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TECHNICAL EVALUATION OF A SOLAR HEATING SYSTEM HAVING CONVENTIONAL HYDRONIC SOLAR COLLECTORS AND A RADIANT PANEL SLAB

Final Report

By
Robert J. Starr
Jon G. McGowan
Bran P. McNiff

Work Performed Under Contract No. FG01-82CE15140

The Solar Option One Company
Lyndonville, Vermont

and

The University of Massachusetts
Amherst, Massachusetts

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SECTION ONE - SUMMARY OF FINDINGS

PART ONE OVERVIEW

A simple innovative solar heating design using conventional hydronic solar collectors and a radiant panel slab was partially developed by Robert J. Starr of Lyndonville, Vermont.

The invention was disclosed to the Invention Support Division at The National Bureau of Standards for their assessment of technical validity.

In May of 1981, the Bureau of Standards determined that the invention was "technically valid and worthy of consideration for appropriate Government support."

Second stage review of the invention (termed The Solar Option One Heating System) was performed by Mr. Michael Brown, a consultant evaluator, who recommended support of the invention because "the design provides utilization of solar energy at lower initial cost and with improved efficiency".

A recommendation was made to the Department of Energy by the National Bureau of Standards to provide support in the form of a complete technical investigation.

Dr. Jon G. McGowan, of the Department of Mechnical Engineering at the University of Massachusetts was contacted. The University subsequently agreed to collaborate with Mr. Starr for the purpose of carrying out the investigation.

The status of the invention prior to federal support was that a few working models had been installed in single family homes within the Northeastern portion of Vermont. These low cost working models seemed to be working well as evidenced by high collector efficiencies (low collector inlet temperatures),and low auxiliary energy useages. The models which were designed to achieve solar performances in the vicinity of 50% were observed to have relatively stable temperatures and steady inputs of auxiliary energy. These observations suggested that higher levels of solar heating performance were possible without diminishing returns.

Market penetration was limited due to the lack of credible independent performance data. Data aquisition from working models was confounded by the presence of occupants whose habits were unpredictable and by the use of wood heat as the auxiliary backup.

The results of the research demonstrate that the invention offers significant advantages over state of the art active and passive approaches. Substantial improvements were noted in system efficiency, overall performance, initial cost and architectual flexibility.

A patent and literature search by Michael Brown, a consultant to The National Bureau of Standards revealed that the design approach is a unique one and that its benefits are not yet understood by the energy community.

PART TWO - INVENTION DESCRIPTION AND DISCUSSION

An objective of hybrid solar design is to combine the relative advantages of active and passive design approaches while minimizing their respective disadvantages.

Active collection methods tend to harvest solar energy with good efficiency and do not lose energy during periods when they are not operational (as passive collectors do). Operational efficiency is greatest when the solar resource is harvested at low temperatures relative to the ambient air. The usefulness of active heating systems has been compromised by the cost and complexity of the various mechanical systems needed to collect, store and distribute the solar energy. Cost and practical considerations limit the size of the storage component which tends to raise system temperatures and lower collector efficiency.

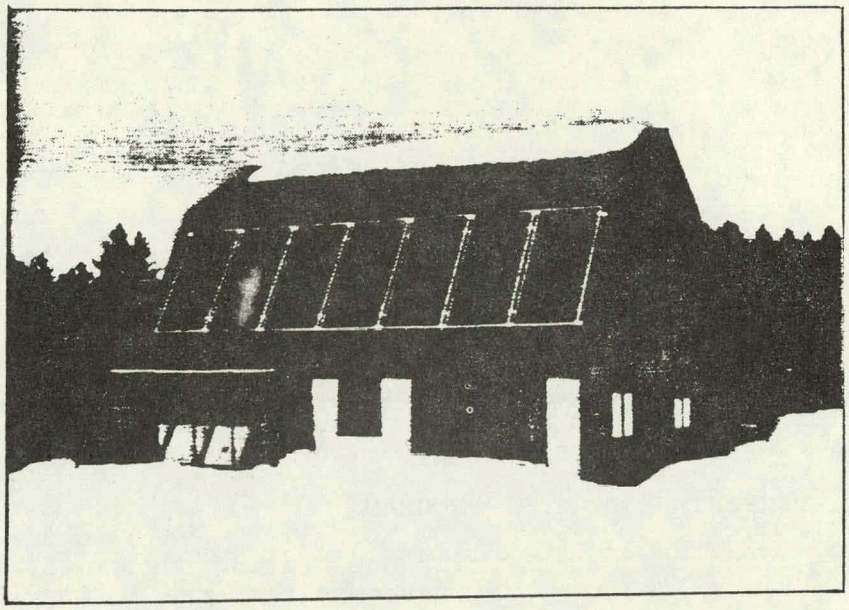
Many passive approaches reduce cost and complexity by using conventional building components to collect, store and deliver solar energy. The usefulness of passive methods is compromised by the fact that the collection element is a part of the building envelope causing it to lose heat at night. These losses lower overall efficiency and in cold cloudy regions can result in negative energy gains. The size of the storage element, as in active systems is limited by cost, architecture and other considerations.

The Solar Option One(Figure #1)is a hydronic heating system using conventional hydronic solar collectors to heat a radiant panel slab.

A heated fluid is pumped in an active manner from the solar collectors throughout the radiant slab whenever solar energy is available. Heat is stored within the slab and compacted earth beneath. It is released to the heated space in a passive manner without controls by radiation and convection. Solar energy which exceeds heating load requirements is diverted to the domestic hot water load in residential applications.

High collector efficiencies are achieved with active collectors. The design approach raises a uniquely large thermal mass to relatively modest temperatures unlike conventional systems which raise a smaller thermal mass to relatively high temperatures. Solar energy is utilized at the lowest possible temperature resulting in the highest possible collector efficiencies. Overall cost and complexity is reduced by using a structural component of the building to store and release the solar energy.

High collector efficiencies increase the amount of solar energy harvested on sunny days and permit operation under marginal solar conditions (early AM, late PM, cloudy days) when collectors operating at higher temperatures will not reach "threshold temperature". An increase in collector efficiency



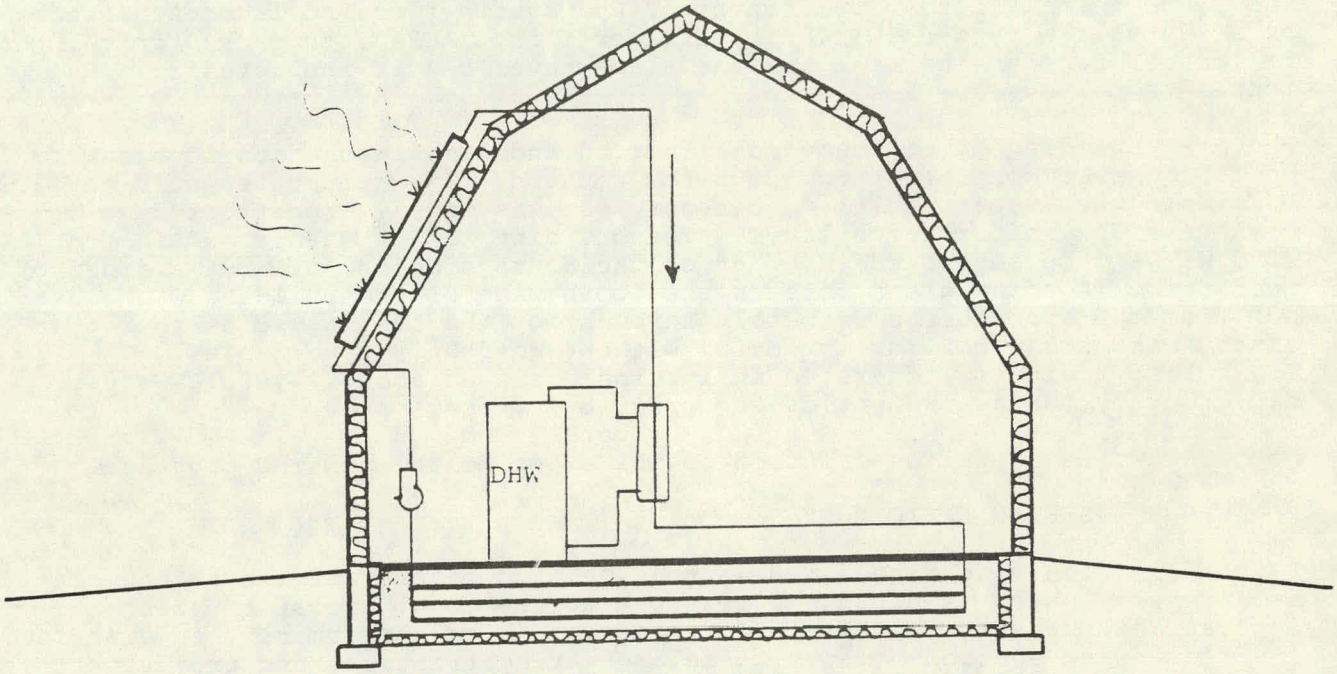


Figure #1 Schematic of The Solar Option One Heating System

translates into fewer solar panels, lowered costs, and easier design integration into accepted building styles.

A large thermal mass, integrated with the buildings structure provides prolonged solar storage, radiant comfort and further lowered costs.

The overall simplicity of the design results in improved reliability and greater consumer confidence. The design lends itself to convenient "packaging" which can lower cost, simplify design and installation, improve reliability and present the product in the manner that building professionals are accustomed to receiving it.

PART THREE - EXPERIMENTAL TEST PROGRAM

A test house using the Solar Option One heating system was experimentally monitored to determine its enery based performance during the 1982-83 heating season. The test residence is located in Lyndonville, Vermont, an area which has a characteristicly cold and cloudy climate. The two story residence has a floor area of about 1,400 square feet and is constructed on a 720 square foot 5.5 inch thick floor slab. A 24 inch packed gravel bed is located beneath the slab and the slab-gravel bed is insulated by two inches of polystyrene insulation.

The test building is of frame construction and uses insulation levels which have become commonplace throughout the country. The structure would not fall into the "superinsulated" category but was tightly constructed so as to have a low infiltration level. The building is "sun-tempered" in that windows were concentrated somewhat on the South side and all but avoided on the North. A solar greenhouse on the South side of the building was closed off from the structure permanently throughtout the testing so as to better observe the solar heating invention without confounding variables. The monitoring equipment generated an internal gain of about 17,000 BTUs per day, roughly the equivalent of occupancy by two persons.

Section two is a full description of the experimental testing program.

PART FOUR - SYSTEM EFFICIENCY

System efficiency as discusssed in this section refers to the amount of solar energy which is harvested relative to the total amount of solar insolation which is available at the site. System performance, as discussed in a following section relates to solar heating fractions and productivities which result when a particular system is applied to a particular heating load.

Table 2.19 is a summary of the measured monthly efficiencies which were observed at the test building in Vermont.

Figure 14 is based on the performance of active heating systems using air, hydronic and evacuated tube solar collectors at Colorado State University. These systems were designed, installed and operated by solar specialists in a closely controlled measurement program. (1.1)

It is seen that the low cost Solar Option One heating system, in its Vermont location provides substantially higher efficiencies than the active heating systems monitored in Colorado. It is significant that Colorado receives more than twice as much winter solar insolation as the Vermont location.

TABLE 2.19

SUMMARY OF COLLECTOR PERFORMANCE

Month	Total Solar Input to Collectors (BTU X 10^6)	Measured Output from Collectors (BTU X 10^6)	Average Monthly Efficiency (%)
November	3.358	1.668	49.7
December	3.926	1.972	50.2
January	4.915	2.350	47.9
February	6.632	3.334	50.3
March	6.390	3.104	48.6
April	2.967	2.967	49.2

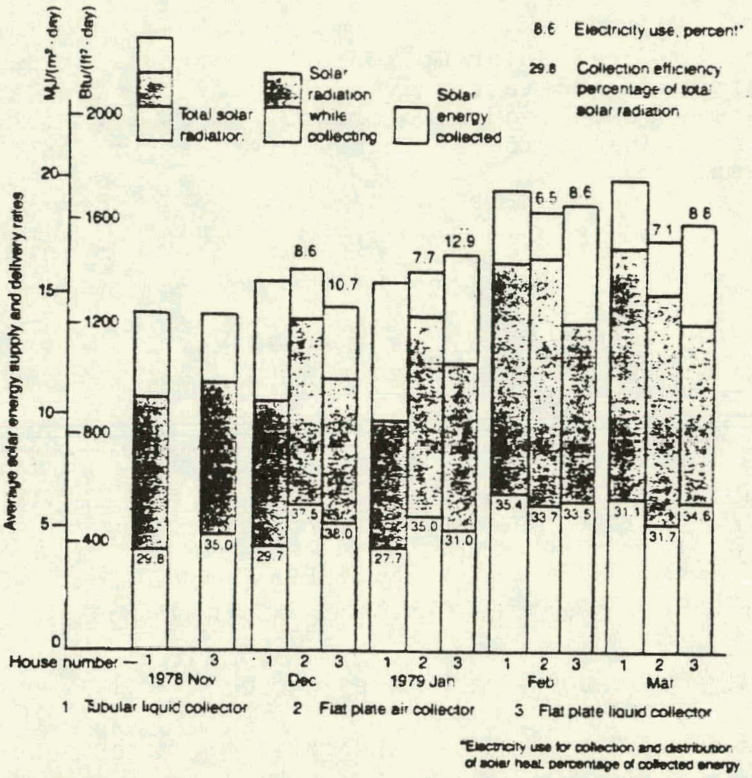


Fig. 14 Performance of solar space heating systems in three solar heated houses at Colorado State Univ. [Ref. 12]

Low solar collector temperatures were the primary reason for the favorable efficiencies which were observed. Electrical energy consumed by the pump and controller at the test site was 5.3% of the total collected solar energy. The additional flow resistance of the monitoting equipment (BTU meter, flow meter etc.) resulted in a need to select a pump with 2 times the output of the pump which would be used if the monitoring equipment were not present.

The electrical energy consumed by the pump and controller in a similar system which is not monitored would therefore be about 2.7% of the solar energy harvest.

PART FIVE - SLAB STORAGE HEAT EXCHANGER EFFICIENCY

The slab storage heat exchanger is constructed of high molecular weight polyethylene tubing. This material is replacing copper tubing in radiant panel applications. It is manifolded to achieve reasonable pressure drops and appropriate flow through the system. The Final Technical Report by The National Bureau of Standards reports that the heat exchanger "is superior to copper because it is lower in cost, can be installed without inaccessible joints, and has low friction losses, high resistance to corrosion and a long service life. The pipe's low cost permits redundency in design."(1.2)

Figure #2 is a temperature profile which was observed at 11:09 on Julian day #297 (October 24), under conditions of strong sunlight all morning. Under these conditions, storage temperatures are non uniform (with temperatures higher about the pipe than throughout the mass in general), and energy output of the solar panels is high.

Collector temperatures are more closely coupled with the average slab temperature under conditions of less intense sunlight or when storage temperatures are more uniform (in the AM).

Under the observed conditions on Julian Day #297, the collector /slab heat exchanger, operating with an efficency of .67, harvests 97.3% of the energy which would be harvested by an ideal heat exchanger (one of infinite area and length). (61.0% of the available insolation vs 62.7%)

A heat exchanger having two times the length and area of the reference design would harvest 98.7% while an exchanger with one half of the length and area of the reference design would harvest 91.9%.

It would appear that the reference heat exchanger has a size which is effective and in the optimal range considering costs and benefits.

Redundency in the design is also apparant as the loss of one half of the heat exchanger would result in a system performance loss of only 5.4%.

PART SIX - HEAT LOSSES TO THE GROUND

Figure #3 is a temperature profile of ground temperatures observed in the latter part of January, 1983 when earth temperatures were at their lowest.

The temperature of an unheated slab under the design conditions is estimated to be 60 degrees F. The temperature of a slab which is at a temperature which would fully heat the building to design conditions is 68 degrees F.

The additional heat loss which results from this 8 degree additional temperature requirement would be 612 BTU hour in the reference test building or 7% of the building's average heating demand if the ground beneath the polystyrene insulation presented no additional capacitance or resistance to heat flow.

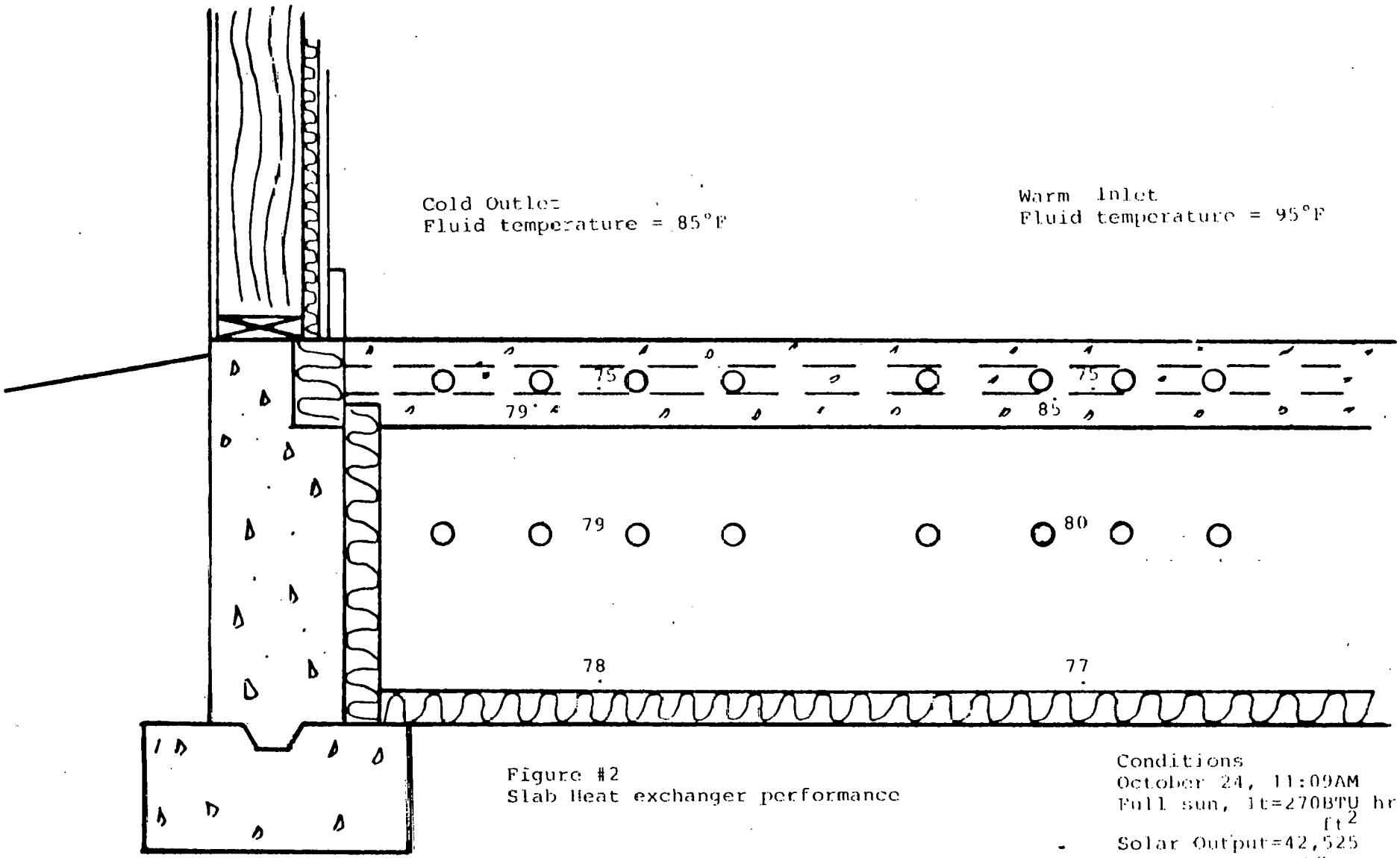


Figure #2
Slab Heat exchanger performance

Conditions
October 24, 11:09AM
Full sun, It=270BTU hr ft^2
Solar Output=42,525 BTU/hr
Average Mass Temperature=80°F

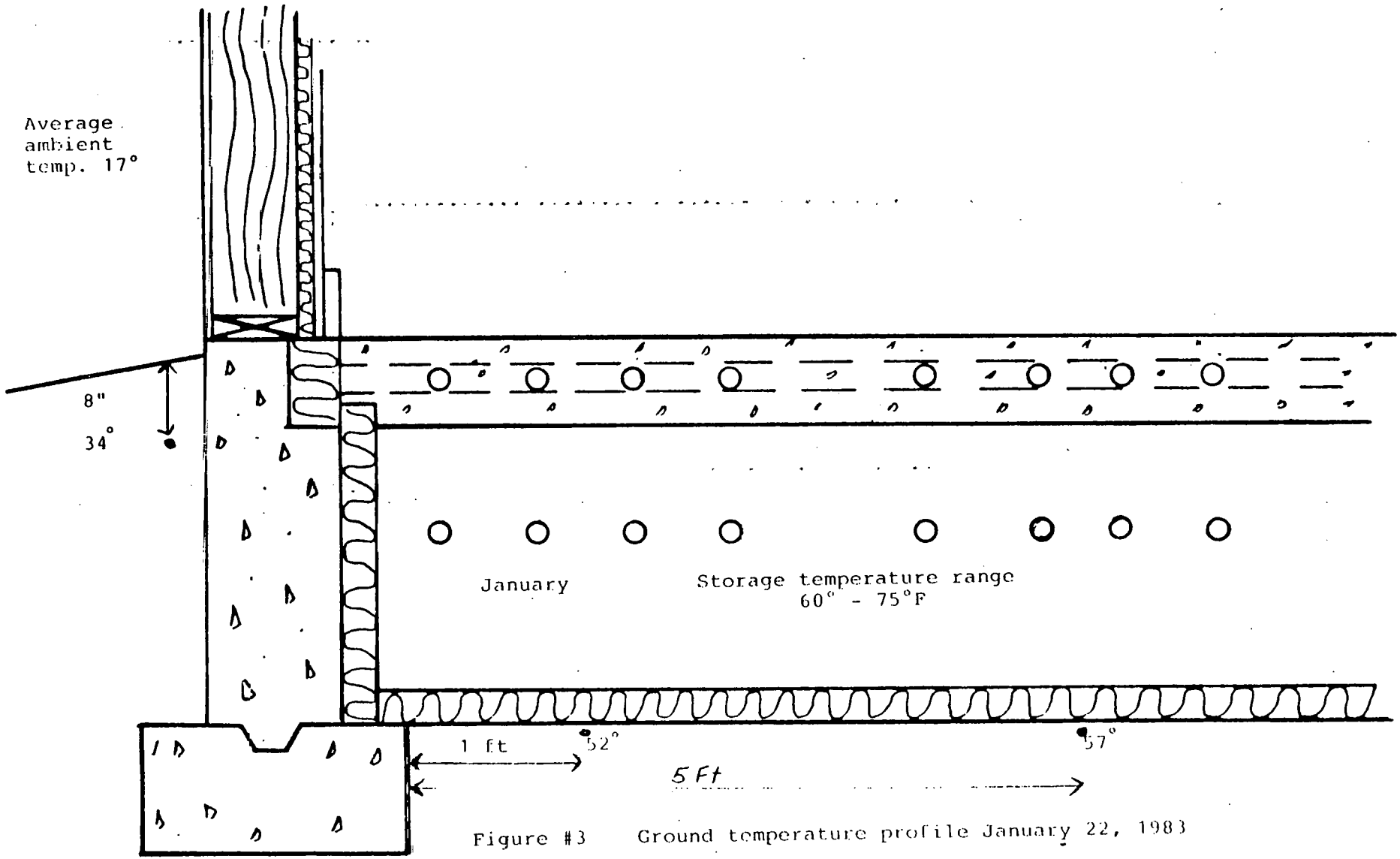


Figure #3 Ground temperature profile January 22, 1983

This capacitance and resistance to heat flow is observed however, and the phenomenon will result in a lower heat loss than is calculated above.

