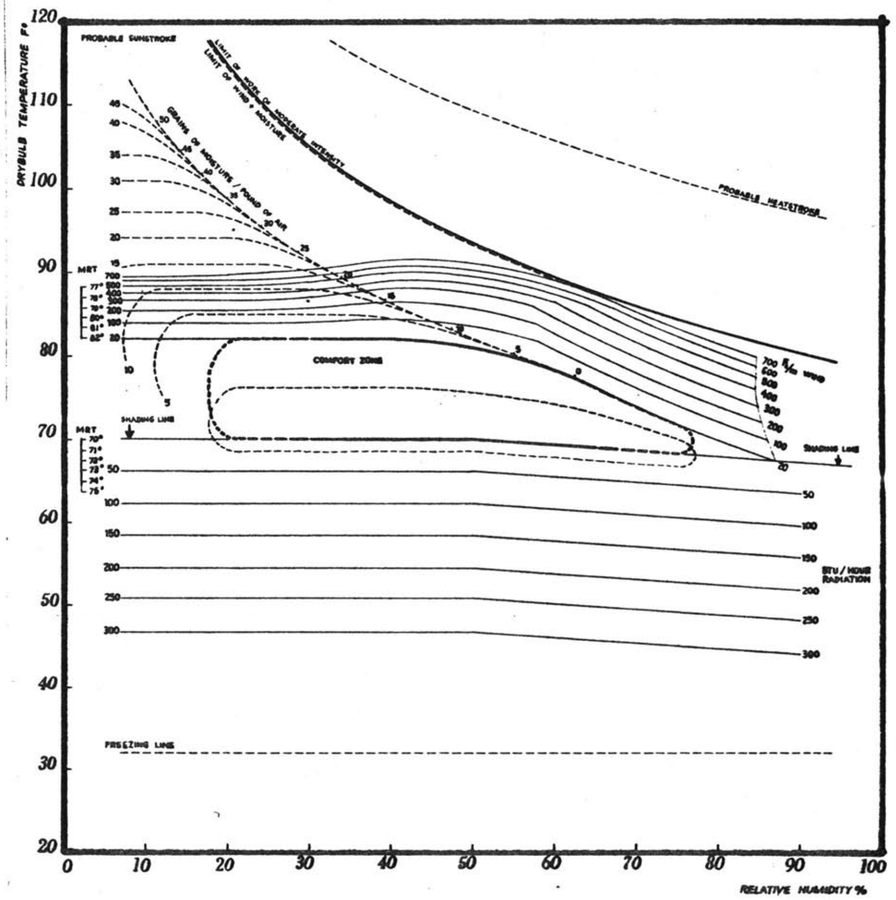


FIG. 5–25. Temperature factor, F_T, as a function of temperature in degrees Fahrenheit.

8 HEAT TRANSFER BY RADIATION[16]



BIO-CLIMATIC CHART FOR
U.S. MODERATE ZONE
INHABITANTS[8]

9

PREDICTION OF SUNSHINE

Components of Solar Radiation

The sun's radiation is reflected, scattered and absorbed by the earth's atmosphere. The total amount of direct radiation is:

$$I_t = (I_{DN} \times \text{Cos}\theta) + I_d + I_r \qquad \text{in BTUH/ft}^2 \qquad (16)$$

where:

I_{DN} = direct normal radiation component, BTUH/ft^2

I_d = diffuse sky radiation component, BTUH/ft^2

I_r = reflected radiation from surrounding surfaces, BTUH/ft^2

Cosθ = L of incidence between sun's ray and line normal to surface being calculated

Direct

On a clear day I_{DN} is described by:

$$I_{DN} = \frac{A}{\exp(B/\sin\beta)} \tag{17}$$

where:

A = apparent solar radiation at air mass = 1.

B = coefficient of extinction for atmosphere at given angle.

β = solar altitude, °.

(for A and B see Figure 7 Appendix A) and

$$B = \cos L \ \cos \delta \cos H + \sin L \ \sin \delta \tag{18}$$

where:

L = local latitude, °.

δ = solar declination, °.