It is noted that additional comfort can be provided by a radiantly heated floor.

The Final Technical Report by The National Bureau of Standards notes the following about radiant panel systems, "...such systems function on the basis of providing a comfortable environment by controlling surface temperatures and minimizing excessive air motion within the heated space. The occupant is not aware that the environment is being heated. As learned from physiological studies, the mean radiant temperature (MRT) strongly influences the feeling of comfort. When the temperature of room surfaces begin to deviate excessively from the ambient air temperature of the heated space, it becomes difficult for convective systems to counteract the resulting discomfort felt by the occupant. Large surface heating panels neutralize this deficiency and minimize excessive radiation losses from the occupant's body."(1.3)

Calculations by Swisher at the Solar Energy Research Institute suggest that, "Introducing a warm radiant surface in a passive or hybrid design raises T_{mr} (mean radiant temperature) usually above T_r. This allows the comfort level to be achieved at a lower room air temperature. ...Reducing the thermostat set temperature by this amount decreases the heating load by about 10% in most climates." (1.4)

PART SEVEN - PERFORMANCE

System performace as discussed in this section refers to solar heating fractions and system productivities which, occur when a particular heating system is applied to a particular load.

The Solar Option One heating system stores and releases solar energy in a passive manner. The storage element is integral with the building envelope and its thermal capacitance buffers the various energy flows such that the interior temperature tends to remain within the comfort zone despite the varying energy gains and losses of the building.

The amount of thermal mass strongly influences the degree to which an input of solar energy can meet a building's heating load (solar heating fraction). If thermal mass is inadequately large, lower solar heating fractions result. In the passive instance, the mass is overcharged, resulting in unacceptably high room temperatures and a dumping of heat. In the active instance, storage temperatures rise to the point where collector efficiency is impaired.

The Solar Option One thermal storage subsystem differs from conventional active and passive systems in that the storage is uniquely large. In the experimental test structure, the storage mass contains 1,440 cubic feet of concrete and packed gravel and weighs over 70 tons. The incremental cost of this storage is nil in the slab on grade building.

The temperature of an unheated floor slab is coupled more closely to the mean radiant temperature than to the thermostat set temperature in a convectively heated building. The floor slab loses radiant heat to the relatively cooler walls and windows. In a building under moderate heating load, the floor temperature will be approximately 5-10 degree F cooler than the thermostat setpoint.

The temperature of a floor slab which is heated sufficiently to maintain room temperature in a building insulated to modern standards will be 5-10 degrees F above room temperature under moderate heating load.

If acceptable daytime comfort levels lie within a room temperature range between 65 degrees F and 78 degrees F, storage temperatures could range between 60 degrees F (when fully discharged) and 83 degrees F (when fully charged).

Figure 2.23 shows the response of the residence (via slab and inside temperatures) to the outside temperature and solar collector input for six days in January. As shown, the interior is maintained at a reasonable comfor level despite wide fluctuations and low ambient temperatures.

Table 2.20 gives a summary of the system performance on a month by month and seasonal basis. The months of November and February showed very high solar heating fractions (97.6% and 93%) of the controlled heat requirement without the need to dump heat by ventilation.

These observations suggest that the slab storage subsystem is large enough and effective enough to enable high solar heating fractions in cold months without the diminishing returns associated with periodic overheating.

Observations of other buildings in Vermont using Solar Option One heating system indicate that room temperature as compared to thermostat set temperature depends upon the solar heating fraction at the time.

When solar heating fractions are in the vicinity of 50% on a monthly basis, actual room temperatures are coupled fairly closely to the thermostat set temperatures.

Observations at the experimental test site during months with higher solar heating fractions (November and February) show that daytime temperatures ranged up to 13 degrees F above the minimum thermostat setpoint. A daytime temperature profile would resemble a bell shaped curve with few observations about the 65 degree minimum, the majority of observations about 5 degrees above the setpoint within the full comfort range and a few observations at th high end of the acceptable temperature range.

The heat loss of a Vermont building in January which has an average temperature of 70 degrees F will be eleven percent greater than that of a building which maintains 65 degrees.

It would seem that a solar energy input of at least 111% of the calculated load will be required to produce a temperature profile in which few observations are seen at the thermostat setpoint (a high solar heating fraction).

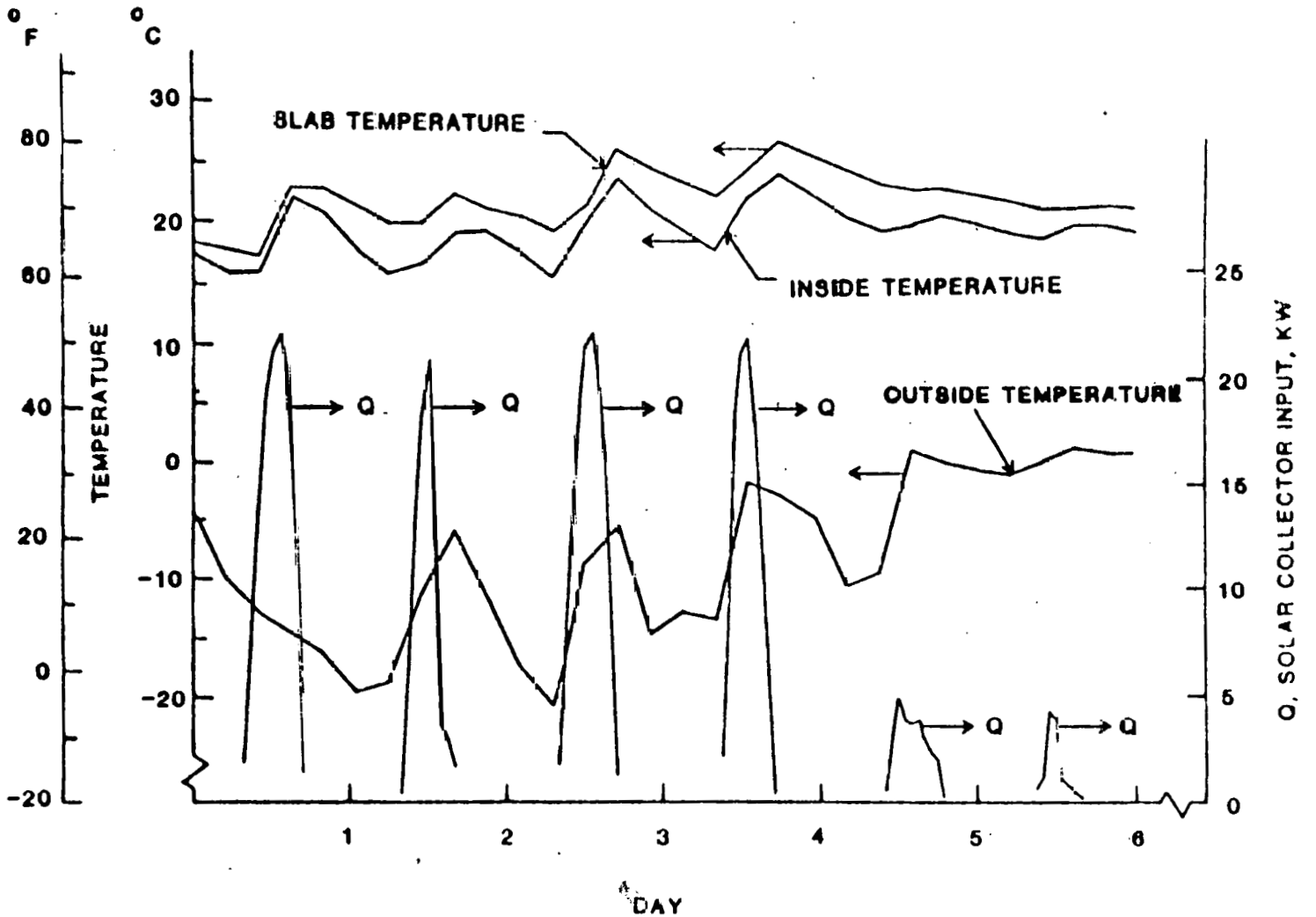

°F
°C
80
60
40
20
0
-20
30
20
10
0
-10
-20
TEMPERATURE
SLAB TEMPERATURE
INSIDE TEMPERATURE
OUTSIDE TEMPERATURE
Q
25
20
15
10
5
0
Q, SOLAR COLLECTOR INPUT, KW
1
2
3
4
5
6
DAY

FIGURE 2.23

TABLE 2.20

SYSTEM PERFORMANCE SUMMARY
(All Values in Units of 1000 Btu)

	Heating Loads			Electrical Energy Input		
Month	Simple ASHRAE	Computer Model	Auxiliary Heating Energy	Pumping Energy	Appliance Energy	Total Electrical Input
November	3,830	2,038	41	177	505	723
December	5,423	3,447	653	123	522	1,298
January	6,576	4,472	859	143	522	1,524
February	5,564	3,655	251	164	471	886
March	4,824	2,742	0	182	522	704
April	3,259	1,409	0	188	505	693
Totals	29,576	17,763	1,804	977	3,047	5,828

Room temperatures in a building with a radiant floor slab tends to be variable depending upon the degree of heating load which is placed upon the building. Heating loads during the night are higher due to the absence of passive gains, a lower ambient temperature and a lessening of internal gains. A higher temperature difference between slab temperature and room temperature is required to meet the higher load. These phenomena result in a lower nighttime room temperature and in effect give a natural night setback.

PART EIGHT - SIMPLIFIED PERFORMANCE METHOD

An objective of the simplified performance method is to provide a prediction tool which can be used by persons with basic arithmetic and graph reading skills but little knowledge of solar heating design.

Another objective is to present information about the performance of the Solar Option One heating design in a way that is more familiar to people who work with conventional heating systems (BTU OUTPUTS, etc.).

Any simplified prediction tool makes certain concessions to simplicity at the expense of precision. Section three provides a detailed computer method which can be used by those who require a higher level of precision.

The method presented here will yield results which are sufficiently accurate for most residential and small commercial applications.

An important assumption is that a nighttime setback of about 5 degrees is acceptable and that temperature excursions within the comfort range (65-80 degrees F) are allowed. It must be emphasized that the method is based on longterm <u>averages</u> of building load and solar insolation. The performance predictions are therefore also averages. Actual performance, particularly on a monthly basis, can and probably will be higher or lower depending upon these weather related variables.

The method standardizes important variables such as collector performance, heat exchanger design, flow rates, control scheme and the amount of thermal mass to those values which were seen to work well in the research program. It is assumed that "prepackaged" systems will be developed which would eliminate the need for the end user to deal with these variables.

The five step method is:

STEP ONE - Calculate the average monthly heating BTU output of the solar collectors (S'). (Average monthly solar insolation in BTU's/ft^2 for the particular tilt angle is multiplied by the Efficiency factor (50%) and then by the square footage of the collector array.

STEP TWO - Calculate the average monthly heating load of the structure using standard methods. (L)

STEP THREE-Calculate BTUs harvested per BTUs required (S'/L) by dividing results of Step One by the results of Step Two.

STEP FOUR - Determine the Solar Heating Fraction (SHF) from a graph or with the relationship below.

1. If S'/L is greater than 120%, SHF equals 1.0/
2. If S'/L is less than 80%, SHF equals S'/L.
3. If S'/L is between 120% and 80%, interpolate by solving

$$SHF = .8 + \frac{S'/L - .8}{2}$$

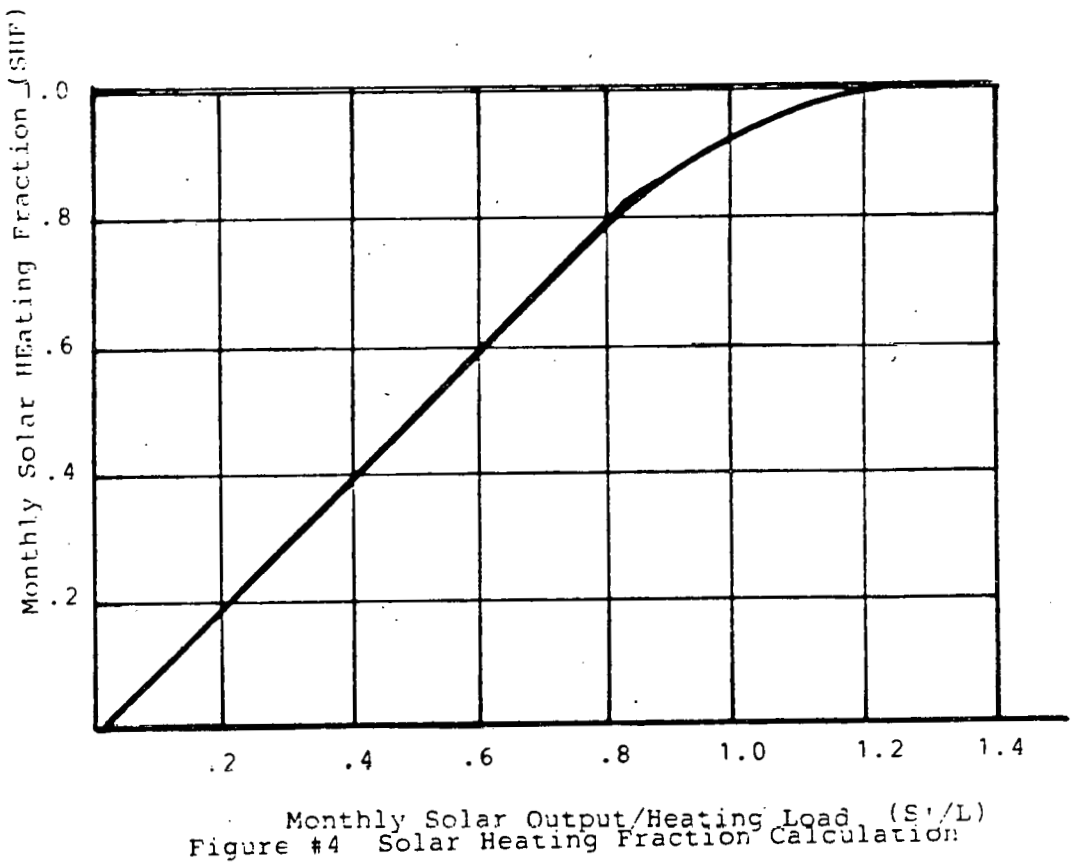


Figure #4 Solar Heating Fraction Calculation

STEP FIVE - Productive energy produced equals SHF X L.

The heating load of the domestic hot water can simply be added to the space heating load if design is such that solar energy which exceeds the space heating load can be applied to that use. The method will overstate the DHW actually produced to some extent during the swing season but will not greatly affect the overall productivity calculation.

Examples of the calculation are presented below for Boston, Massachusetts and Denver, Colorado.

EXAMPLE #1

Calculate Solar Heating Fraction and productivity for a building located in Boston, Massachusetts having a heat loss coefficient of 200 BTU/hour/degree F and a solar aperture of 263 ft^2 (seven 4' X 10' solar panels).

STEP ONE

	SOLAR RADIATION BTU/ft^2 60 degree tilt		EFFICIENCY FACTOR		COLLECTOR AREA	AVERAGE MONTHLY BTU OUTPUT (MBTU)
JAN	30,349	X	.5	X	263	3.991
FEB	33,404	X	.5	X	263	4.392
MARCH	42,532	X	.5	X	263	5.593
APRIL	41,760	X	.5	X	263	5.491
MAY	44,206	X	.5	X	263	5.813
JUNE	46,320	X	.5	X	263	6.091
JULY	48,794	X	.5	X	263	6.416
AUGUST	49,755	X	.5	X	263	6.542
SEPT	50,640	X	.5	X	263	6.659
OCT	48,019	X	.5	X	263	6.315
NOV	30,030	X	.5	X	263	3.949
DEC	27,249	X	.5	X	263	3.583

STEP TWO LOAD CALCULATION

	DEGREE DAYS BASE 65		DAILY HEAT LOSS PER DEGREE F (UA X 24)		MONTHLY HEAT LOAD		DHW	TOTAL HEATING LOAD (MBTU)
JAN	1110	X	4.800	=	5.328	+	1.54	6.868
FEB	969				4.651		1.39	6.041
MARCH	834				4.003		1.54	5.543
APRIL	492				2.362		1.49	3.852
MAY	218				1.046		1.54	2.586
JUNE	27				.130		1.49	1.62
JULY	0				0		1.54	1.54
AUGUST	8				.038		1.54	1.578
SEPT	76				.365		1.49	1.855
OCT	301				1.445		1.54	2.985
NOV	594				2.851		1.49	4.341
DEC	992				4.762		1.54	6.302
Total	5,621				26,981		18,13	45,111

EXAMPLE #1

	STEP#3 S'/L	STEP#4 SHF	STEP#5 Useful energy produced
JAN	.58	.58	3.983
FEB	.73	.73	4.410
MARCH	1.01	.91	5.044
APRIL	1.43	1.0	3.852
MAY	2.25	1.0	2.586
JUNE	3.76	1.0	1.620
JULY	4.17	1.0	1.540
AUGUST	4.15	1.0	1.578
SEPT	3.59	1.0	1.855
OCT	2.12	1.0	2.935
NOV	.91	.86	3.733
DEC	.57	.57	3.592
			36.728

Annual SHF $\frac{36.728}{45.111}$ .81

Productivity/ft^2 $= \frac{36,728,000}{263} = 139,650$

EXAMPLE #2

Calculate SHF and productivity for a building located in Denver, Colorado having a heat loss coefficient of 200 BTU/hour/$^{\circ}$F and a solar aperture of 150 ft^2 4 (4X10) solar panels.

STEP ONE - Average monthly BTU output

	SOLAR RADIATION BTU/ft^2 60 degree tilt	EFFICIENCY FACTOR	COLLECTOR AREA	AVERAGE MONTHLY BTU OUTPUT (MBTU)
JAN	52.601	X.5	X 150	3.945
FEB	50.490			3.787
MARCH	58.339			4.375
APRIL	52.424			3.931
MAY	52.285			3.921
JUNE	51.487			3.862
JULY	52.847			3.964
AUGUST	55.126			4.135
SEPT	57.509			4.313
OCT	59.241			4.443
NOV	50.331			3.775
DEC	49.242			3.693

STEP TWO - Load Calculation

	DD		UAX24		Space heating load		DHW		Total heating load (MBTU)
JAN	1088	x	4800	=	5.222	+	1.54	=	6.762
FEB	902				4.330		1.39		5.720
MARCH	868				4.166		1.54		5.706
APRIL	525				2.520		1.49		4.010
MAY	253				1.214		1.49		2.704
JUNE	80				.384		1.49		1.874
JULY	0				0		1.54		1.54
AUGUST	0				0		1.54		1.54

	DD		UAX24		Space Heating Load		DHW		Total heating load (MBTU)
SEPT	120	x	4800	=	.576	+	1.49	=	2.066
OCT	408				1.958		1.54		3.498
NOV	768				3.686		1.49		5.176
DEC	1004				4.819		1.54		6.359
Total	6016				28.875		18.13		47.005

	STEP #3 S'/L	STEP #4 SHF	STEP #5 Useful energy produce (BTU)
JAN	.50	.58	3.922
FEB	.66	.66	3.775
MARCH	.77	.77	4.393
APRIL	.98	.89	3.569
MAY	1.42	1.0	2.754
JUNE	2.06	1.0	1.540
JULY	2.57	1.0	1.540
AUGUST	2.69	1.0	1.540
SEPT	2.09	1.0	2.066
OCT	1.27	1.0	3.498
NOV	.73	.73	3.778
DEC	.58	.58	3.688
Total			36.397

$$\text{Annual SHF} = \frac{36.397}{47.005} = .77$$

Productivity = 36.397 (BTU)

Productivity/ft^2 36.397/150 = 242,647 BTU

PART NINE - PERFORMANCE AND COST PERFORMANCE ANALYSIS: THE SOLAR OPTION ONE HEATING SYSTEM vs REPRESENATIVE ACTIVE AND PASSIVE SYSTEMS

Table six presents system performance and cost performance data for the Solar Option One heating system and typical active and passive systems when installe in a represenative residential dwelling located in Boston, Massachusetts. (UA=200 BTU/hr/F)

Table five presents the design parameters which were used.

TABLE FIVE - DESIGN PARAMETERS FOR THREE SOLAR HEATING SYSTEMS Boston, Massachusetts

	ACTIVE	PASSIVE (THOMBE WALL,VENTED)	SOLAR HEATED SLAB
COLLECTOR AREA	263 ft^2	263 ft^2	263 ft^2
COLLECTOR GLAZING	single	double	single
ABSORBER SURFACE	selective	non selective	selective

	ACTIVE	PASSIVE (TROMBE WALL, VENTED)	SOLAR HEATED SLAB
COLLECTOR TILT	60 degrees	90 degrees	60 degrees
STORAGE VOLUME	66.8 ft^3	263 ft^3	1,440 ft^3
STORAGE CAPACITY (BTU/F/FT^2 solar aperture)	15.85	30	136.88
NIGHT INSULATION	NA	R=9	NA
HOT WATER PROVIDED?	yes	no	yes

TABLE SIX - SYSTEM PERFORMANCE AND COST EFFECTIVENESS DATA Boston, Massachusetts

	ACTIVE	PASSIVE	SOLAR HEATED SLAB
SPACE HEAT (MBTU)	18.35	14.57	23.86
(SOLAR FRACTION)	.68	.54	.89
DOMESTIC HOT WATER	12.41	0	12.87
(SOLAR FRACTION)	.68		.71
TOTAL ENERGY DELIVERED	30.76	14.57	36.73
INSTALLED COST	11,500 (1984)	$5,500	$6,600
CAPITAL COST/MBTU/YR	$374	$377	$180

In actual practice, consumers who elect to install a Solar Option One heating system instead of a conventional heating system take a furnace credit on the backup heating equipment which varies on a case by case basis.

Some consumers will downsize the backup heating system from typical design heating requirements. Others substitute a heating system with low capital costs and higher operating cost (electric) for one with high capital costs but lower operating costs (oil or gas). Others use a low cost manually operated backup heating source (wood or coal stove).

A consumer who takes a $1,500 furnace credit will have an incremental cost for his solar heating system of $5,100 in the reference case located in Boston, Massachusetts.

His solar investment will yield a 12.66 return on his investment (tax free) in the first year if equivalent energy would cost $17.58/MBTU or 6¢/KWH.

The performance of his investment will increase over time if the price of conventional energy rises due to escalation and/or inflation.

These calculations do not account for solar tax credits. To the extent that they may apply, cost performance improves. Higher cost performance is also to be expected in sunnier and milder regions.

Under a variety of cost benefit calculations which factor depreciation, avoided energy costs, avoided capital costs in the conventional system, the value of invested capital, inflation, etc., the Solar Option One heating system yields attractive returns in the first year of operation with higher returns to be expected in the future.

Conventional energy prices are an aggregation of the prices of "old" energy and the price of "new" energy sources (new electric plants, off shore oil, new clean coal plants, synthetic fuels, etc.) The "new" sources of energy are considerably more expensive than the existing sources which are being depleted.

It is assumed that if a particular "new" and renewable energy source has a cost benefit which is attractive when compared to conventional energy prices its price is even more favorable when compared to the other "new" conventional energy sources to which it is more appropriately compared.

PART TEN - MECHANICAL PERFORMANCE

Applications of the Solar Option One heating system have been operating in the field for five years now. Preliminary information suggest that these systems should provide a long and relatively trouble free service life.

The Solar Option One is a simple system with few moving parts and fewer components than either active solar heating systems or conventional hydronic systems.

Most components are identical to those of conventional hydronic heating system. These components have achieved very high reliability due to their long development and service history in conventional systems.

The pump should last a long time due to low operating temperatures and good lubrication by the glycol fluid. No pumps have needed replacement to date.

The solid state controllers have proven very reliable and none have been replaced to date.

The glycol heat transfer fluid is showing good service life because of low operating temperatures and lack of exposure to air (oxidation of glycol to glycoloc acids). Glycol solutions which have been in service for five years are still showing effective levels of corrosion inhibitors.

Abusive testing of the plastic slab heat exchanger tubing was conducted. Repeated dumping of collector fluid at stagnation temperatures (300+F), produced no ill effects. Prolonged exposure to very high fluid temperatures (an improbable event which requires multiple simultaneous system failures) can cause failure of the joint at the plastic to copper connection. This event leakes the glycol transfer fluid into the gravel bed and shuts down

the system completely. The joint, which is accessable, must then be remade. No damage to the pipe itself occurs.

The heat exchanger tubing is flexible and resists considerable cracking of the concrete slab.

STATEMENT REGARDING THE PLANNED "NEXT STEP"

The following section will fulfill the DOE reporting requirements for a statement of the planned next step which will be taken to advance the status of the invention towards the goal of introducing a new product to the market.

TECHNOLOGY TRANSFER - This portion of the work will transfer knowledge of the invention's properties to a broader segment of the public. Whereas the invention is a simple, unpatented design approach, the technology transfer will require the cooperation of the various solar trade publications, architectural and engineering journals. If The Department of Energy feels that this work should be published, a statement to that effect would facilitate the effort. The inventor and other members of the research team will prepare papers and respond to inquiries to the extent that resources permi

PRODUCT DEVELOPMENT - If the opportunity exists, the subject invention will be incorporated into a broader product line of heating and cooling systems which will be more responsive to current and future energy situations than the products currently available. These hydronic heating systems will emphasize high thermal mass, low initial cost, and simple conversion capability to a number different energy sources including solar.

Heating systems with higher thermal mass provide benefits which are of interest in todays marketplace.

When electricity is the choice (usually because of low initial cost), it is most efficiently and economically used during "off peak periods". The utility and the society at large benefits when utilities have high load factors. The need for expensive new generating plants is reduced due to more efficient management of the load. The consumer benefits in most regions by the availability of low "off peak" rate structures. A high thermal mass electric boiler is essentially a modified domestic hot water tank. These units are low in cost due to mass production and will be comparable in price to conventional hydronic heating systems.

If solid fuels are considered, additional thermal mass provides convenience, efficiency and low emissions. Conventional installations must be attended to frequently, and are are usually "banked" (shut down with a load of fuel remaining) in order to control heat output. This practice results in pollution, creosote and poor temperature control.

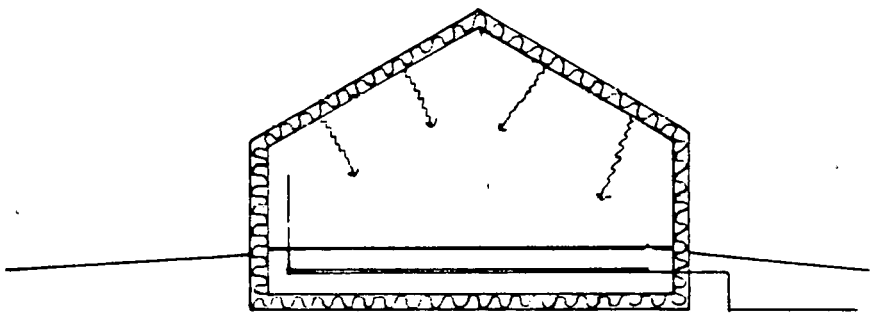
When solar is considered, either initially or at some future date, adequate thermal mass improves efficiency, performance and cost benefit. If a good conventional heating system is seen to have a higher level of thermal mass, the incremental cost of using solar heat is the cost of the solar panels.

Products will come in the form of "packaged systems" in order to lower costs, simplify design, decrease installation problems and present the product in a format similar to conventional heating systems and thus more familiar to the public.

The production and characterization of convertable heating systems would benefit individuals and the society at large by providing resiliency and flexibility in the present uncertain energy situation.

FURTHER RESEARCH - The Solar Option One research program has suggested the following corrollary applications:

RADIANT COOLING WITH COLD WATER SUPPLY



OPERATION - Cold water from the supply passes through a heat exchanger within the slab on its way to the fixtures. Heat is extracted from the building in the process.

APPLICATION - Slab on grade structures in climates with a cooling load and appropriate ground water temperatures. Assuming a water supply termperature of 55 degrees, a design temperature of 78 degrees, consumption of 300 gallons per day and a heat exchanger efficiency of 90%, 51,667 BTUs per day will be extracted from the building by this natural flow of energy which is present whether it is used or not. This application has very low initial cost and of course no operating cost.

Applications in high humidity climates may still require air conditioning

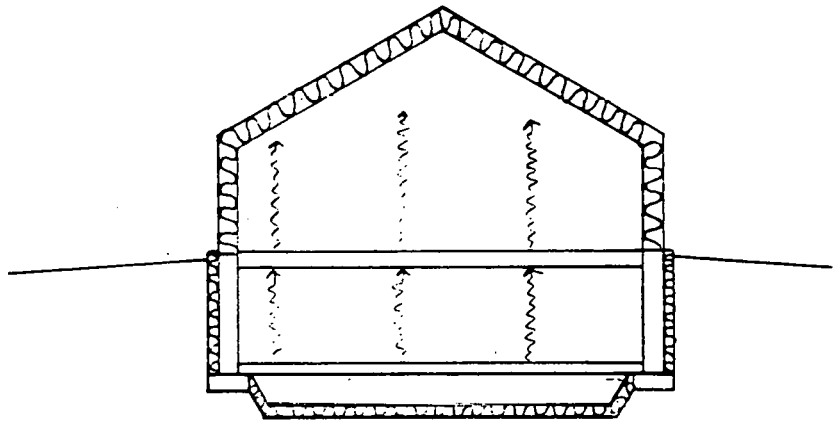
to lower the moisture content of infiltration air. In dry arid climates, the application will enhance comfort by not lowering the moisture content of room air.

RADIANT PANEL HEATING WITH DRAIN DOWN SOLAR AND COLD WATER SUPPLY COOLING

OPERATION- Solar heated potable water is circulated through the slab when needed for space heating. Supply water passes through the slab on its way to the fixtures and draws heat from the building. During the heating season, supply water bypasses the slab and goes directly to the fixtures.

APPLICATION - The application can be used in temperate climates where freeze protection is less pressing and where cooling loads exist. Excellent cost performance is predicted due to lowered initial cost (elimination of the glycol loop) and low cost cooling. Very high solar fractions can be expected in moderate climates.

INDIRECT RADIANT HEATING WITH SOLAR, OFF PEAK ELECTRIC OR SOLID FUELS



OPERATIONS - A "second story" above a radiantly heated "first story" is heated by transfer of heat through the floor ceiling structure.

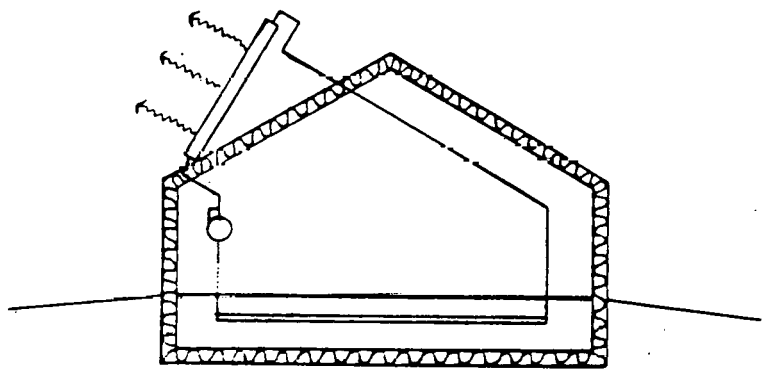
APPLICABILITY - The method applies when a full basement is used or when a second story is provided with slab on grade construction.

Some knowledge of the mechanisms involved was gained in the testing program. The test building is a two story structure. Temperatures in the second story are coupled within less than 5 degrees of the first story on below zero F nights. Inputs of very small amounts of auxiliary energy to the second floor will equalize temperatures indicating that the primary heat transfer mechanism is probably radiation through the floor rather than

convection through the stairwell opening.

Many Vermont buildings are now being fully heated by wood stoves in the basement. Information on these mechanisms however has not been characterized in a manner that would be useful to a designer.

RADIANT NIGHTTIME COOLING WITH UNGLAZED SOLAR COLLECTORS



OPERATION - Solar thermal energy is harvested during the day in the conventional manner and put to some use other than space heating. The building is cooled at night by radiating heat to the nighttime sky via the unglazed solar collectors.

APPLICATION - Climates which have cooling loads, particularily arid regions.

The high efficiencies which were observed in the Solar Option One testing program suggest that the cover sheet in the solar collectors may not really be needed in milder climates at low collector operating temperatures.

At high operating temperatures, the cover sheet lowers heat loss from the panel by absorbing energy radiated from the absorber plate and by sheltering the panel from convective losses.

The cover sheet also blocks about 20% of the incoming solar radiation by refraction, reflection and absorbtion.

New selective absorber coating techniques have decreased the importance of the cover sheets ability to trap energy which radiates from the absorber.

A favorable potential exists to develop a low cost, low temperature solar collector which would have a partially selective, weather resistent absorber and no cover sheet.

A solar collector such as this may produce heating efficiencies comparable to those observed in The Solar Option One testing program with glazed solar panels.

A nighttime cooling benefit coupled with possible spa or pool heating during warm months could result in very high productivities.

SOLAR RADIANT PANEL HEATING WITH PHASE CHANGE MATERIALS

OPERATION - Active solar panels charge a phase change material (eutectic salt) located within the building envelope. Heat transfers from storage in a passive manner by radiation and convention. Phase change modules are installed within interior partitions and floor joists.

APPLICABILITY - Phase change materials can store 15 time more energy than an equivalent volume of masonary material within a 15 degree temperature swing.

The development of this application would lead to retrofit possibilities and application of solar radiant panel heating systems to multi-story structures.

Statement of the status of the invention at the completion of the Grant period.

The increased use of solar energy is widely viewed as desireable.

Significant market penetration of solar heating applications have been limited by a number of factors. The more important ones are summarized below.

1. A need to reduce initial cost.
2. A need to improve efficiency.
3. A need to improve overall performance.
4. A need to reduce complexity and improve reliability.
5. A need to reduce the architectual constraints which solar design imposes.
6. A need to develop standardized designs with reasonable cost benefits over a broader range of climate conditions.

The research and development program has shown that the subject invention offers significant advantages in each of these areas.

The benefits which the invention offers were theoretical at the beginning of the R & D effort. These benefits have now been demonstrated in practice and have been verified by independent testing.

The underlying thermodynamic mechanics have been characterized in a manner than can be verified by others.

Opportunities to lower the installed cost of the invention (packaging, standardization,etc)have been identified.

Theses opportunities could lower installed cost by about 35%.

It would appear that the prospect for market penetration have improved as a result of the federally sponsored research and development effort.

An opinion of the effectiveness of Federal support in the evaluation, funding, and other support, as it affected the grantee's ability to develop his energy related invention.

The grantee feels that Federal support was effective and indispensable in the development of his invention.

The evaluation process at the National Bureau of Standard is time consuming but very through. This throughness is appreciated because it is easy to miss important points with a cursory investigation.

The invention was simply not ready for significant market penetration prior to federal support.

The free marketplace is often reluctant to undertake the research and development of simple technologies if proprietary ownership of the technology is uncertain. Futhermore, improvements in efficiency are not always welcome if these improvements would result in the sale of less material.

The inventor agrees that it is often desirable for the free marketplace to make decisions about which development efforts will show the greatest promise.

The inventor appreciates the ability of the Department of Energy to show flexibility in the application to this principle when appropriate.

REFERENCES

1.1 Solar Energy Applications Laboratory, CSU, "Operations, Performance and Maintenance of Integrated Solar Heating, Cooling and DHW Systems", prepared for the Solar Energy Research Institute, October, 1981.

1.2 The National Bureau of Standards, Final Technical Review; The Solar Option I, OERI #006040, Joel S. Premack, May, 1981.

1.3 Ibid

1.4 Solar Energy Research Institute, Active Charge/Passive Discharge Solar Heating Systems: Thermal Analysis and Performance Comparisons, Joel Swisher, June, 1981.

2. EXPERIMENTAL TEST PROGRAM SUMMARY

2.1 Objectives

The overall objective of this phase of the work was to carry out a detailed instrumentation and performance measurement of a full-scale operational test residence using a solar heated slab. Specifically, the system to be tested was a residence in Lyndonville, Vermont constructed by the Solar Option One Company. In this section, we will describe the overall system, data collection instrumentation, data reduction, and the results of analysis for the experimental tests carried out during the 1982-83 heating season.

2.2 Overall System Description

2.2.1 Residence

1. General Construction Details

The dwelling has 1,400 square feet of floor space on two stories. A gambrel type roof covers the 28 ft by 24 ft structure. Standard 2 in by 6 in framing (24 in on center) was used in the walls; 2 in by 8 in in the grambrel roof sides and 2 in by 4 in prefabircated trusses capped the roof. The shell was sheathed with 1/2 in aspenite and covered with cedar clapboards on the walls and asphalt shingles on the roof. The seven collector array (Grumman Model 32A - 32 ft^2 panels) faces due south on the steep part (inclined 60 degrees) of the gambrel.

The house is well insulated, the inner part of the exterior walls have 1 in Dow Blueboard insulation over the 4 mil vapor barrier followed by 1/2 in sheetrock. Oak flooring (7/16 in thick) covers a quarter of the 720 ft^2 slab-on-grade. On the remainder, 1/8 in linoleum has been laid.

All windows in the house are double glazed (5/8 in). The window distribution in the house is as follows:

East	35 ft^2
South	40 ft^2
West	30 ft^2
North	6 ft^2 (door)

The roofline runs east-west and no windows (with the exception of entry door glazing) were installed on the north side. Insulating window shades were installed for use at night.

Special care was taken during construction to assure a low infiltration rate. Also, the layout of the interior is open enough such that air circulated quite freely between rooms on both floors.

2. Summary of Heating Load Calculations

On site measurement of the test residence as well as construction details supplied by the Solar Option One Company were used to determine the heating load. Standard ASHRAE procedures (Reference 2.1) were utilized to determine the various R-values. Also, all framing was assumed to be 10 percent of the area involved. The following tables summarize the individual results of this analysis and Table 2.1 presents the overall heating load calculation summary.