H = hour angle = $\frac{\text{number of minutes from solar noon}}{4}$ (See Figure 3, App. A)

Diffuse

The diffuse component from a clear sky is described by:

$I_{ds} = C \times I_{DN} \times F_{ss}$ (BTUH/ft^2) (19)

where:

$C =$ diffuse radiation factor -- (see Figure 6, Appendix A)

$F_{ss} =$ correction factor for particular surface --

$[(F_{ss} = (1+\cos\varepsilon)/_2)$

(where: $\varepsilon =$ tilt angle of surface measured up from horizontal)]

Ground Reflected

This includes the diffuse sky radiation plus the direct solar radiation incident on a horizontal surface that is reflected to a particular surface. First, the intensity is given by:

$I_{tH} = I_{DN}(C+\sin\beta)$ (20)

where:

$I_{dn} =$ (as above)

$C =$ from chart, Figure 6, Appendix A.

β = solar altitude, °.

The ground-reflected diffuse radiation incident on any surface is given by:

$$I_{dg} = I_{th} \times Q_g \times F_{sg} \qquad (21)$$

where:

I_{th} = (from above)

Q_g = foreground reflectance, -. (Figure 2, App. A)

F_{sg} = surface-ground angle factor, -.

(F_{sg} = $(1 - \cos\varepsilon/2)$

where: ε is the tilt angle)

Solar Time

To determine the true north-south coordinates at a building site it may be necessary to determine the true 'solar noon'. The basic relationship is given by:

$$\text{LST} = \text{LCT} + \text{Eq. of Time}. \qquad (22)$$

where:

LST = local solar time (equivalent)
SCT = local civil time (clock time)
Eq. Time = equation of time as listed in (Figure 4, Appendix A)

The four standard meridians are:

75 deg.	EST
90 d.	CST
105 d.	MST
120 d.	PST

To calculate LST simply subtract from the time given at a rate of 4 min/degree East/West longitude. The chosen location is compared to the above standard meridians. Then add the equation of time factor listed in (Figure 4, Appendix A).

Example: Find LST for 12 Noon CST on February 8, 95° West longitude.

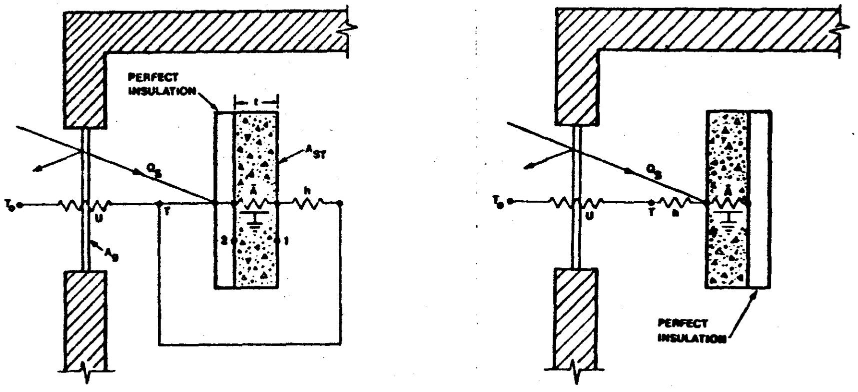
1. 12:00 - 5 (4) min/deg. = 11:40 LCT (5 is 5° off standard longitude)
2. From tables the equation of time = -14 min^{+}, and LST = 11:40 - :14
   = 11:26 am.
3. The local solar noon is at 11:26 and N/S bearing lines can be set at this time.

APPENDIX B

T.S.P.

TEMPERATURE SWING PROGRAM

(Niles Method)



convective radiative

This program predicts maximum and minimum temperatures for indirect and direct passive solar hearing with an error of ± 15%. The product is two sets of temperature swings. The first, is typical of a configuration where the heat transfer of solar energy to storage mass is dominated by convective exchange. The second, is where transfer is dominated by radiative exchange(see Figures). Program limitations include ability to model only south facing solar glazing, and only concrete or plaster as a storage medium.[17]

METHOD

Step 0	Execute program on T.1.59 with printer.
Step 1	Read sides 1 & 2 of data card into calculator (normal partitioning)
Step 2	Input the following information:

	Location	Description	Units
STO	01	Indoor design temp. to be maintained	°F
	02	Outdoor temp. (average over a 24 hr. period)	°F
	03	House loss total minu~~m~~s losses through south glazing $= (U \times A_{total} - U \times A_{south\ glazing})$	BTUH/°F
	04	Average daily insolation received inside bldg. divided by 24 hrs./per sq. ft. of glass (after transmission)	BTUH/ft^2
	05	"U" value of south glazing	BTUH/ft^2 -°F
	06	Outdoor temp. swing/2 over selected 24 hr. period	°F
	07	Ratio of storage surface area divided by south glass area	--
	08	Surface conductance of storage heavy wt. conc., plaster = 1	BTUH/ft^2 -°F
	09	Period of daily temp. swing = constant 24	hrs.
	10	Storage mass heat capacity per thickness specified (fraction of a foot) (conc. = 29.4)	BTU/F^2 - °F

(Temp. Swing Prog. - continued)

Location	Description	Units
11	Enter only if known - area of south glazing (go to LBL B)	Ft^2
48	Ave. hourly internal gains	BTU/hr.

Step 3	Press: LBL A Gives the area of south glass req'd. to achieve thermal equilibrium with environmental conditions given (note: it may be necessary to check numbers stored in 03 and 07 before proceeding).	NOTE: If glass area is already known go to LBL B and bypass glass area computation.
Step 4	Press: R/S Gives °F temp swing/w when storage is dominated by convective coupling,	Press: LBL B Gives same
Step 5	Then gives °F temp swing/w when storage is dominated by radiative coupling,	Gives same
Step 7	Gives base temp. and resulting indoor air temps for 4 and 5.	Gives same

(Temp. Swing Prog. - continued)

EXAMPLE

0. Data based on measured data from M.I.T. Solar Demonstration Bldg. 5, Cambridge, Mass. Building is a direct gain system dominated by radiative coupling.

1. Ambient air temps........ Min. = 30°   Max = 50
   Swing/2   20°/2 = 10°
2. ~~T~~°indoor swing   63°-76° = 13°   69.5° ave. temp.
3. House loss   = 240 BTUH/°F - [.18 x 180 SF = 32.4]
   = 207.6 BTUH/°F
   (total - south glass loss)
4. Average solar insolation   = 175 BTU/SF @ noon ≈ 33 BTU/hr
   (over 24 hours)
5. $U_{glass} = .18$
6. Effective storage surface area = 400 SF
7. Ratio of mass to glass   = 400/180 = 2.16
8. Storage surface conductance   = 1.0 BTUH/SF • °F
9. Storage mass heat capacity   = 22.5
10. Given: south glass area   = 180 SF and
11. internal gains   = 1563 BTUH

(Temp. Swing Prog. - continued)

Enter Data	List Data		Results	
Press <u>B</u> since glass area is known	0.	00	21.88952137	CONV
	69.5	01	6.712796639	RAD
	40.	02		
	207.6	03		
	33.	04	....	
	0.18	05		
	10.	06	71.2625	°F
	2.16	07	49.37297863	TO
	1.	08	93.15202137	
	24.	09		
	22.5	10	64.54970336	TO
	180.	11	77.97529664	COMPARE WITH 2. IN EXAMPLE
	⋮	⋮		
	1563.	48		