ITEM	AREA (ft^2)	U-VALUE (W/SHADES) (ft^2 hr °F/Btu)	UA (Btu/hr °F)	UA (W/SHADES) (Btu/hr °F)
South				
Door	20	.19 (.165)	3.8	3.3
Windows	40	.45 (.25)	18.0	10.0
Wall	157.4	.0388	6.1	6.1
Total	217.4			
North				
Door	20	.19 (.165)	3.8	3.3
Wall	197.4	.0388	7.6	7.6
Total	217.4			
West				
Windows	31.4	.45 (.25)	14.1	7.9
Wall	299	.0388	11.6	11.6
Total	331.4			
East				
Windows	35.9	.45 (.25)	16.2	9.0
Wall	295.4	.0388	11.5	11.5
Total	331.3			
Roof				
Ceiling	418	.0276	11.5	11.5
Wall	495	.0345	17.1	17.1
Slab			26	26
Infiltration			57	57
Totals			204	182

TABLE 2.1

BUILDING HEAT LOSS SUMMARY

a. Walls (2" x 6" x 24" on center)

		R-Value (hr ft^2 °F/Btu) Between Frame	On Frame
1.	Inside Air Film	0.68	
2.	1/2" Gypsum Sheetrock	0.45	
3.	1" Dow Blueboard	6.00	
5.	4 mil Polyethylene Vapor Barrier	negl.	
5.	5 1/2" Fiberglass Batt Insulation	19.00	--
6.	2" x 6" Nominal Fir Frame	--	6.88
7.	7/16" Aspenite Sheathing	0.60	
8.	Cedar Clapboard (1/2 avg. thickness)	0.81	
9.	Outside Air Film	0.17	
	Total R-Value	27.71	15.59
	U-Value (Btu/hr ft^2 °F)	0.036	0.064

Average Wall U-Value = 0.9 (0.036) + 0.1 (0.064)
= 0.0388 Btu/hr ft^2 °F

b. Roof: (Wall (inclined 60°)

2" x 8" x 24" on center

		R-Value (hr ft^2 °F/Btu) Between Frame	At Frame
1.	Inside Air Film (60° inclination)	0.65	
2.	1/2" Gypsum Sheetrock	0.45	
3.	1" Dow Blueboard	6.00	
4.	4 mil Polyethylene Vapor Barrier	negl.	
5.	2" x 8" Nominal Fir Frame	--	9.06
6.	7 1/2" Fiberglass Batt	23.50	
7.	1/2" CDX Plywood	0.62	
8.	#15 Felt (Tar) Paper	0.06	
9.	Asphalt Shingles	0.44	
10.	Outside Air Film	0.17	
	Total R-Value	30.89	17.45
	U-Value (Btu/hr ft^2 °F)	0.0323	0.0573

Average Roof Wall U-Value = 0.9 (0.0323) + 0.1 (0.0573)
= 0.0345 Btu/hr ft^2 °F

c. Roof: Ceiling

2" x 4" trusses, 24" on center

The attic is treated as an adjacent unheated space. This assumes good ventilation.

		R-Value (hr ft^2 °F/Btu) Between Frame	At Frame
1.	Inside Air Film	0.61	
2.	1/2" Gypsum Sheetrock	0.45	
3.	1" Dow Blueboard	6.00	
4.	4 mil Polyethylene Vapor Barrier	negl.	
5.	2" x 4" Truss Frame	--	5.00
6.	12" Fiberglass Batt	38.00	--
7.	Adjacent Space Airfilm	0.61	
	Total R-Value	45.67	12.67
	U-Value (Btu/hr ft^2 °F)	0.0219	0.0789

Average U-Value of Roof Ceiling = 0.9 (0.0219) + 0.1 (0.0789)
= 0.0276 Btu/hr ft^2 °F

d. Windows and Doors

All windows are 5/8" double glazed side swing with a wood sash. Window areas noted previously are net of any wood.

	U-Value (Btu/ft^2 hr °F)
Doors (3'-0" x 6'8" - foam core)	0.19
Windows - plain	0.45
Windows - with window quilts	0.25 (Manuf. data)

e. Slab on Grade

The perimeter of the 5 1/2" thick concrete slab is insulated with 3" of polystyrene. Beneath the slab is 2' of gravel which is surrounded by 2" of polystyrene (sides and bottom).

$$UA = F \times P$$

Where F = heat loss per foot of perimeter of slab
P = length of perimeter

$$UA = 0.25 \times 104 = 26 \text{ Btu/hr °F}$$

f. Infiltration

A one third air change per hour was assumed.

House Volume = [98" x 246" x 274" + 92" x 225.5" x 246"]/12^3

= 9531 ft^2

UA Infiltration = 1/3 x volume x Cp_{air} = 1/3 x 9531 ft^3 x

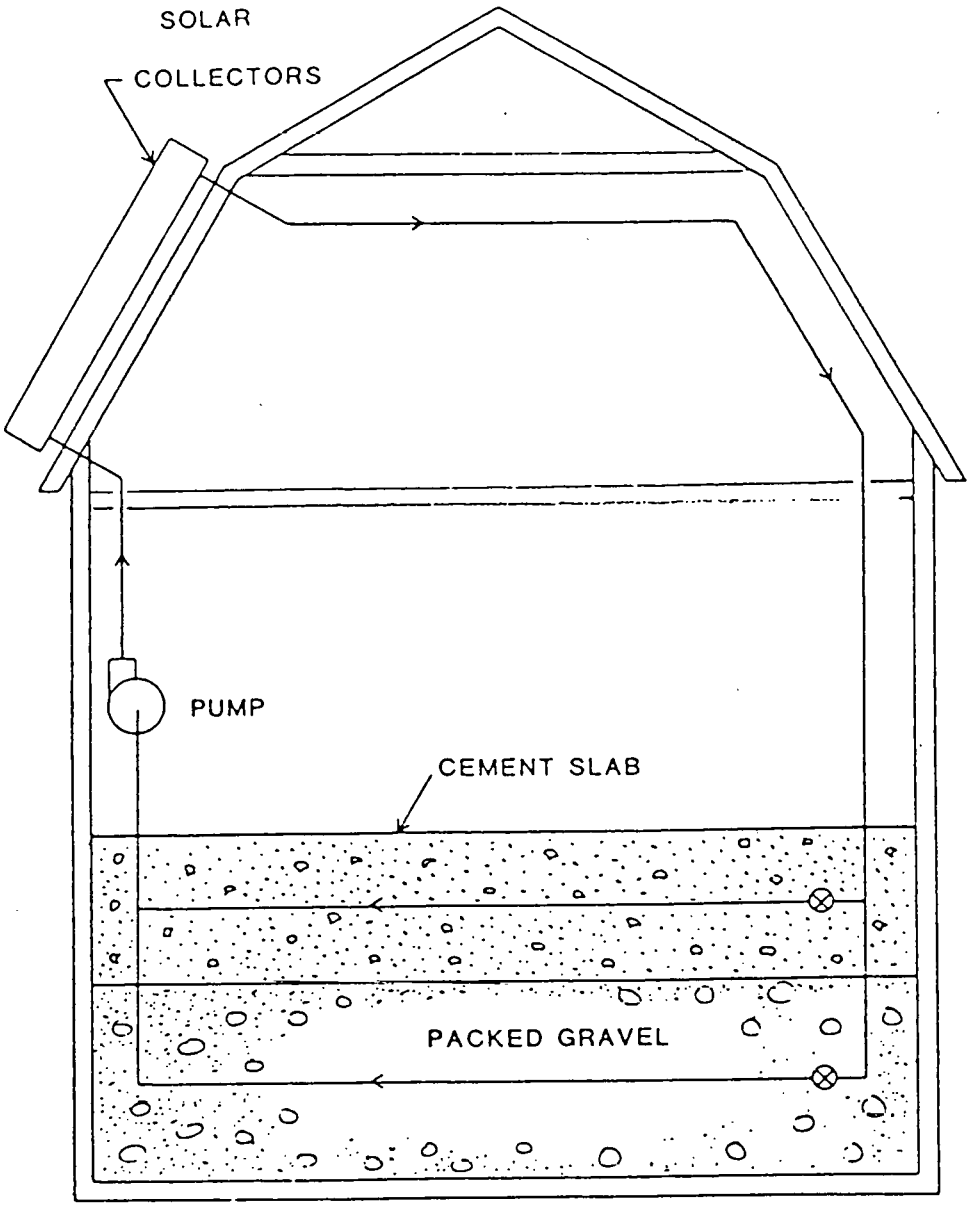
.018 Btu/°F ft^3 = 57

2.2.2 Solar Heating System

1. Overall System Design

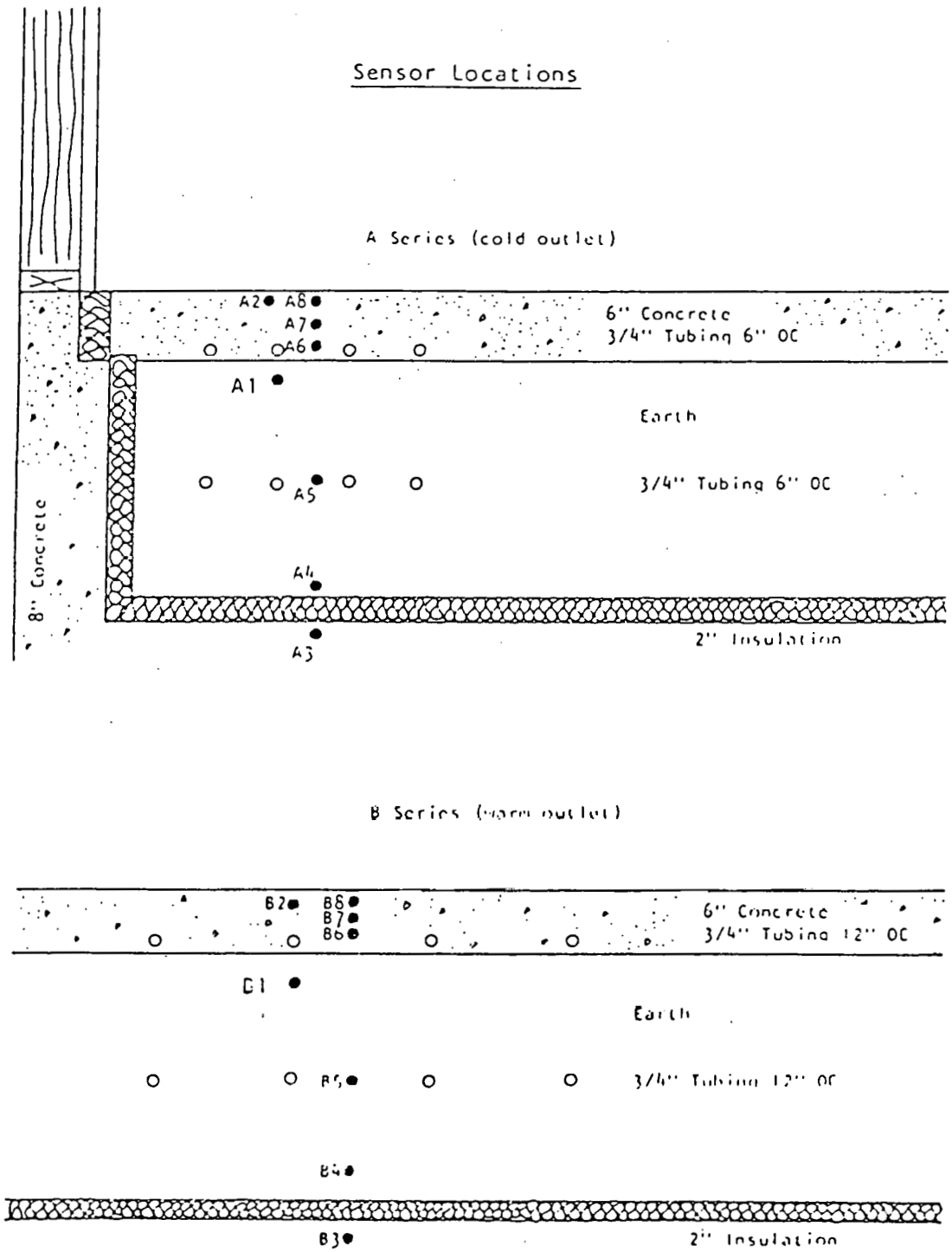
As shown in Figure 2.1, the basis of the Solar Option One system is the solar collection/slab storage system. Seven Model 32A Grumman solar hot water collectors are plumbed in series giving 210 ft^2 of aperture to the sun. The collector fluid (50 percent ethylene glycol/50 percent water) is pumped through the collectors at a rate that varies with the difference between monitored collector and storage temperatures. The collected solar energy is transferred directly to a slab and gravel bed storage via imbedded pipes. The residence receives its heat passively from radiative and convective transfer from this storage.

The 5 1/2" thick slab-on-grade has four 200 foot lengths (800 feet total) of high density polyethylene (HDPE) pipes (3/4 in inside diameter) imbedded in it. Beneath the slab is a two foot layer of bank run gravel with 600 feet of HDPE pipe running through the middle of it. The slab is insulated around its perimeter by 3 in of polystyrene. The gravel is insulated around the sides and bottom with 2 in of polystyrene. Details of this installation are shown in Figure 2.2.



SCHEMATIC OF SOLAR OPTION 1 SYSTEM

FIGURE 2.1



CONSTRUCTION AND SENSOR DETAILS OF SLAB/GRAVEL STORAGE

FIGURE 2.2

A proportional differential thermostatic controller (Natural Power Model S26) is employed to monitor the difference between the slab storage and collector outlet temperatures and to supply a collector flow rate proportional to that difference. In its original control scheme, the fluid is passed through the slab pipes to transfer its energy until the house temperature goes above 75°F. At this point, the fluid is routed to flow through both the slab and gravel bed. When the house reaches 80°F, the fluid is sent solely through the gravel.

The basis for this control logic lies in the greater lag time in the transfer of energy between the gravel and the house versus that between the slab and the house. The latter, of course, is directly coupled to the load whereas the former must conduct its stored energy through the slab before arriving at the load.

2. Operation and Control of the Heating System

During the measurement period, the test residence heating system had a number of possible adjustments that could be made. In the morning, the window shades were removed and the collectors were cleared of any snow. In the evening, the shades would be redeployed. If at any time there was overheating, the windows were opened. Manually read data and pertinent notes involving daily weather, the time shades were removed, and equipment status were tabulated in appropriate notebooks. A decision could also be made as to whether to warm the slab or the gravel with that day's heat by manually adjusting the appropriate valves. During most of the heating season, fluid was input simultaneously to both the gravel and the slab.

The house also contained a two setting thermostat which regulated the operation of a 2000 watt electric resistance baseboard heater to provide the auxiliary energy necessary to maintain 65°F house temperature in the daytime (2:00 p.m. to 10:00 p.m.) and 55 °F at night.

2.3 Experimental Test Program

2.3.1 System Instrumentation

The test residence was experimentally monitored between October 13, 1982 and May 1, 1983 in order to valuate its integrated energy collection, storage and distribution system. Measurement of various parameters in the residence was undertaken for the purpose of (a) trend analysis and (b) gathering data with which to calibrate a computer model to be used in a parametric analysis.

The data collection system consisted of numerous temperature and energy sensors distributed throughout the house. Table 2.2 gives a summary of the sensors involved. The sixteen resistance temperature devices (RTD's), the Li-Cor Solar Meter, the ISTA Btu Meter and two electrical watt hour meters as well as two temperatures (outside ambient and room) were recorded manually on data sheets. This data collection was performed twice a day - once in the morning and once in the early evening. In addition, a log book was kept to note items such as equipment malfunctions, night shade installation or removal, and a general description of the day's weather. The twelve thermocouples and the Eppley Pyranometer were sampled every fifteen minutes with a Fluke Model 2240A Data Logger coupled to a Texas Instrument's 733 ASR/KSR Electronic Data Terminal (equipped with cassette drives). The digitized data on the tape cassettes were transferred (via the TI 733 in TTY mode)

Table 2.2

Summary of Experimental Instrumentation Sensors

1. Temperature

   8 - RTD Sensors in Cement Slab
   8 - RTD Sensors in Gravel Bed
   4 - Thermocouples in Slab
   2 - Thermocouples Outside House
   2 - Thermocouples in Solar Collector Loop
   3 - Thermocouples Inside Residence

2. Energy

   1 - Eppley Pyranometer Model 8-48
   1 - Hollis Laboratory Recording Pyranometer System
       [LM-3000 (Recorder); MR-5A (Pyranometer)]
   1 - Li-Cor Model L1-175 Solar Meter/Integrator
   1 - Ista Btu Meter Model WMZ 2/50
   2 - Electrical Power Meters

3. Flow Rate

   1 - Brooks Rotameter in Collector (and Heat Exchanger) Flow Loop

to and processed with the University of Massachusetts Control Data Cyber 175 computer system.

The arrangement and location of the slab and gravel bed RTD's are shown in Figure 2.2. The B series RTD's are in a vertical line at the center of the beginning of the tubes at the warm inlet. There are four RTD's in the slab, three in the gravel and one just below the base insulation. The A series RTD's are similarly placed, but at the cold exit.

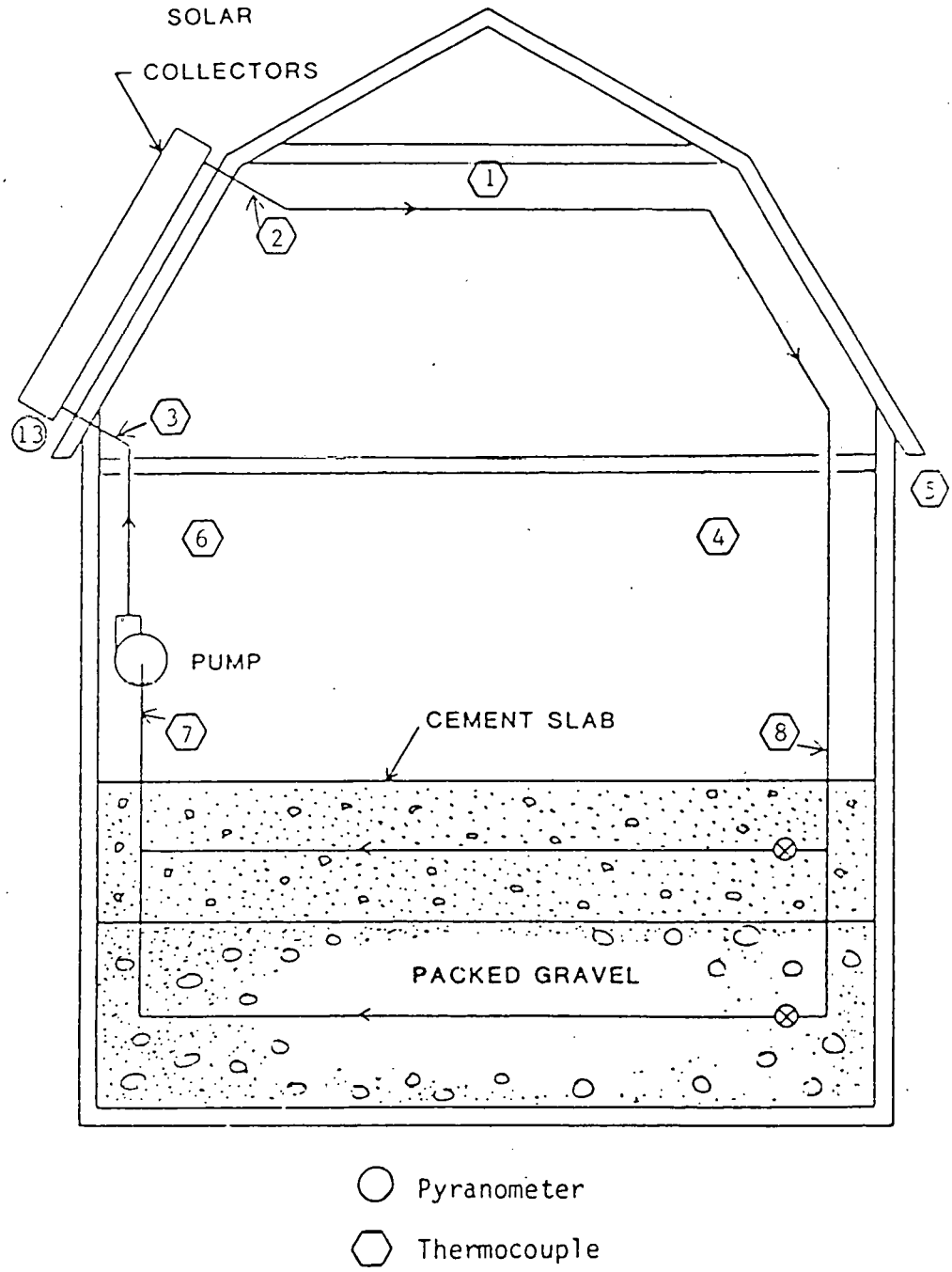
The thermocouples (TC) and the Eppley Pyronometer are situated as shown in Figure 2.3 and Figure 2.4. Table 2.3 gives a description of each location.

The Li-Cor Solar Meter and the Hollis Lab Pyronometer were employed as back ups for the Eppley Pyronometer. Both of these units were photovoltaic based. The Li-Cor was read manually twice a day for its electronically integrated total insolation. The Hollis Lab device gave a continuous record on a Russtrak Chart Recorder.

The ISTA Btu Meter (Model WM2 2/50) integrated energy absorbed by the storage by monitoring collector inlet outlet temperatures and fluid flow rate. Internal algorithms translated these parameters continuously to energy flow and incremented the Btu counter.