Program Listing (printer version)

```
000  76 LBL
001  11  A
002  43 RCL
003  01  01
004  75  -
005  43 RCL
006  02  02
007  95  =
008  65  ×
009  43 RCL
010  03  03
011  95  =
012  42 STO
013  13  13
014  43 RCL
015  01  01
016  75  -
017  43 RCL
018  02  02
019  95  =
020  65  ×
021  43 RCL
022  05  05
023  95  =
024  42 STO
025  30  30
026  43 RCL
027  04  04
028  75  -
029  43 RCL
030  30  30
031  95  =
032  42 STO
033  46  46
034  02  2
035  01  1
036  03  3
037  07  7
038  07  7
039  00  0
040  69 OP
041  04  04
042  43 RCL
043  13  13
044  55  ÷
045  43 RCL
046  46  46
047  95  =
048  42 STO
049  11  11
050  69 OP
051  06  06
052  98 ADV
053  91 R/S
054  76 LBL
055  12  B
056  43 RCL
057  03  03
058  55  ÷
059  43 RCL
060  11  11
061  95  =
062  85  +
063  43 RCL
064  05  05
065  95  =
066  42 STO
067  28  28
068  43 RCL
069  01  01
070  75  -
071  43 RCL
072  02  02
073  95  =
074  65  ×
075  01  1
076  93  .
077  06  6
078  06  6
079  06  6
080  95  =
081  33 X²
082  42 STO
083  15  15
084  43 RCL
085  06  06
086  33 X²
087  42 STO
088  12  12
089  43 RCL
090  01  01
091  75  -
092  43 RCL
093  02  02
094  95  =
095  65  ×
096  01  1
097  93  .
098  06  6
099  06  6
100  06  6
101  65  ×
102  43 RCL
103  06  06
104  65  ×
105  01  1
106  93  .
107  04  4
108  01  1
109  04  4
110  95  =
111  85  +
112  43 RCL
113  12  12
114  85  +
115  43 RCL
116  15  15
117  95  =
118  34 ΓX
119  42 STO
120  39  39
121  43 RCL
122  07  07
123  65  ×
124  43 RCL
125  08  08
126  95  =
127  55  ÷
128  43 RCL
129  28  28
130  95  =
131  85  +
132  02  2
133  95  =
134  65  ×
135  43 RCL
136  07  07
137  65  ×
138  43 RCL
139  08  08
140  95  =
141  55  ÷
142  43 RCL
143  28  28
144  95  =
145  42 STO
146  47  47
147  43 RCL
148  09  09
149  65  ×
150  43 RCL
151  08  08
152  95  =
153  42 STO
154  45  45
155  43 RCL
156  10  10
157  65  ×
158  06  6
159  93  .
160  02  2
161  08  8
162  03  3
163  95  =
164  42 STO
165  17  17
166  43 RCL
167  45  45
168  55  ÷
169  43 RCL
170  17  17
171  95  =
172  33 X²
173  85  +
174  01  1
175  95  =
```

```
176  42 STO     211  06  06     246  43 RCL     281  03   3     316  37  37
177  18  18     212  43 RCL     247  32  32     282  65   ×     317  95   =
178  43 RCL     213  01  01     248  95   =     283  43 RCL     318  42 STO
179  47  47     214  75   -     249  85   +     284  10  10     319  43  43
180  55   ÷     215  43 RCL     250  01   1     285  95   =     320  43 RCL
181  43 RCL     216  02  02     251  95   =     286  42 STO     321  06  06
182  18  18     217  95   =     252  65   ×     287  35  35     322  33 X²
183  95   =     218  55   ÷     253  43 RCL     288  43 RCL     323  95   =
184  85   +     219  93   .     254  06  06     289  08  08     324  42 STO
185  01   1     220  06   6     255  95   =     290  65   ×     325  44  44
186  95   =     221  95   =     256  65   ×     291  43 RCL     326  43 RCL
187  35 1/X     222  42 STO     257  01   1     292  09  09     327  43  43
188  34 √X      223  29  29     258  93   .     293  95   =     328  65   ×
189  95   =     224  06   6     259  04   4     294  42 STO     329  43 RCL
190  42 STO     225  93   .     260  01   1     295  36  36     330  33  33
191  40  40     226  02   2     261  04   4     296  43 RCL     331  95   =