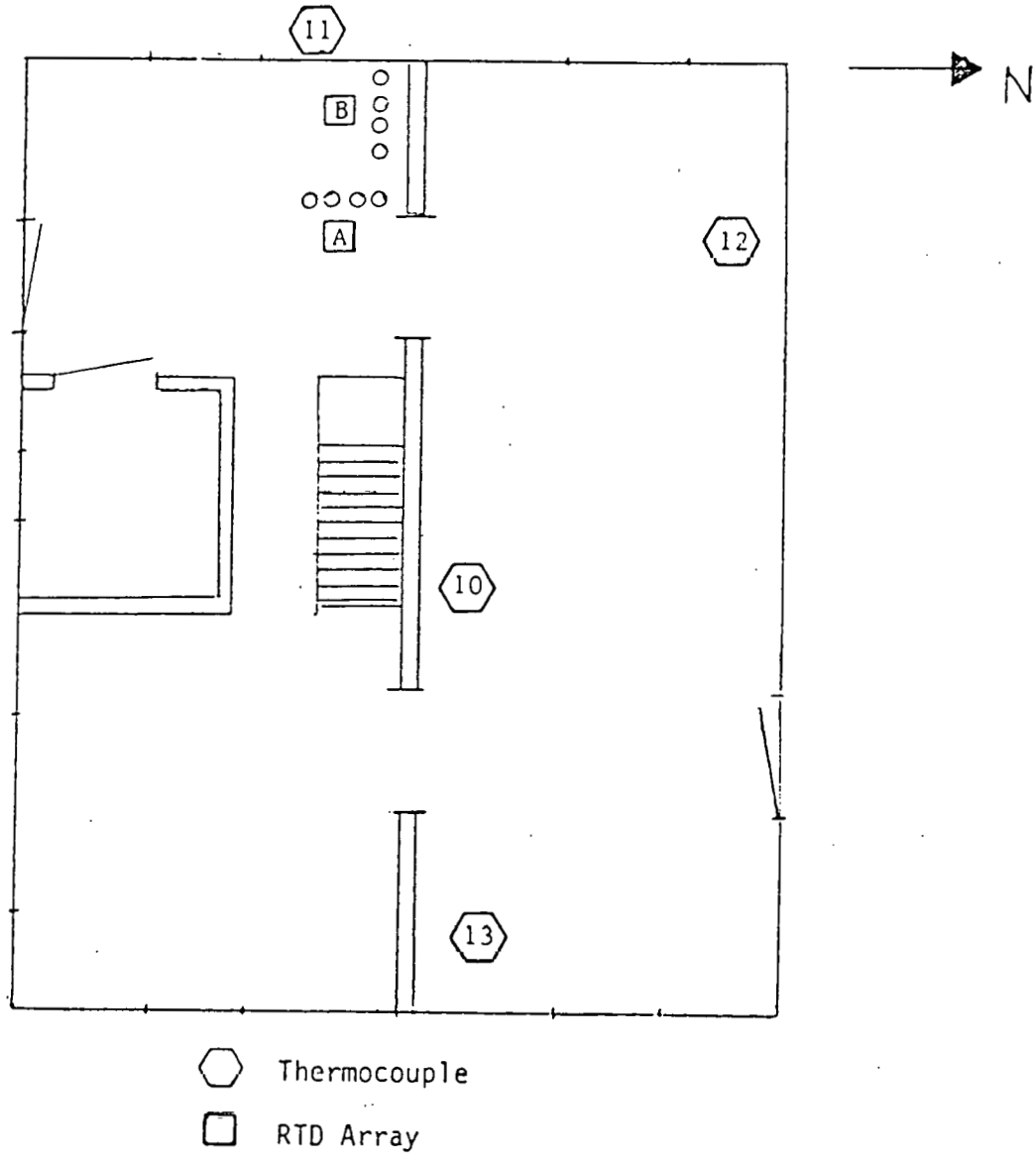
Electric power consumption meters in the residence were used to determine auxiliary energy requirements. A 2000 watt electric baseboard backup heater was activated as necessary according to the set point on a multiple setting thermostat. The data recording devices also drew electricity and dissipated it as heat to the residence.

A rotameter was utilized to find the relation between system flow rate and the temperature differential between collector and storage. This was



SENSOR LOCATIONS - HOUSE

FIGURE 2.3



SENSOR LOCATIONS - SLAB

FIGURE 2.4

SENSOR NUMBER	LOCATION	DESCRIPTION
1	House	Upstairs air temp
2	Collector	Outlet pipe fluid temp
3	Collector	Inlet pipe fluid temp
4	House	Downstairs North
5	Outside	Ambient temp on north side of house
6	House	Downstairs south
7	Storage	Inlet fluid temp
8	Storage	Outlet fluid temp
9	Slab	East side (imbedded 2 1/2"
10	Slab	Center (imbedded 2 1/2")
11	Ground outside	West yard of house (1 foot down)
12	Slab	North side (imbedded 2 1/2)
13	Pyranometer	Eppley

TABLE 2.3

THERMOCOUPLE LOCATIONS

necessary to determine the actual range of flow rates provided by the variable speed pump as dictated by the previously mentioned proportional controller.

2.3.2 Data Reduction Procedure

1. Automatically Recorded Data

The bulk of the data analyzed were the twelve house and system temperatures as well as the Eppley Pyranometer output. The thermocouple and pyranometer readings and corresponding sensor location numbers (see Table 2.3) as well as the time (Julian Day:Hour:Min:Sec) were sample and stored on magnetic tape every 15 minutes from October 13, 1982 to May 1, 1983. This raw information was transferred to the University of Massachusetts Computing Center Cyber 175 mainframe computer in order to facilitate the processing of data. Computer programs incorporating FORTRAN V were utilized as shown in Figure 2.5 to statistically reduce and arrange the sensor readings into usable formats.

The sensors (TC's and the pyranometer) all output a small voltage (millivolt range) that is read when sampled. The Fluke Data Logger was programmed to translate the TC readings directly to temperatures in degrees Fahrenheit before being transferred to the TI 733 to be written on cassette tape. Since this could not be done for the Eppley Pyranometer output, the reading was directly recorded as a voltage. In a recent (May 6, 1982) factor calibration of the Eppley device, it was found to develop an EMF of 11.52×10^{-6} volts/watt meter^{-2}. Therefore, the insulation was found from the pyranometer reading as follows:

$$\underset{(W/m^2)}{\text{INSOLATION}} = \underset{(mV)}{\text{EPPLEY READING}} / \underset{(mV/Wm^{-2})}{11.52 \times 10^{-3}}$$

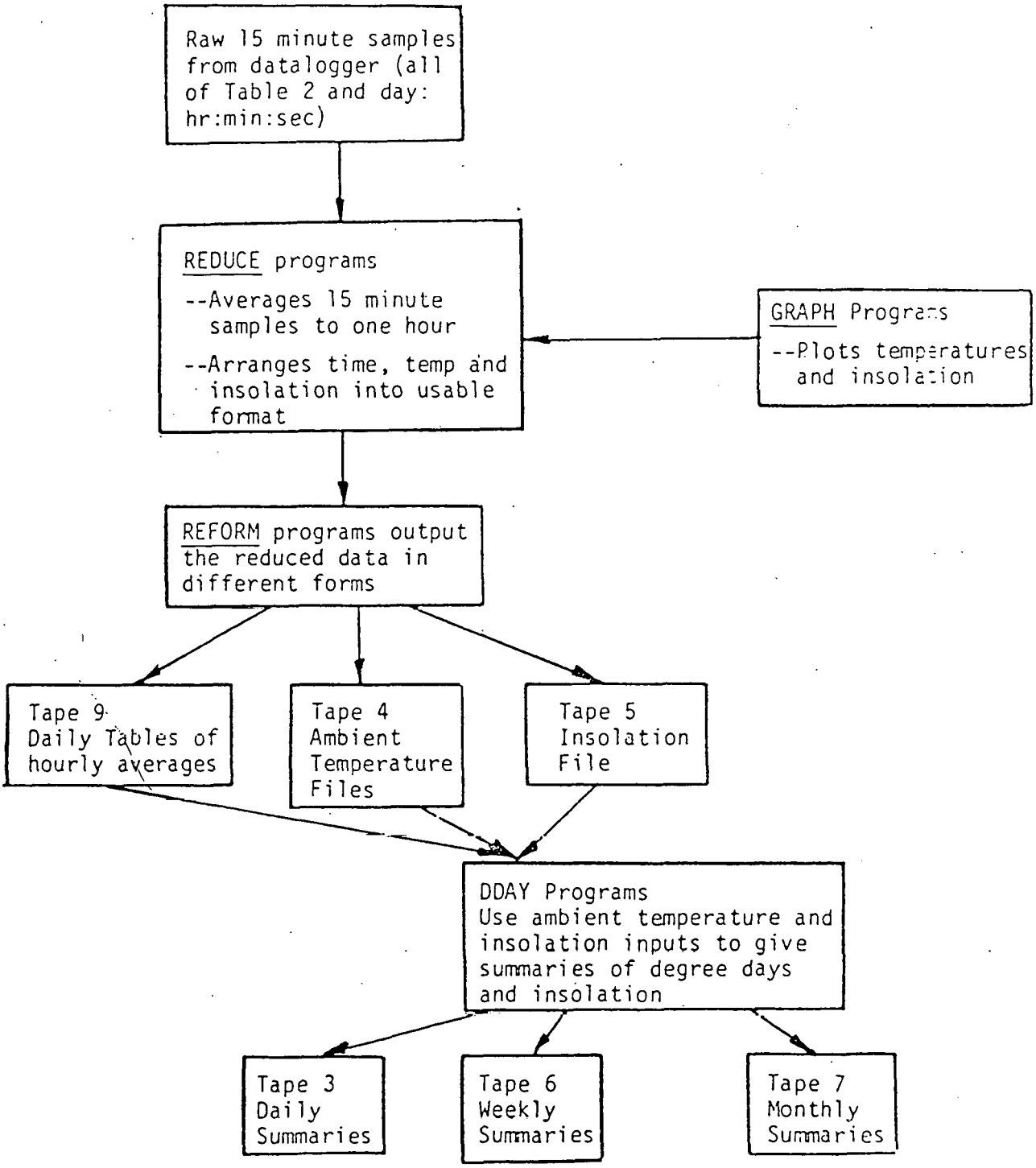


Figure 2.5

Data Reduction Flow Chart

This could, of course, be changed to English units with the conversion:

$$1 \text{ Btu hr/ft}^2 = 3.153 \text{ W/m}^2$$

The first level of data manipulation was to generate hourly averages from the 15 minute samples. This was the form used for further data manipulation. Daily printouts (Figure 2.6) for each measurement station were produced for all the days available in the monitoring period. A complete set of these printouts as well as computer generated plots of solar collector and house temperatures are summarized in Appendix A.

Daily (Table 2.4), weekly (Table 2.5), and monthly (Table 2.6) summaries of average ambient temperatures, degree days and solar insolation were also created for data analysis and comparison.

Input tapes of ambient temperature and insolation for every hour in the monitoring period were constructed for use in the computer model of the system. Gaps in the data were filled in (for the sake of continuity as model inputs) with the Hollis Lab Pyranometer data (for insolation) and the National Weather Service summaries for Burlington, Vermont (for ambient temperature).

2. Manually Recorded Data

The manually recorded data (RTD's, electric meter, and monitoring notes) was generally used for trend analysis. A complete set of this data is included in Appendix B. For comparative purposes, some of the manual readings for the month of January were input into the computer. The most interesting element of this data was the electric watt hour meter reading, a gauge of the auxiliary energy usage. The base consumption of electricity was determined

JULIAN DAY 32

HR	HOUSE UP	COLL OUT	COLL IN	HOUSE NORTH	OUT AMB	HOUSE SOUTH	STOR IN	STOR OUT	SLAB EAST	SOLR RAD	COLL %EFF
1	64	38	33	66	33	67	67	66	70	0	0.0
2	64	38	33	65	34	66	66	66	70	0	0.0
3	64	38	33	65	34	66	66	66	69	0	0.0
4	63	37	33	65	34	66	66	65	69	0	0.0
5	63	37	33	65	33	66	66	65	69	0	0.0
6	63	36	33	64	32	65	66	65	69	0	0.0
7	63	35	32	64	30	65	65	65	69	0	0.0
8	62	34	31	64	29	65	65	64	69	2	0.0
9	62	33	31	64	27	65	65	64	69	11	0.0
10	62	37	36	64	26	65	65	64	69	33	0.0
11	62	58	56	64	26	65	67	66	69	64	0.0
12	62	72	69	64	26	65	71	68	68	71	26.0
13	63	79	71	65	27	66	78	70	69	183	53.3
14	65	93	77	68	28	70	93	77	70	280	70.0
15	67	90	79	70	27	72	90	79	74	210	64.1
16	69	84	78	71	26	73	84	77	75	143	51.3
17	69	71	66	71	24	73	75	74	76	25	0.0
18	69	47	47	70	19	72	72	72	75	0	0.0
19	68	41	24	69	16	71	72	71	75	0	0.0
20	68	39	14	69	13	70	71	71	74	0	0.0
21	67	37	8	68	11	69	70	70	74	0	0.0
22	66	36	6	68	9	69	69	69	73	0	0.0
23	65	34	4	67	8	68	69	68	73	1	0.0
0	64	32	4	66	8	67	68	67	73	0	0.0

DEGREE DAYS= 40.8
TOTAL INSOL=1023
T-AVG INSIDE= 67.8
T-AVG OUTSIDE= 24.2

SAMPLE DAILY PRINTOUT

FIGURE 2.6

Table 2.4

Sample of Daily Data Summary

Month 10

Julian Day 7	Day of Month	T_{amb} Avg	Degree Days	Total Insol
286	13	48	17	116
287	14	49	16	473
288	15	46	19	648
289	16	40	25	466
290	17	39	26	337
291	18	34	31	673
292	19	39	26	1857
293	20	47	18	1891
294	21	48	17	681
295	22	36	29	680
296	23	37	28	835
297	24	33	32	2002
298	25	31	34	1714
299	26	39	26	1652
300	27	34	31	1856
301	28	37	28	1389
302	29	43	22	1175
303	30	47	18	1334
304	31	44	21	509

Degree Days = 464

Average T_{amb} = 40

Table 2.5

Weekly Data Summary

Week Ending	Degree Days (Base 65F)	Daily Average Insolation (BTU/Ft^2 - Day)
10/16	73	243
10/23	169	993
10/30	184	1588
11		
11/ 6	110	229
11/13	182	537
11/20	246	1110
11/27	210	305
12		
12/4	197	331
12/11	262	718
12/18	347	845
12/25	291	464
1		
1/1	235	549
1/8	304	636
1/15	322	763
1/22	395	808
1/29	313	997
2		
2/5	272	594
2/12	392	1262
2/19	303	1243
2/26	274	1089
3		
3/5	245	1305
3/12	211	536
3/19	201	841
3/26	284	1148
4		
4/2	249	1465
4/9	184	663
4/16	169	913
4/23	186	998
4/30	119	989
5		

Table 2.6

Monthly Summary of Data

Month	Degree Days (Base 65F)	Insolation (Btu/ft^2 day)
October	446	1067
November	840	533
December	1184	603
January	1442	755
February	1242	1128
March	1059	981
April	716	958

by finding the minimum average daily electric usage. This was the amount used by appliances and such items in the house in the course of the day and dissipated as internal energy gains. Such gains were subtracted from the meter reading to give the auxiliary energy consumption. Figure 2.7 gives a graphical representation of this consumption for the month of January.

2.3.3 Measurement Calibration

Several of the devices used for data collection were carefully calibrated before use. Specifically, calibration was carried out on all thermocouples, the rotameter and the pyronometers. In addition to this, tests were carried out to determine the validity of using 15 minute samples to generate an hourly average of solar insolation.

All the thermocouples (Copper-Constantan) were tested in situ by wiring them to the Fluke Data Logger and measuring the temperatures of boiling water and an ice bath. All sensors used were found to give the correct readings to within $\pm$ 0.5 °F for both standards.

A Rotameter was used to measure the rate of fluid flow through the collectors which varied according to the temperature difference between the collector and the storage. In order to do this, the Rotameter itself was first calibrated using a stopwatch, a bucket and a laboratory scale. The water flow rate (from the line supply) was adjusted to various readings on the rotameter and the mass of water collected in 15 seconds was weighed. The following equation was used to determine the volumetric flow rate in gallons per minute:

$$GPM = X(lbm/15\ sec) \times (60\ sec/min)/(8.38\ lbm/gal)$$

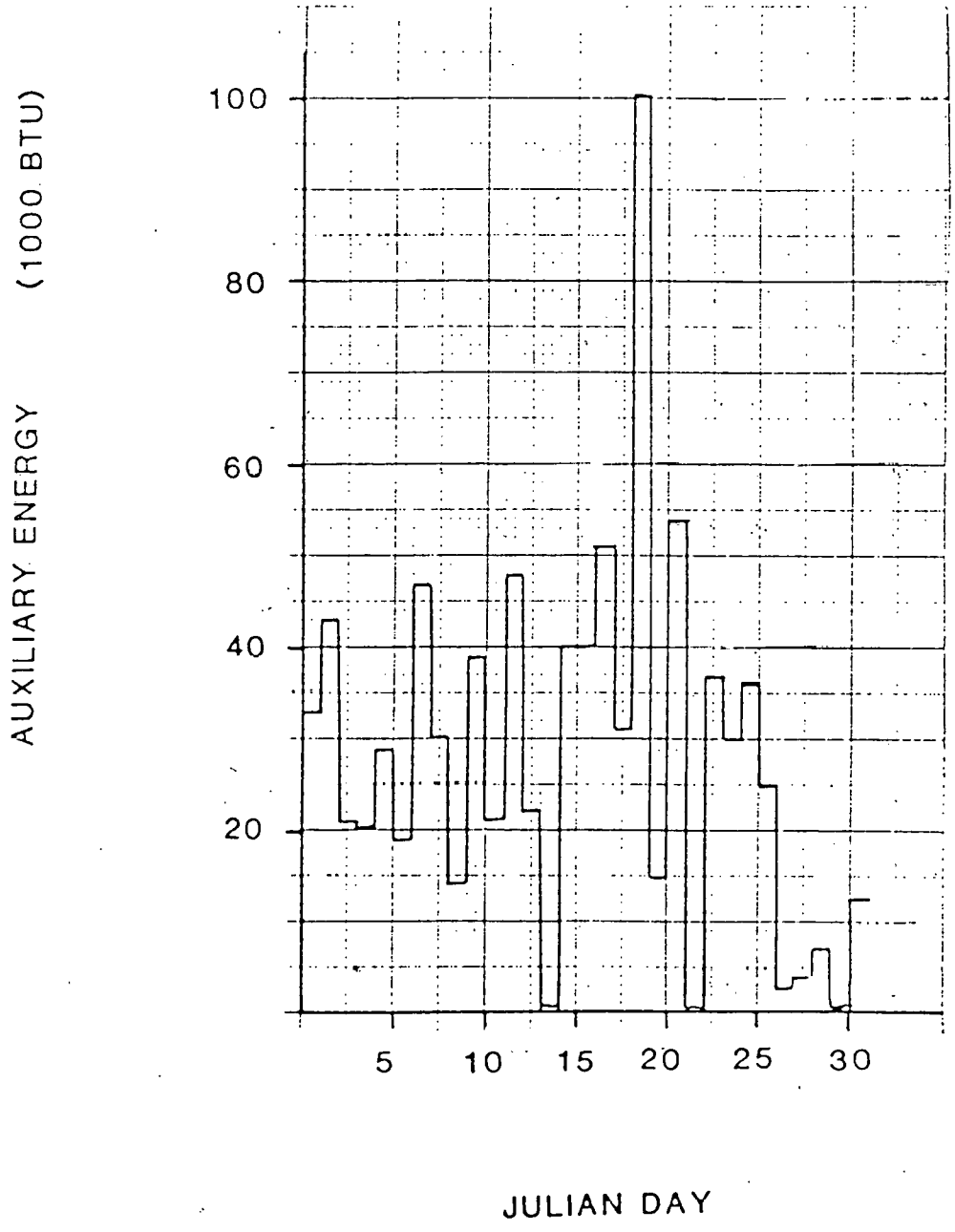

AUXILIARY ENERGY (1000 BTU)
100
80
60
40
20
5
10
15
20
25
30
JULIAN DAY

FIGURE 2.7

Data from this calibration test is shown in Table 2.7. A straight (see Figure 2.8) line was fitted to the flow rate versus the rotameter reading via regression analysis giving :

$$GPM = 0.0860 \left[\begin{matrix}\text{ROTAMETER}\\ \text{READING}\end{matrix}\right] - 0.027$$

A differential controller varied the flow rate as a function of the temperature difference across the collector (ΔT). The relationship between ΔT and the flow rate was found by setting the controller to various ΔT's and reading the rotameter once at steady state. Based on the data summarized in Table 2.8, the following equation gives flow rate as a function of ΔT:

$$GPM = 1.46\Delta T - 1.28$$

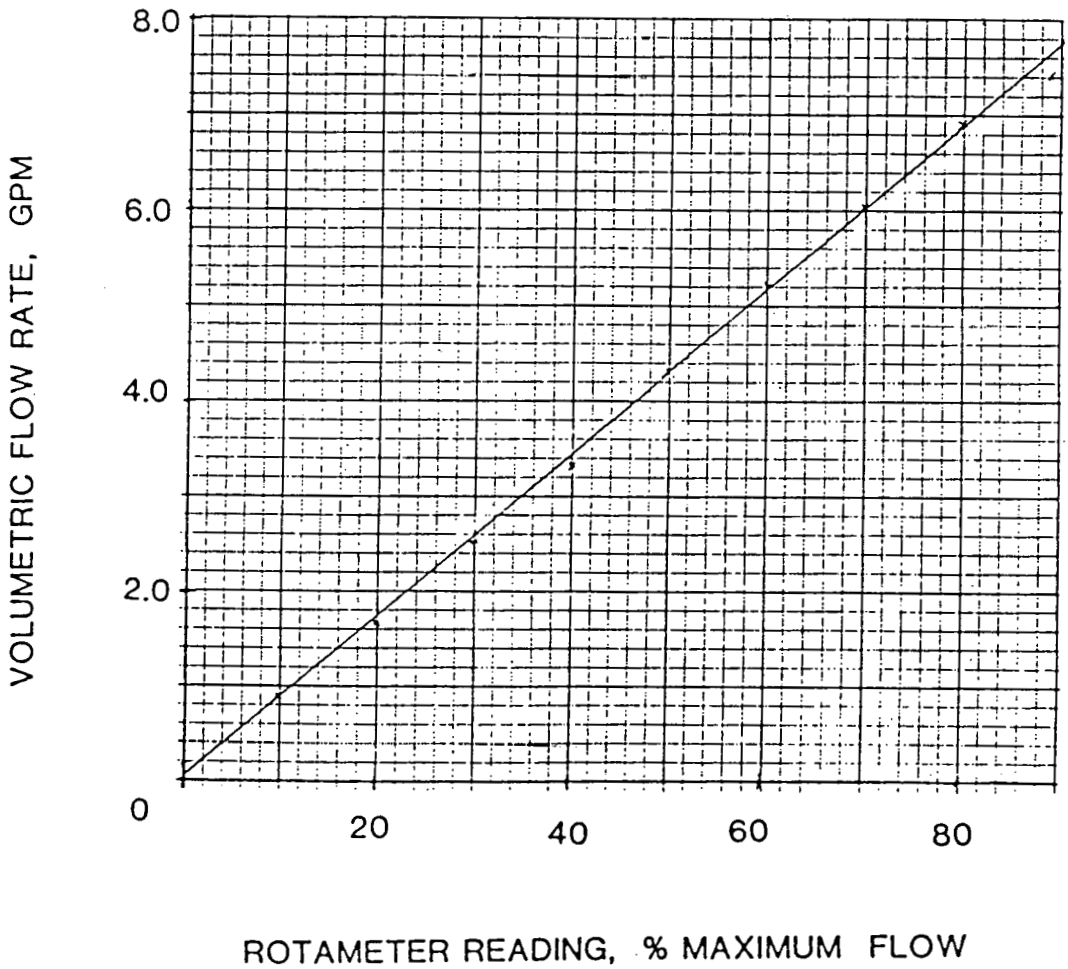
This relation was used for the collector efficiency analysis and the computer modeling part of this study.

The redundant or back-up pyranometer (Hollis Lab Model LM-3000) was calibrated to the primary pyranometer (Eppley Black and White Model 8-48) used in the automatic data recording. The Hollis Lab unit's output was recorded on a Russtrak chart recorder. The calibration test was carried out with both devices mounted on the test residence inclined (60° to horizontal) and oriented (due south) in accord with the collectors. The outputs of both devices were compared in Table 2.9 for a three hour test period on a sunny afternoon. Since the Eppley was calibrated at the factory on May 6, 1982, this unit was used as the standard. The resulting correlation between the two devices was obtained as follows:

TABLE 2.7

ROTAMETER CALIBRATION TEST

Rotameter Reading (% of Max. Flow)	Pounds of Water Flow in 15 Seconds	Gallons Per Minute
10	1.87	0.90
20	3.40	1.65
30	5.20	2.52
40	7.00	3.36
50	8.95	4.32
60	10.70	5.13
70	12.45	6.03
80	14.24	6.90
87	15.60	7.41



ROTAMETER CALIBRATION
FIGURE 2.8

TABLE 2.8

COLLECTOR FLOW RATE VERSUS COLLECTOR TEMPERATURE DIFFERENTIAL

DELTA	Rotameter (% of Maximum)	Flow Rate (GPM)
1.25 (min)	12	1.005
2.0	18	1.521
2.5	24	2.037
3.5	41	3.499
4.0	55	4.703
5.0+	74	6.337

TABLE 2.9

CORRELATION OF PYRANOMETERS
(Hollis Labs LM 300 vs. Eppley 8-48)

Time	Hollis (mV)	Eppley (mV)
12:45	8.5	9.18
13:00	8.4	9.04
13:15	8.3	8.89
13:30	8.1	8.75
13:45	7.8	8.52
14:00	7.5	8.27
14:15	7.2	7.91
14:30	6.9	7.62
14:45	6.5	7.19
15:00	6.0	6.74
15:15	5.4	6.18
15:30	4.7	5.48

$$\text{INSOLATION (EPPLEY)} = 0.964 \times \text{INSOLATION (HOLLIS)} + 0.963$$

(Correlation Coefficient = 0.9995)

When gaps in the recorded Eppley data occured, the Hollis unit's chart recorder tape was used along with the above equation to determine the hourly average insolation.

An assumption in the data collection and reduction process was that an hourly average generated from 15 minute samples is a reasonable approximation of the true average for that hour. To test this assumption, the data logger was programmed to take samples every 2.5 minutes for a 33 hour period. Thus, two sets of hourly average temperatures and insolation could be found for the two different sampling intervals. The temperature averages were very similar due to relatively slow fluctuations with time. The comparison of the two sets of hourly average insolation for the test period is shown in Figure 2.9. As shown, the insolation average was different in some cases but not by a significant amount. It is interesting to note that when the slope of the insolation curve is positive, the 2.5 minute average is less than the 15 minute average. The inverse is true when the slope of the curve is negative.

2.3.4 Experimental Results

1. Tabulation of Reduced Data

Appendix A contains the daily printouts of the hourly average temperatures and insolation for all available times during the measurement period. Also, graphical representations of selected temperatures and insolation for the month of January are included in this report along with daily, weekly and monthly summaries of insolation and degree days. It should be noted

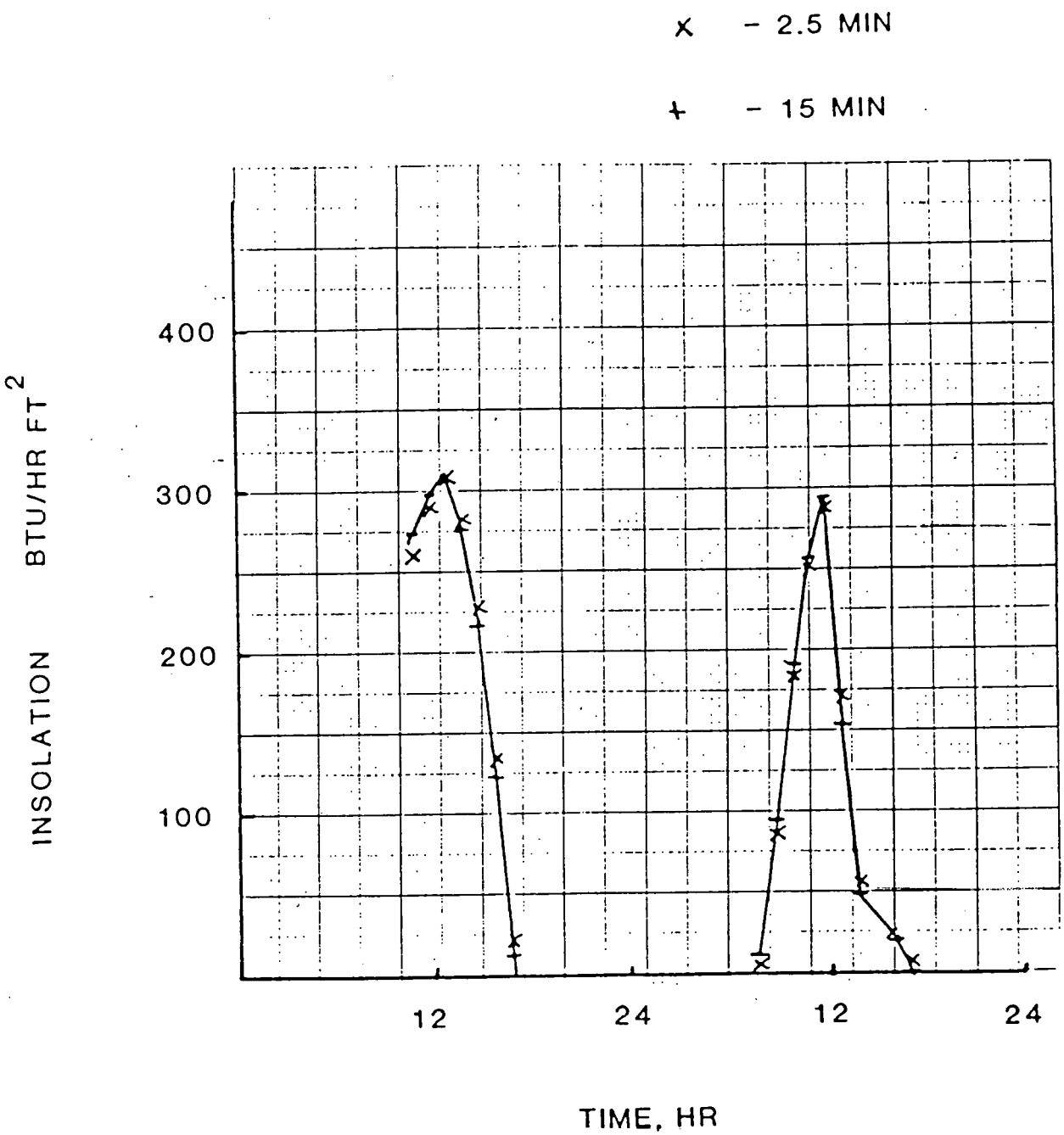

x - 2.5 MIN
+ - 15 MIN
400
300
200
100
INSOLATION BTU/HR FT^2
12
24
12
24
TIME, HR

FIGURE 2.9

that all temperatures in these tables and graphs are in °F, solar radiation is in Btu/hr ft^2 and the degree days are based on 65 °F.

Figure 2.6 shows a sample of the daily printouts. These are arranged by Julian Day where 1 is January 1 and 365 is December 31. The hour of the day is listed initially followed by the hourly average temperature for the first nine sensors noted in Table 2.3. (Sensors 10, 11, and 12 were note included in these printouts.) The hourly average incident solar radiation (measured at 60°) and collector efficiency follow the temperature columns.

The efficiency of the collector (see Reference 2.2) for the averaged hour is found by using the following equation:

$$\text{Efficiency (\%)} = \frac{\text{Energy Output}}{\text{Incident Energy}} = \frac{\text{MDOT} \times \text{CP} \times (T_{inc} - T_{outc}) \times 100}{\text{Insolation} \times \text{Area}}$$

where:

Area = Collector Area (210 ft^2)

MDOT = Mass Flow Rate (lb/hr)

RHO = Density of Fluid (lb/gal)(Reference 2.3)

$= 8.33 \times (1.0694 \times T_{avg} \times 0.00042)$

T_{inc} = Collector Inlet Temperature

T_{outc} = Collector Outlet Temperature

T_{avg} = Average Collector Fluid Temperature

$= (T_{inc} + T_{outc})/2$

At the bottom of the daily printout is a summary of that day's pertinent weather and system data: degree days, total insolation (Btu/day ft^2), average interior temperature and average ambient temperature.

Tables 2.10 to 2.16 present the month by month compendiums of the daily summaries. The Julian day, day of the month, average ambient temperature, degree day total, and total insolation (measured at 60°) are presented in each month's printout. Also included at the bottom of these printouts are the month's total degree days and average ambient temperature. Weekly breakdowns of the degree days and average daily insolation (as measured at 60°) are shown in Table 2.5. Table 2.6 gives a monthly summary of the same data.

Computer generated graphical representations of house and system temperatures as well as the weather inputs were developed for all days in January. Figures 2.10 to 2.15 show the outside ambient, inside house and the slab temperatures as a function of time. Figures 2.16 to 2.21 present the insolation plus collector inlet and outlet temperatures. As can be seen, despite wide fluctuations in ambient temperatures and insolation, the slab and residence temperatures remain within a comfortable range.

2. Summary of Experimental Results

The ability of the solar option one system in meeting the heating load of the test residence is described in this section. The climatalogical factors (insolation and degree days) are compared with long term data from Burlington. Also presented are the house and system temperatures and auxiliary energy requirements which respond to those weather inputs.

a. House temperature control

An important indicator of the system performance is its ability to keep the test residence temperature within a comfortable range. Table 2.17 and the histogram of Figure 2.22 give indoor temperature (°F) as a function of number of occurances for all hours available in the monitoring period. The mean temperature was 65 °F and very few hours were found to be less

Table 2.10

Month 10

Julian Day	Day of Month	T_{amb} Avg	Degree Days	Total Insol
286	13	48	17	116
287	14	49	16	473
288	15	46	19	648
289	16	40	25	466
290	17	39	26	337
291	18	34	31	673
292	19	39	26	1857
293	20	47	18	1891
294	21	48	17	681
295	22	36	29	680
296	23	37	28	835
297	24	33	32	2002
298	25	31	34	1714
299	26	39	26	1652
300	27	34	31	1856
301	28	37	28	1339
302	29	43	22	1175
303	30	47	18	1334
304	31	44	21	509

Degree Days = 464

Average T_{amb} = 40

Table 2.11

Month 11

Julian Day	Day of Month	T_{amb} Avg	Degree Days	Total Insol
305	1	49	16	116
306	2	49	16	84
307	3	52	13	113
308	4	64	1	374
309	5	45	20	45
310	6	36	29	364
311	7	35	30	458
312	8	41	24	101
313	9	36	29	668
314	10	29	36	1400
315	11	33	32	752
316	12	52	13	291
317	13	40	25	90
318	14	30	35	1360
319	15	33	32	145
320	16	25	40	1721
321	17	30	35	1100
322	18	26	39	1495
323	19	26	39	1540
324	20	32	33	413
325	21	42	23	116
326	22	42	23	116
327	23	47	18	213
328	24	38	27	120
329	25	26	39	135
330	26	31	34	140
331	27	12	53	1296
332	28	14	51	1100
333	29	32	33	83
334	30	34	31	68

Degree Days = 869

Average T_{amb} = 36

Table 2.12

Month 12

Julian Day	Day of Month	T_{amb} Avg	Degree Days	Total Insol
335	1	37	28	97
336	2	40	25	120
337	3	45	20	37
338	4	49	16	817
339	5	36	29	72
340	6	51	14	585
341	7	37	28	1396
342	8	27	38	1328
343	9	10	55	1110
344	10	6	59	222
345	11	19	46	317
346	12	6	59	531
347	13	-5	70	1503
348	14	13	52	979
349	15	28	37	83
350	16	37	28	41
351	17	14	51	1365
352	18	9	56	1416
353	19	13	52	447
354	20	25	40	105
355	21	23	42	203
356	22	13	52	917
357	23	15	50	1366
358	24	31	34	39
359	25	37	28	174
360	26	38	27	585
361	27	24	41	1366
362	28	40	25	39
363	29	38	27	174
364	30	25	40	413
365	31	20	45	854

Degree Days = 1214

Average T_{amb} = 25

Table 2.13

Month 1

Julian Day	Day of Month	T_{amb} Avg	Degree Days	Total Insol
1	1	28	37	413
2	2	27	38	63
3	3	14	51	1174
4	4	-2	67	1599
5	5	23	42	640
6	6	29	36	197
7	7	30	35	42
8	8	24	41	1360
9	9	2	63	1629
10	10	14	51	289
11	11	42	23	142
12	12	27	38	197
13	13	11	54	1274
14	14	9	56	1409
15	15	21	44	401
16	16	18	47	132
17	17	10	55	283
18	18	-1	66	894
10	10	-6	71	974
20	20	0	65	1682
21	21	14	51	326
22	22	21	44	1365
23	23	24	41	156
24	24	33	32	156
25	25	33	32	398
26	26	10	55	1845
27	27	9	56	1109
28	28	8	57	1836
29	29	18	47	1481
30	30	24	41	395
31	31	34	44	185

Degree Days = 1469

Average T_{amb} = 17

Table 2.14

Month 2

Julian Day	Day of Month	T_{amb} Avg	Degree Days	Total Insol
32	1	24	41	1020
33	2	23	42	398
34	3	39	26	120
35	4	36	39	120
36	5	8	57	1925
37	6	8	57	899
38	7	18	47	84
39	8	17	48	396
40	9	9	56	1584
41	10	-4	69	2102
42	11	-1	66	1969
43	12	11	54	1805
44	13	6	59	2048
45	14	17	48	1448
46	15	25	40	215
47	16	19	46	1177
48	17	31	34	72
49	18	28	37	1823
50	19	19	46	1919
51	20	24	41	2161
52	21	35	30	1177
53	22	28	37	1549
54	23	30	35	104
55	24	22	43	773
56	25	18	47	459
57	26	17	48	1405
58	27	20	45	1388
59	28	35	30	1465

Degree Days = 1268

Average T_{amb} = 19

Table 2.15

Month 3

Julian Day	Day of Month	T_{amb} Avg	Degree Days	Total Insol
60	1	34	31	773
61	2	33	32	200
62	3	31	34	771
63	4	27	38	2195
64	5	23	42	2343
65	6	30	35	1848
66	7	33	32	245
67	8	32	33	349
68	9	34	31	332
69	10	37	28	288
70	11	38	27	402
71	12	33	32	288
72	13	33	32	402
73	14	31	34	2206
74	15	34	31	420
75	16	34	31	402
76	17	34	31	1163
77	18	38	27	1114
78	19	43	22	184
79	20	35	30	294
80	21	33	32	428
81	22	31	34	146
82	23	19	46	954
83	24	14	51	1737
84	25	13	52	2276
85	26	20	45	2206
86	27	26	39	622
87	28	34	31	402
88	29	23	42	847
89	30	21	44	2396
90	31	25	40	2184

Degree Days = 1089

Average T_{amb} = 29

Table 2.16

Month 4

Julian Day	Day of Month	T_{amb} Avg	Degree Days	Total Insol
91	1	36	29	1603
92	2	34	31	2201
93	3	32	33	194
94	4	36	29	211
95	5	38	27	226
96	6	36	29	896
97	7	36	29	479
98	8	44	21	311
99	9	42	23	2324
100	10	37	28	311
101	11	34	31	311
102	12	34	31	598
103	13	40	25	2201
104	14	45	20	1603
105	15	45	20	598
106	16	44	21	775
107	17	35	30	558
108	18	35	30	598
109	19	37	28	303
110	20	39	26	1002
111	21	35	30	521
112	22	40	35	1895
113	23	42	23	2115
114	24	39	26	558
115	25	48	17	1002
116	26	38	27	207
117	27	46	19	1630
118	28	52	13	1603
119	29	57	8	1616
120	30	50	15	311