192  01   1     227  08   8     262  95   =     297  35  35     332  85   +
193  05   5     228  03   3     263  85   +     298  55   ÷     333  43 RCL
194  03   3     229  65   ×     264  43 RCL     299  43 RCL     334  44  44
195  02   2     230  43 RCL     265  29  29     300  36  36     335  95   =
196  03   3     231  10  10     266  95   =     301  95   =     336  34 √X
197  01   1     232  95   =     267  42 STO     302  33 X²      337  95   =
198  04   4     233  42 STO     268  33  33     303  85   +     338  42 STO
199  02   2     234  31  31     269  43 RCL     304  01   1     339  42  42
200  69 OP      235  43 RCL     270  01  01     305  95   =     340  03   3
201  04  04     236  09  09     271  75   -     306  65   ×     341  05   5
202  43 RCL     237  65   ×     272  43 RCL     307  93   .     342  01   1
203  39  39     238  43 RCL     273  02  02     308  06   6     343  03   3
204  65   ×     239  08  08     274  95   =     309  95   =     344  01   1
205  43 RCL     240  95   =     275  42 STO     310  42 STO     345  06   6
206  40  40     241  42 STO     276  34  34     311  37  37     346  69 OP
207  95   =     242  32  32     277  06   6     312  43 RCL     347  04  04
208  42 STO     243  43 RCL     278  93   .     313  34  34     348  43 RCL
209  41  41     244  31  31     279  02   2     314  55   ÷     349  41  41
210  69 OP      245  55   ÷     280  08   8     315  43 RCL     350  55   ÷
```

```
351  43 RCL      386  04  04      421  95  =       456  75  -
352  39  39      387  69 OP       422  69 OP       457  43 RCL
353  95  =       388  05  05      423  06  06      458  45  45
354  65  ×       389  06  6       424  42 STO      459  95  =
355  43 RCL      390  05  5       425  46  46      460  69 OP
356  42  42      391  02  2       426  03  3       461  06  06
357  95  =       392  01  1       427  07  7       462  43 RCL
358  69 OP       393  69 OP       428  03  3       463  46  46
359  06  06      394  04  04      429  02  2       464  85  +
360  42 STO      395  98 ADV      430  69 OP       465  43 RCL
361  45  45      396  53  (       431  04  04      466  45  45
362  98 ADV      397  43 RCL      432  43 RCL      467  95  =
363  06  6       398  04  04      433  46  46      468  99 PRT
364  05  5       399  65  ×       434  75  -       469  98 ADV
365  02  2       400  43 RCL      435  43 RCL      470  98 ADV
366  01  1       401  11  11      436  41  41      471  98 ADV
367  69 OP       402  85  +       437  95  =       472  91 R/S
368  04  04      403  43 RCL      438  69 OP
369  04  4       404  48  48      439  06  06
370  00  0       405  95  =       440  43 RCL
371  04  4       406  54  )       441  46  46
372  00  0       407  55  ÷       442  85  +
373  04  4       408  53  (       443  43 RCL
374  00  0       409  43 RCL      444  41  41
375  04  4       410  03  03      445  95  =
376  00  0       411  85  +       446  99 PRT
377  04  4       412  43 RCL      447  98 ADV
378  00  0       413  05  05      448  03  3
379  69 OP       414  65  ×       449  07  7
380  01  01      415  43 RCL      450  03  3
381  69 OP       416  11  11      451  02  2
382  02  02      417  54  )       452  69 OP
383  69 OP       418  85  +       453  04  04
384  03  03      419  43 RCL      454  43 RCL
385  69 OP       420  02  02      455  46  46
```