Degree Days = 744

Average T_{amb} = 40

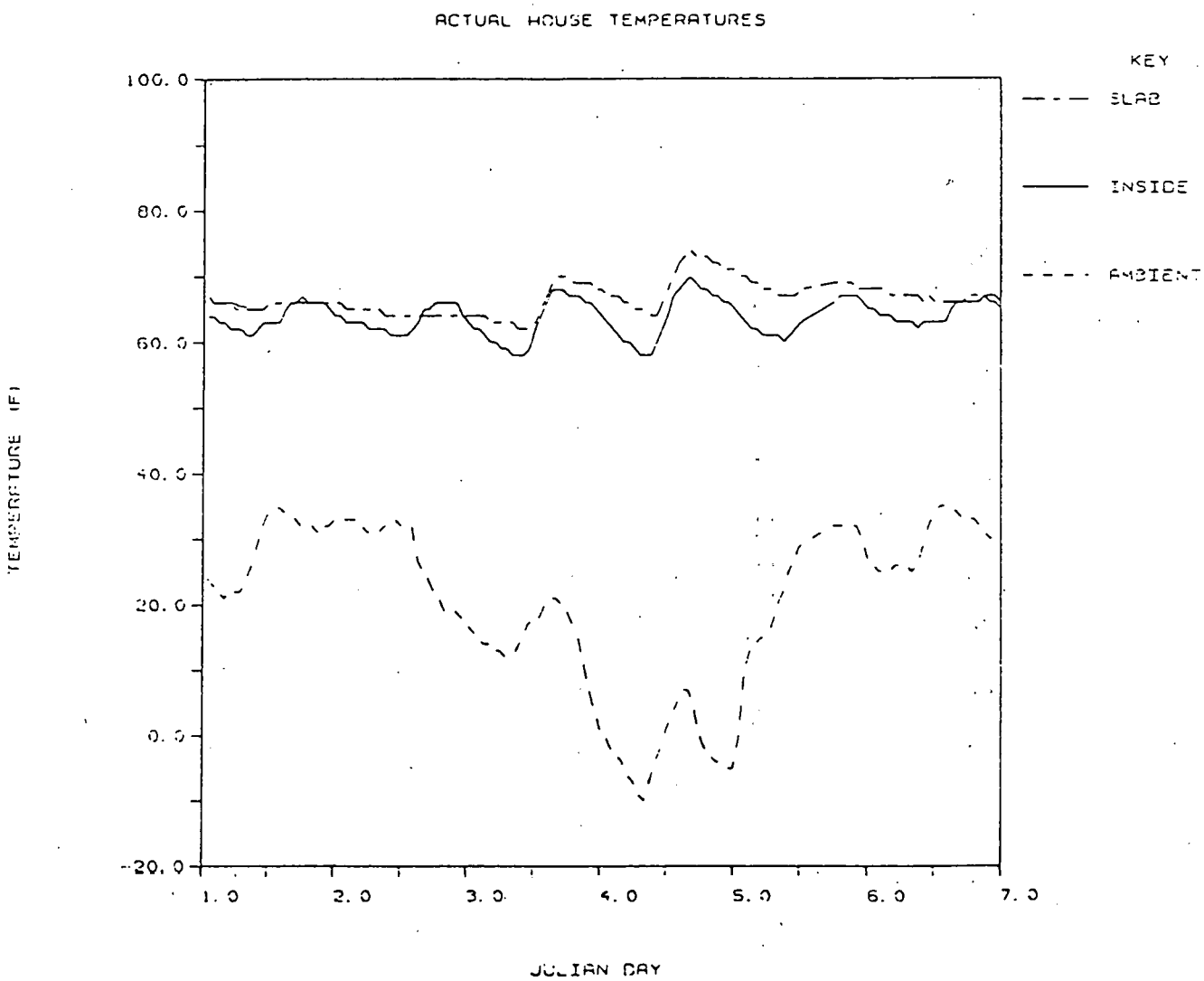

ACTUAL HOUSE TEMPERATURES
KEY
SLAB
INSIDE
AMBIENT
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
TEMPERATURE (F)
1.0
2.0
3.0
4.0
5.0
6.0
7.0
JULIAN DAY

FIGURE 2.10

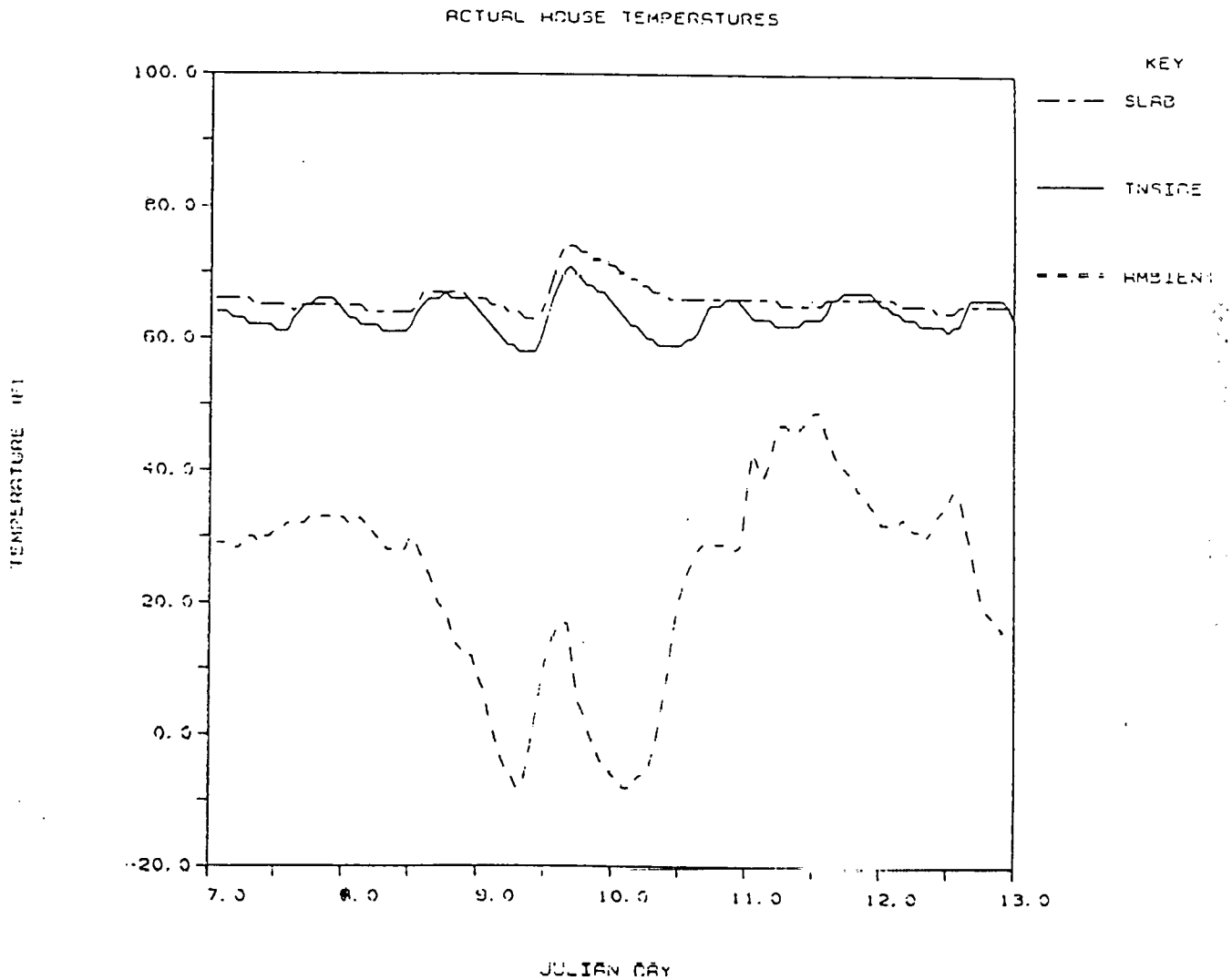

ACTUAL HOUSE TEMPERATURES
KEY
SLAB
INSIDE
AMBIENT
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
7.0
8.0
9.0
10.0
11.0
12.0
13.0
JULIAN DAY

FIGURE 2.11

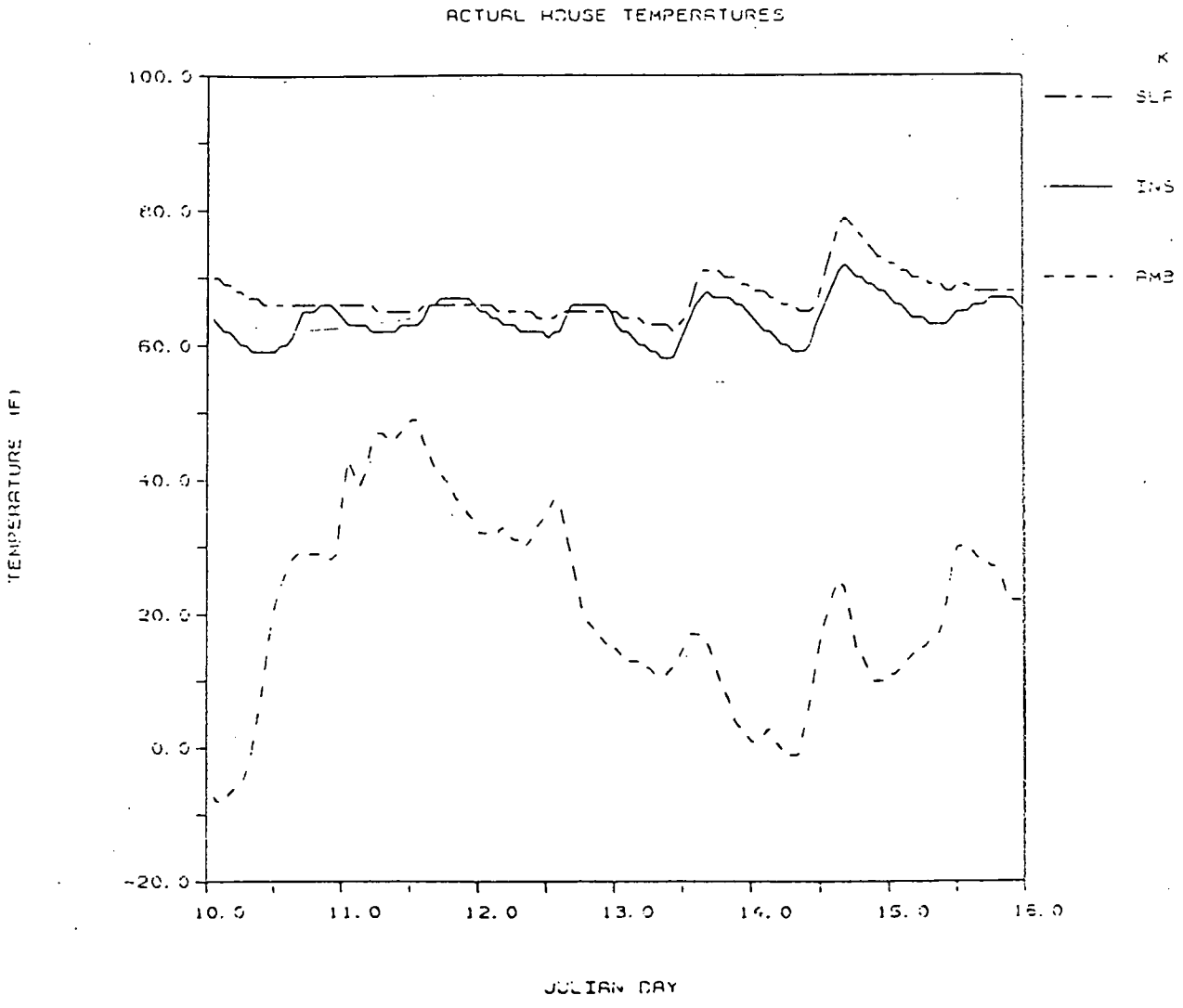

ACTUAL HOUSE TEMPERATURES
K
SLP
INS
AMB
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
TEMPERATURE (F)
10.0
11.0
12.0
13.0
14.0
15.0
16.0
JULIAN DAY

FIGURE 2.12

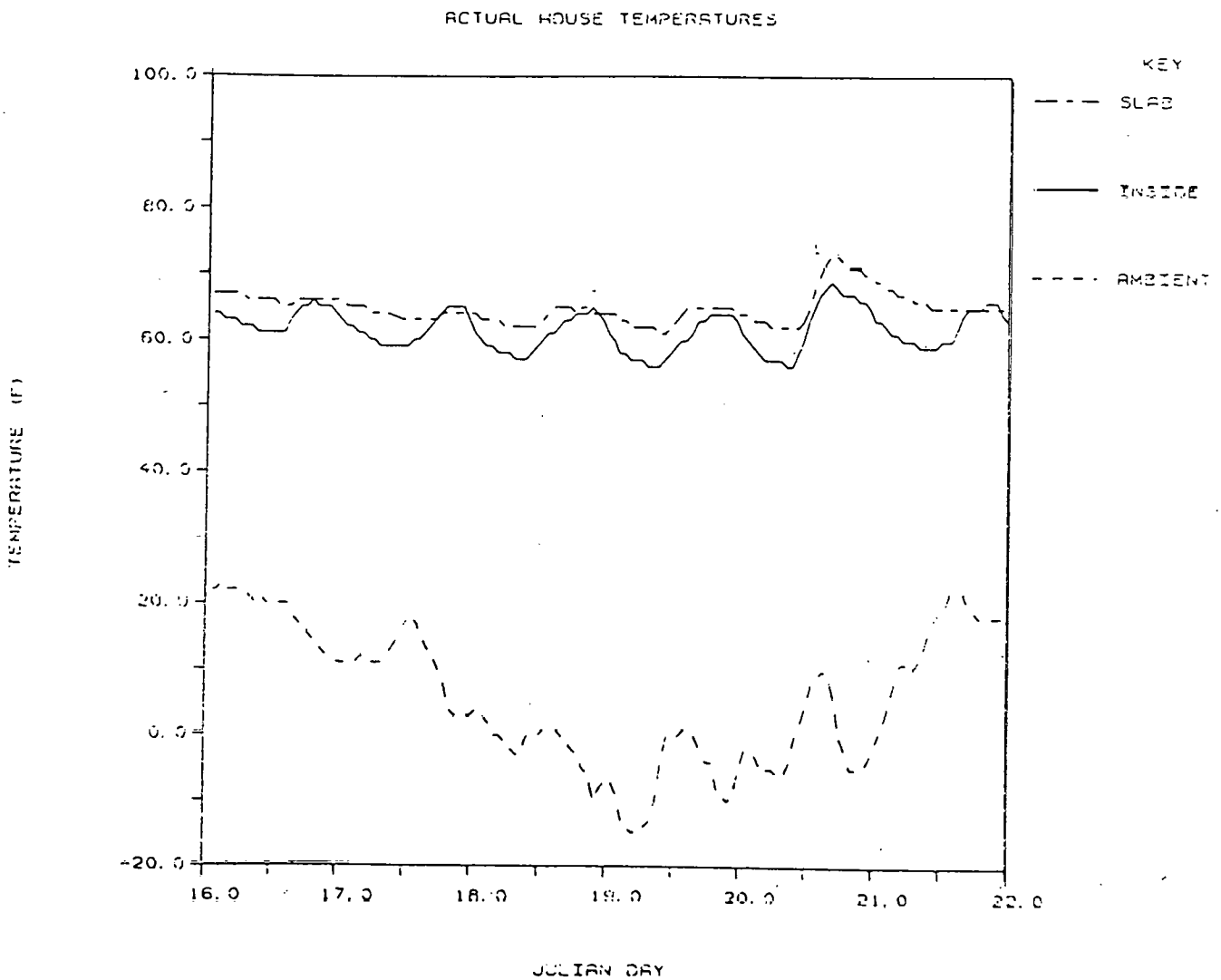

ACTUAL HOUSE TEMPERATURES
KEY
SLAB
INSIDE
AMBIENT
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
TEMPERATURE (F)
16.0
17.0
18.0
19.0
20.0
21.0
22.0
JULIAN DAY

FIGURE 2.13

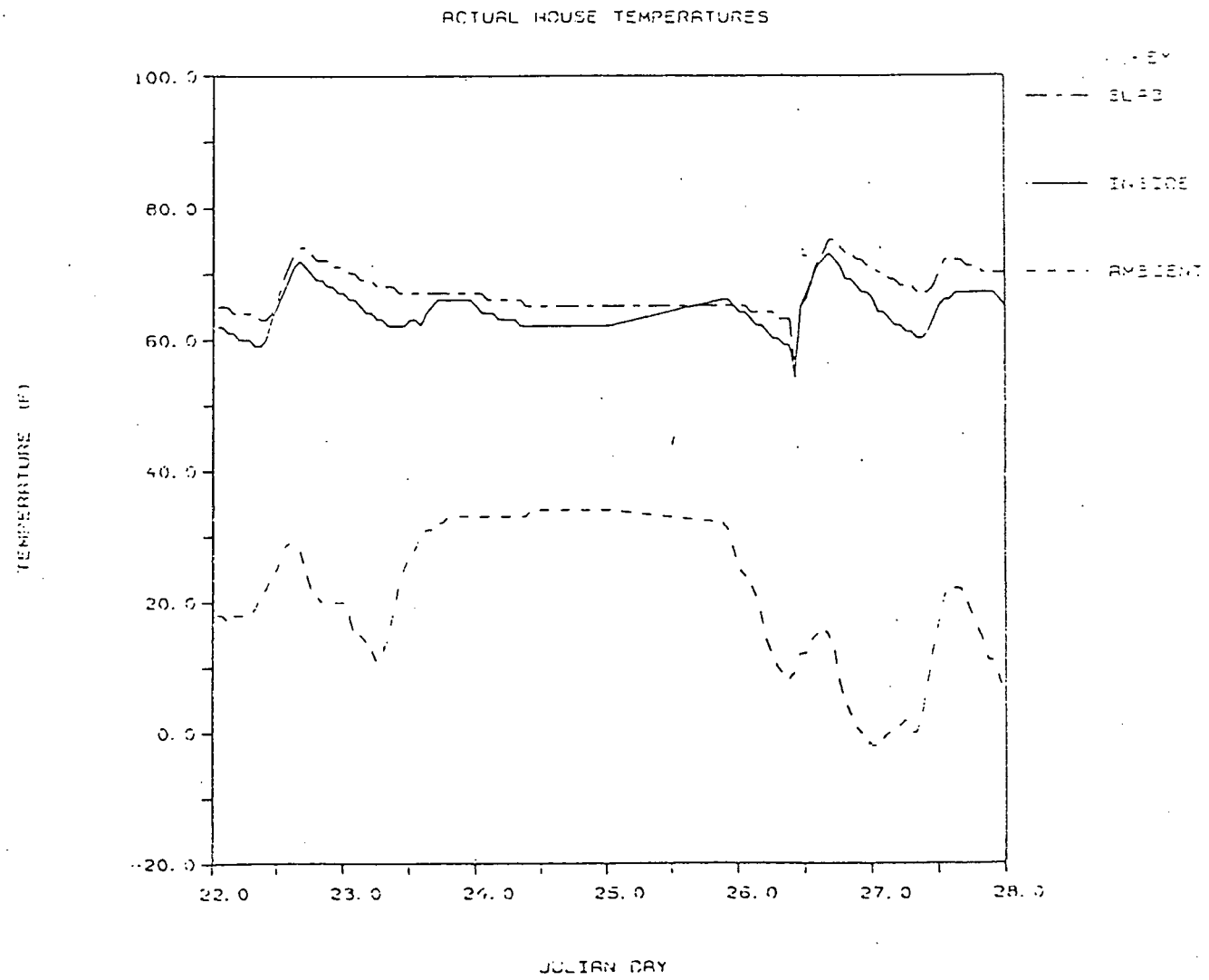

ACTUAL HOUSE TEMPERATURES
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
22.0
23.0
24.0
25.0
26.0
27.0
28.0
JULIAN DAY
SLAB
INSIDE
AMBIENT

FIGURE 2.14

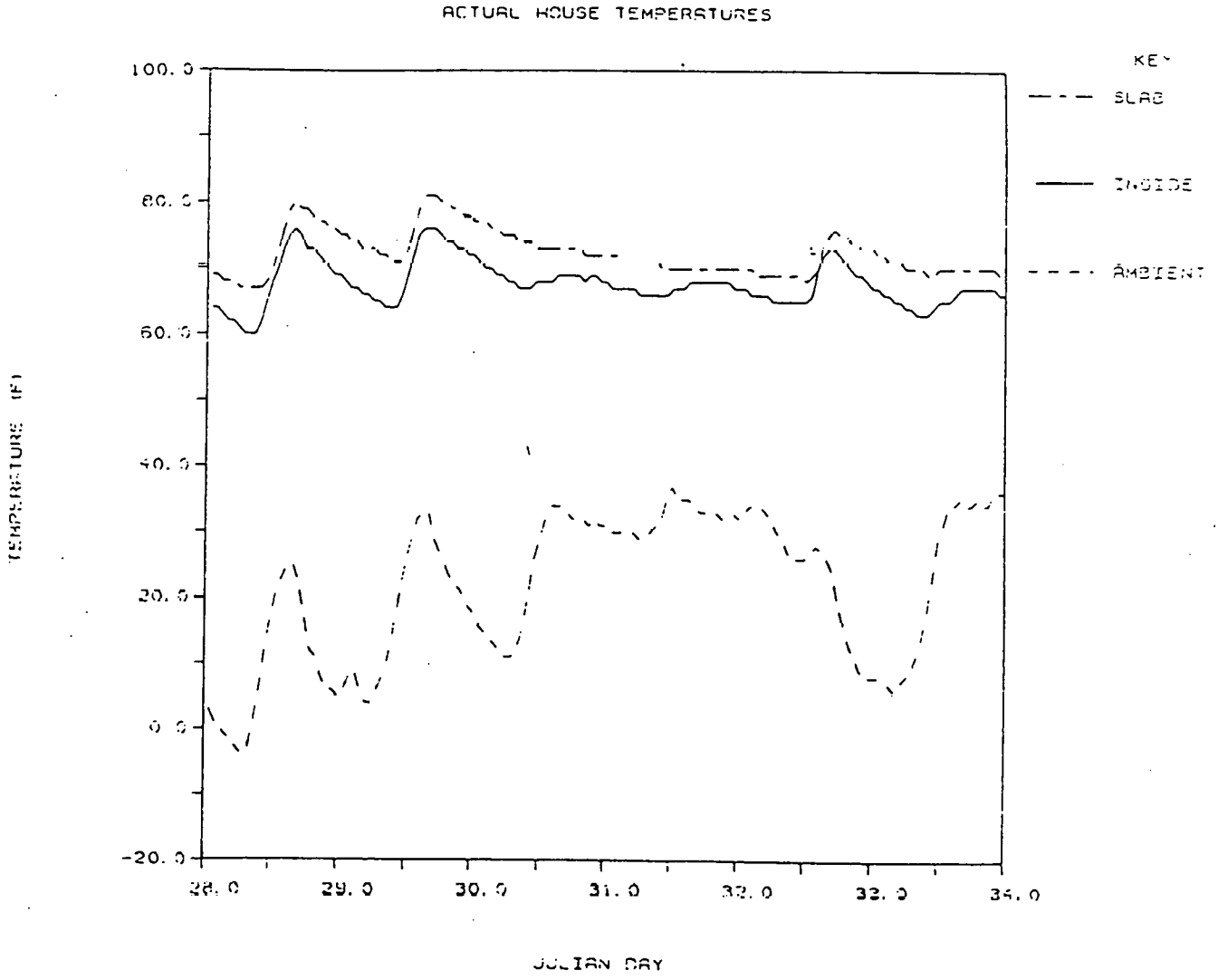

ACTUAL HOUSE TEMPERATURES
KEY
SLAB
INSIDE
AMBIENT
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
28.0
29.0
30.0
31.0
32.0
33.0
34.0
JULIAN DAY