A.R.T.

(Print Version)

This program predicts the abosrption, reflection and transmission percentages of solar energy, through selected glazing. If desired, the quantity of BTU/ft^2 after transmission can also be computed. The program uses Fresnel equations for transmission due to reflection and Bouger's Law for absorption of radiation. The method is fully described in Chapter 6 of Dufie and Beckman's "Solar Energy Thermal Processes."

METHOD

0. Execute program on T.I.59 with printer.
1. Enter data cards sides 1 and 2 at "normal" (479.59) partitioning
2. Enter and store data
   a) Thickness of glass being used (cm) STO 01
   b) Glass coefficient of extinction (x/cm) STO 02
   [This can be obtained from glass mfgs. technical data. Typical values are:

(A.R.T. Program - continued)

"water white" (low-iron) glass = .04/cm
"regular" glass = .161/cm
"poor" (hi-iron) glass = .32/cm
"heat mirror" glass ≈ .5/cm]

c) Angle of incidence of sunlight striking glass,° STO 03
(this can also be entered as LBL C)

d) Glass index of refraction (x) STO 04
(reg. glass = 1.526, check mfgs. specs)

e) Enter chart value pd from no. of glazing covers being used.

No. covers:	1	2	3	4
Pd	.16	.24	.29	.32

STO 28

f) Absorptivity of absorber surface (fraction of 1.0) STO 31

g) No. of layers of glass used (x) STO 07

h) Sunshine available for transmission at outer face of glass (BTU/ft^2) (this can also be entered as LBL D STO 09

3. To run program, press

LBL A:	LBL B
If, angle of incidence is = 0	if, angle of incidence is > 0° and < 90°

(A.R.T. Program - continued)

Displays: (flashes incident angle)
% of total absorbed in glass
press $\overline{\text{R/S}}$ (to finish)
% of total reflected by glass
% of total transmitted through glass
Total quantity of BTU/ft^2 transmitted.

$\overline{\text{LBL}}$ $\overline{\text{A'}}$: Tau alpha product (BTUs going into absorber)

<u>EXAMPLE:</u>

What percentage of sunshine is absorbed, reflected and transmitted at an incident angle of 60°, using a single glass cover, 1/8" thick, "regular" glass. How much energy is transmitted if 100 (direct radiation) BTU/ft^2 is available at the outside face of the glass?

Enter Data:

```
     0.3125      01
      0.161      02
        60.      03
      1.526      04
 .0762583328     05
         0.      06
         1.      07
 1.076258333     08
       100.      09
         :        :
       0.16      28
      0.984      29
 .724554483 3    30
        0.9      31
```

Press $\overline{\text{LBL}}$ $\overline{\text{B}}$

Results:

```
         60.     ANGL
 .1794798567       AB
 .0283405749       RE
 .7921795684       TR

 79.21795684      TOT



 .724554483 3
 72.4554483 3
```

Program Listing (printer version)

```
001  76 LBL      036  85  +       071  08  08      106  43 RCL
002  13  C       037  01  1       072  95  =       107  03  03
003  42 STO      038  54  )       073  42 STO      108  95  =
004  03  03      039  95  =       074  19  19      109  38 SIN
005  91 R/S      040  33 X²       075  61 GTO      110  33 X²
006  76 LBL      041  42 STO      076  15  E       111  95  =
007  14  D       042  05  05      077  76 LBL      112  55  ÷
008  42 STO      043  53  (       078  12  B       113  43 RCL
009  09  09      044  53  (       079  53  (       114  12  12
010  91 R/S      045  02  2       080  43 RCL      115  95  =
011  76 LBL      046  65  ×       081  03  03      116  42 STO
012  11  A       047  43 RCL      082  38 SIN      117  11  11
013  01  1       048  07  07      083  54  )       118  43 RCL
014  03  3       049  95  =       084  55  ÷       119  10  10
015  03  3       050  75  -       085  43 RCL      120  85  +
016  01  1       051  01  1       086  04  04      121  43 RCL
017  02  2       052  95  =       087  95  =       122  03  03
018  02  2       053  54  )       088  22 INV      123  95  =
019  02  2       054  65  ×       089  38 SIN      124  30 TAN
020  07  7       055  43 RCL      090  42 STO      125  33 X²
021  69 OP       056  05  05      091  10  10      126  95  =
022  04  04      057  85  +       092  43 RCL      127  42 STO
023  00  0       058  01  1       093  10  10      128  13  13
024  69 OP       059  54  )       094  85  +       129  01  1
025  06  06      060  95  =       095  43 RCL      130  03  3
026  53  (       061  42 STO      096  03  03      131  03  3
027  43 RCL      062  08  08      097  95  =       132  01  1
028  04  04      063  53  (       098  38 SIN      133  02  2
029  75  -       064  01  1       099  33 X²       134  02  2
030  01  1       065  75  -       100  95  =       135  02  2
031  54  )       066  43 RCL      101  42 STO      136  07  7
032  55  ÷       067  05  05      102  12  12      137  69 OP
033  53  (       068  95  =       103  43 RCL      138  04  04
034  43 RCL      069  55  ÷       104  10  10      139  43 RCL
035  04  04      070  43 RCL      105  75  -       140  10  10
```

```
141  75  -       176  43 RCL      211  85  +       246  18  18
142  43 RCL      177  11  11      212  43 RCL      247  43 RCL
143  03  03      178  95  =       213  16  16      248  18  18
144  69 OP       179  55  ÷       214  95  =       249  65  ×
145  06  06      180  43 RCL      215  55  ÷       250  43 RCL
146  95  =       181  15  15      216  02  2       251  19  19
147  30 TAN      182  95  =       217  95  =       252  95  =
148  33 X²       183  42 STO      218  42 STO      253  42 STO
149  95  =       184  16  16      219  19  19      254  20  20
150  55  ÷       185  53  (       220  61 GTO      255  01  1
151  43 RCL      186  43 RCL      221  15  E       256  75  -
152  13  13      187  07  07      222  76 LBL      257  43 RCL
153  95  =       188  65  ×       223  15  E       258  19  19
154  42 STO      189  02  2       224  53  (       259  95  =
155  14  14      190  75  -       225  43 RCL      260  42 STO
156  53  (       191  01  1       226  07  07      261  21  21
157  43 RCL      192  95  =       227  94 +/-      262  01  1
158  07  07      193  54  )       228  65  ×       263  75  -
159  65  ×       194  65  ×       229  43 RCL      264  43 RCL
160  02  2       195  43 RCL      230  01  01      265  58  58
161  75  -       196  14  14      231  65  ×       266  95  =
162  01  1       197  85  +       232  43 RCL      267  42 STO
163  95  =       198  01  1       233  02  02      268  22  22
164  54  )       199  95  =       234  95  =       269  01  1
165  65  ×       200  42 STO      235  54  )       270  75  -
166  43 RCL      201  17  17      236  55  ÷       271  43 RCL
167  11  11      202  01  1       237  53  (       272  20  20
168  54  )       203  75  -       238  43 RCL      273  95  =
169  85  +       204  43 RCL      239  10  10      274  42 STO
170  01  1       205  14  14      240  39 COS      275  23  23
171  95  =       206  95  =       241  54  )       276  43 RCL
172  42 STO      207  55  ÷       242  95  =       277  21  21
173  15  15      208  43 RCL      243  22 INV      278  85  +
174  01  1       209  17  17      244  23 LNX      279  43 RCL
175  75  -       210  95  =       245  42 STO      280  22  22
```

```
281  95  =
282  42  STO
283  26   26
284  43  RCL
285  21   21
286  55   ÷
287  43  RCL
288  26   26
289  95   =
290  65   ×
291  43  RCL
292  23   23
293  95   =
294  42  STO
295  24   24
296  43  RCL
297  22   22
298  85   +
299  43  RCL
300  21   21
301  95   =
302  42  STO
303  27   27
304  43  RCL
305  22   22
306  55   ÷
307  43  RCL
308  27   27
309  95   =
310  65   ×
311  43  RCL
312  23   23
313  95   =
314  42  STO
315  25   25
316  01   1
317  03   3
318  01   1
319  04   4
320  69  OP
321  04   04
322  43  RCL
323  25   25
324  69  OP
325  06   06
326  03   3
327  05   5
328  01   1
329  07   7
330  69  OP
331  04   04
332  43  RCL
333  24   24
334  69  OP
335  06   06
336  03   3
337  07   7
338  03   3
339  05   5
340  69  OP
341  04   04
342  43  RCL
343  20   20
344  69  OP
345  06   06
346  98  ADV
347  03   3
348  07   7
349  03   3
350  02   2
351  03   3
352  07   7
353  69  OP
354  04   04
355  43  RCL
356  20   20
357  65   ×
358  43  RCL
359  09   09
360  95   =
361  69  OP
362  06   06
363  98  ADV
364  98  ADV
365  98  ADV
366  91  R/S
367  76  LBL
368  16  A'
369  01   1
370  75   -
371  43  RCL
372  31   31
373  95   =
374  65   ×
375  43  RCL
376  28   28
377  95   =
378  94  +/-
379  85   +
380  01   1
381  95   =
382  42  STO
383  29   29
384  43  RCL
385  20   20
386  65   ×
387  43  RCL
388  31   31
389  95   =
390  55   ÷
391  43  RCL
392  29   29
393  95   =
394  99  PRT
395  42  STO
396  30   30
397  43  RCL
398  09   09
399  65   ×
400  43  RCL
401  30   30
402  95   =
403  99  PRT
404  98  ADV
405  91  R/S
```