FIGURE 2.15

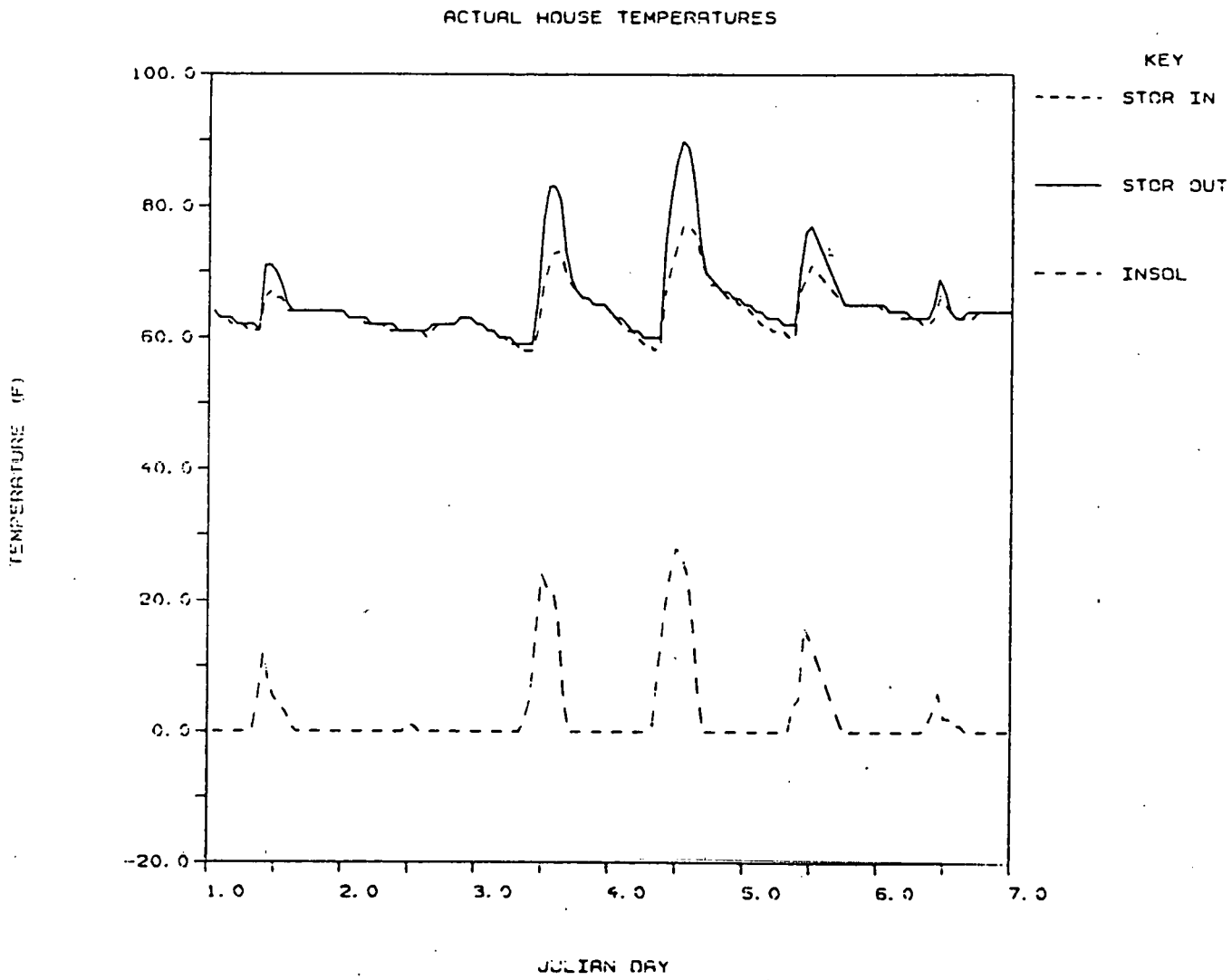

ACTUAL HOUSE TEMPERATURES
KEY
STOR IN
STOR OUT
INSOL
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
TEMPERATURE (F)
1.0
2.0
3.0
4.0
5.0
6.0
7.0
JULIAN DAY

FIGURE 2.16

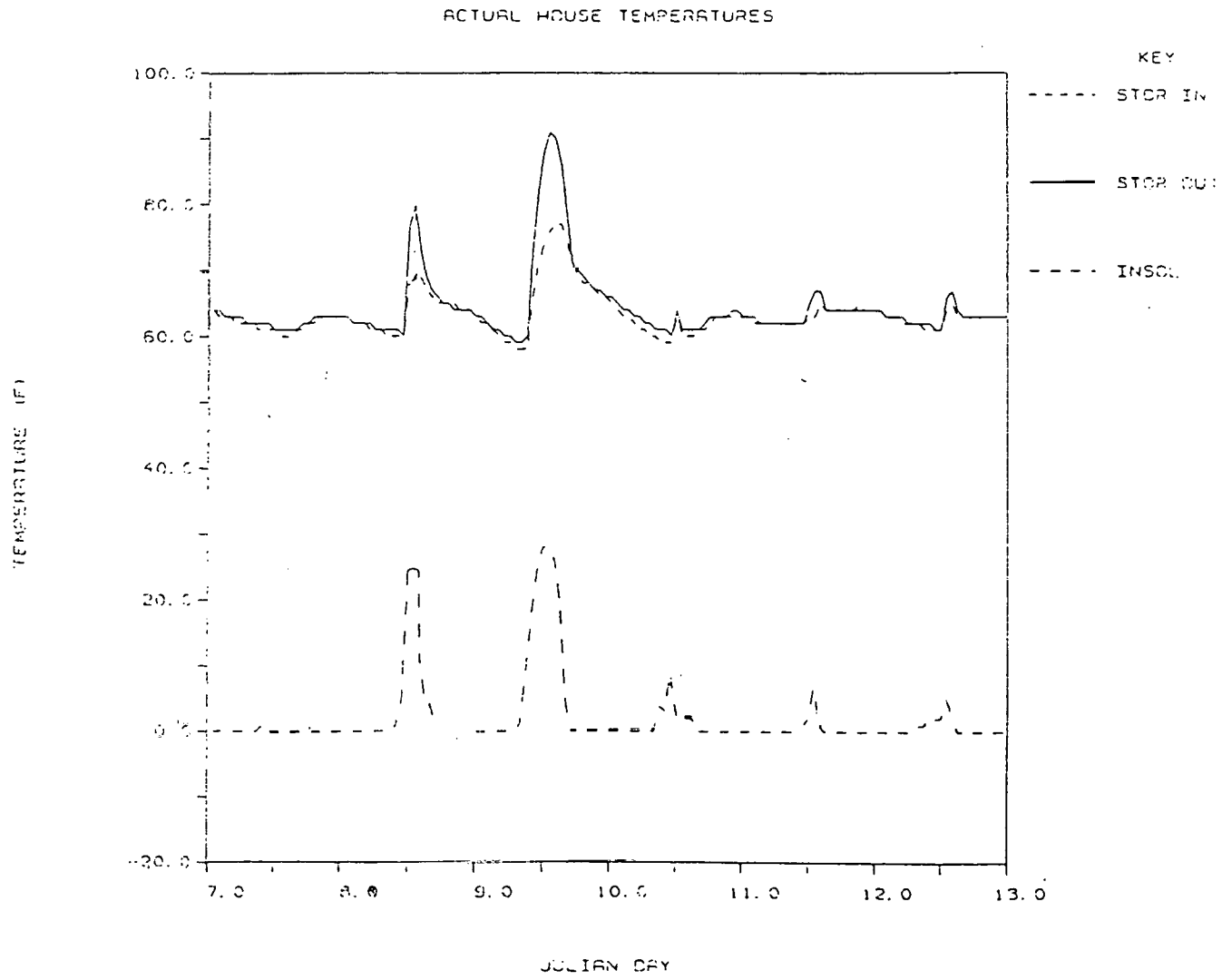

ACTUAL HOUSE TEMPERATURES
KEY
STOR IN
STOR OUT
INSOL
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
7.0
8.0
9.0
10.0
11.0
12.0
13.0
JULIAN DAY

FIGURE 2.17

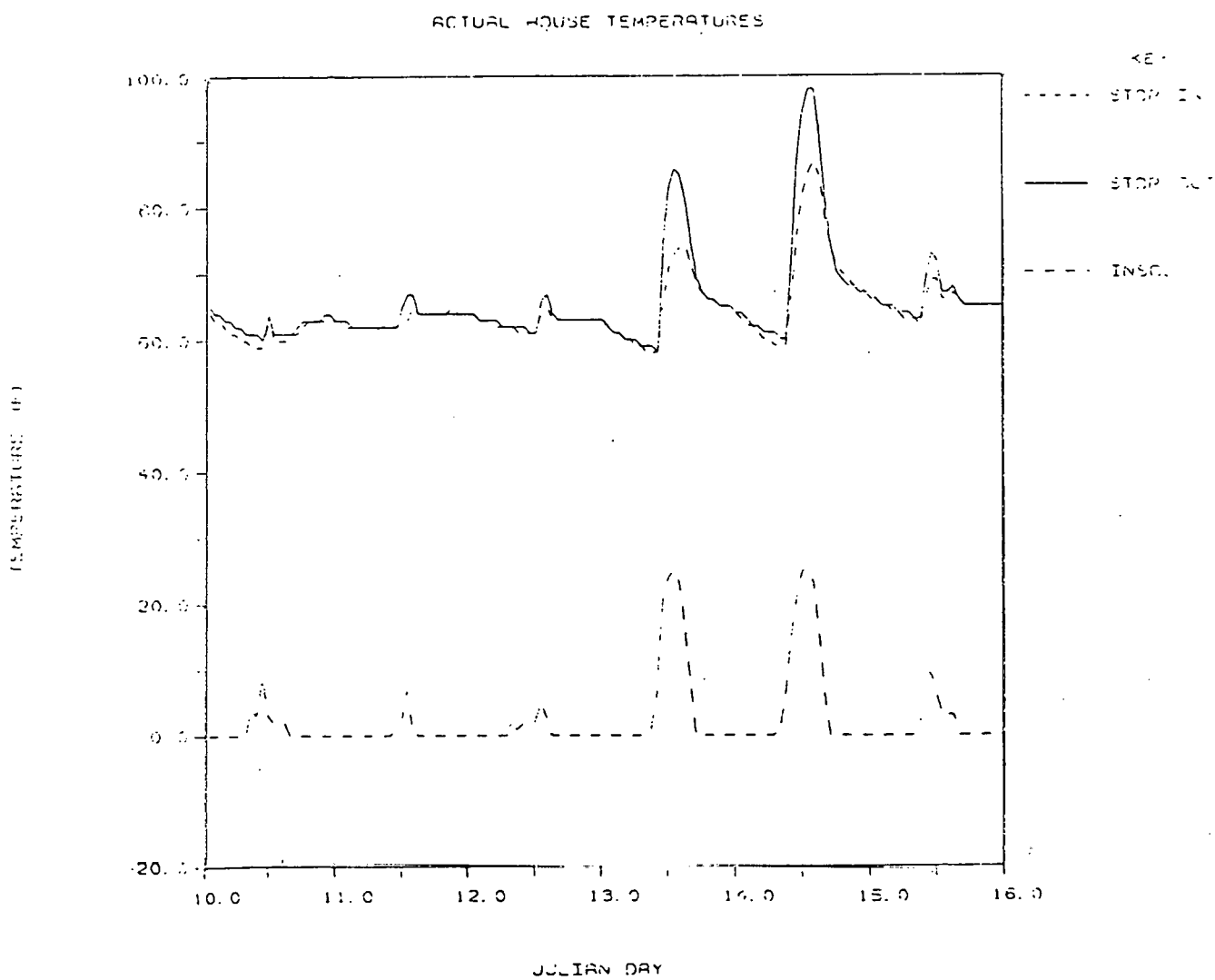

ACTUAL HOUSE TEMPERATURES
KEY
STOP IN
STOP OUT
INSC.
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
10.0
11.0
12.0
13.0
14.0
15.0
16.0
JULIAN DAY

FIGURE 2.18

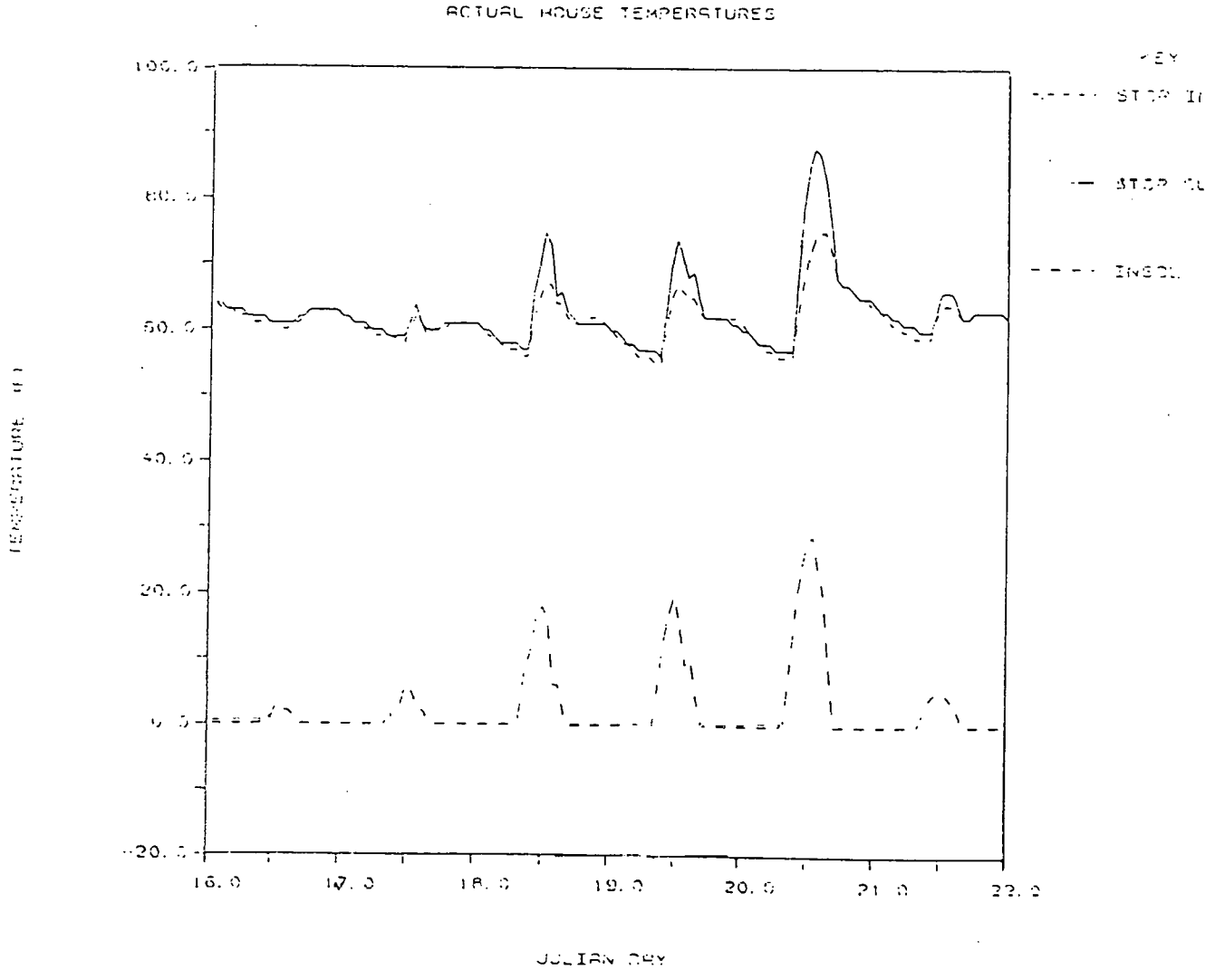

ACTUAL HOUSE TEMPERATURES
KEY
STOP IN
STOP OU
INSOL
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
16.0
17.0
18.0
19.0
20.0
21.0
22.0
JULIAN DAY

FIGURE 2.19

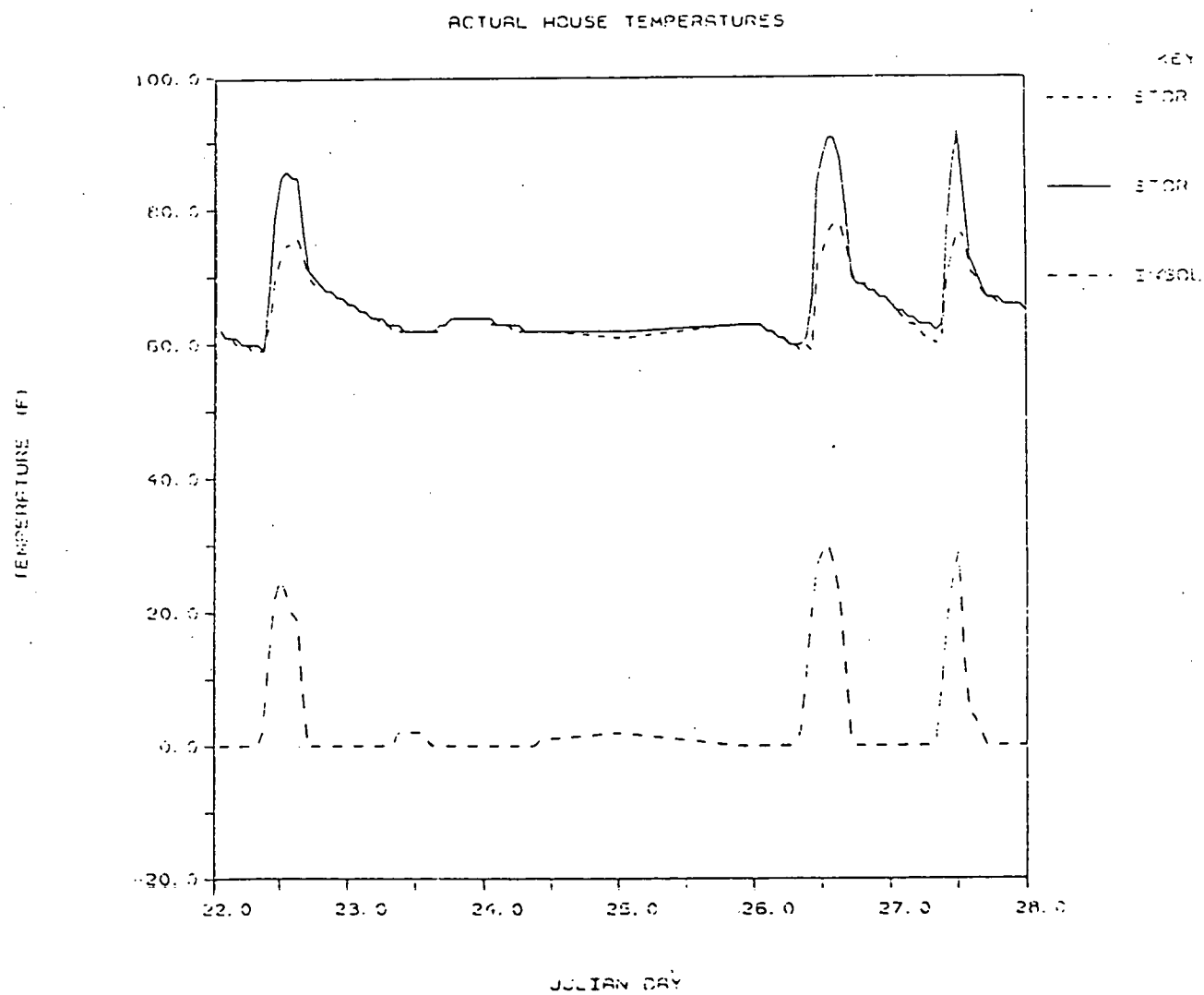

ACTUAL HOUSE TEMPERATURES
KEY
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
22.0
23.0
24.0
25.0
26.0
27.0
28.0
JULIAN DAY

FIGURE 2.20

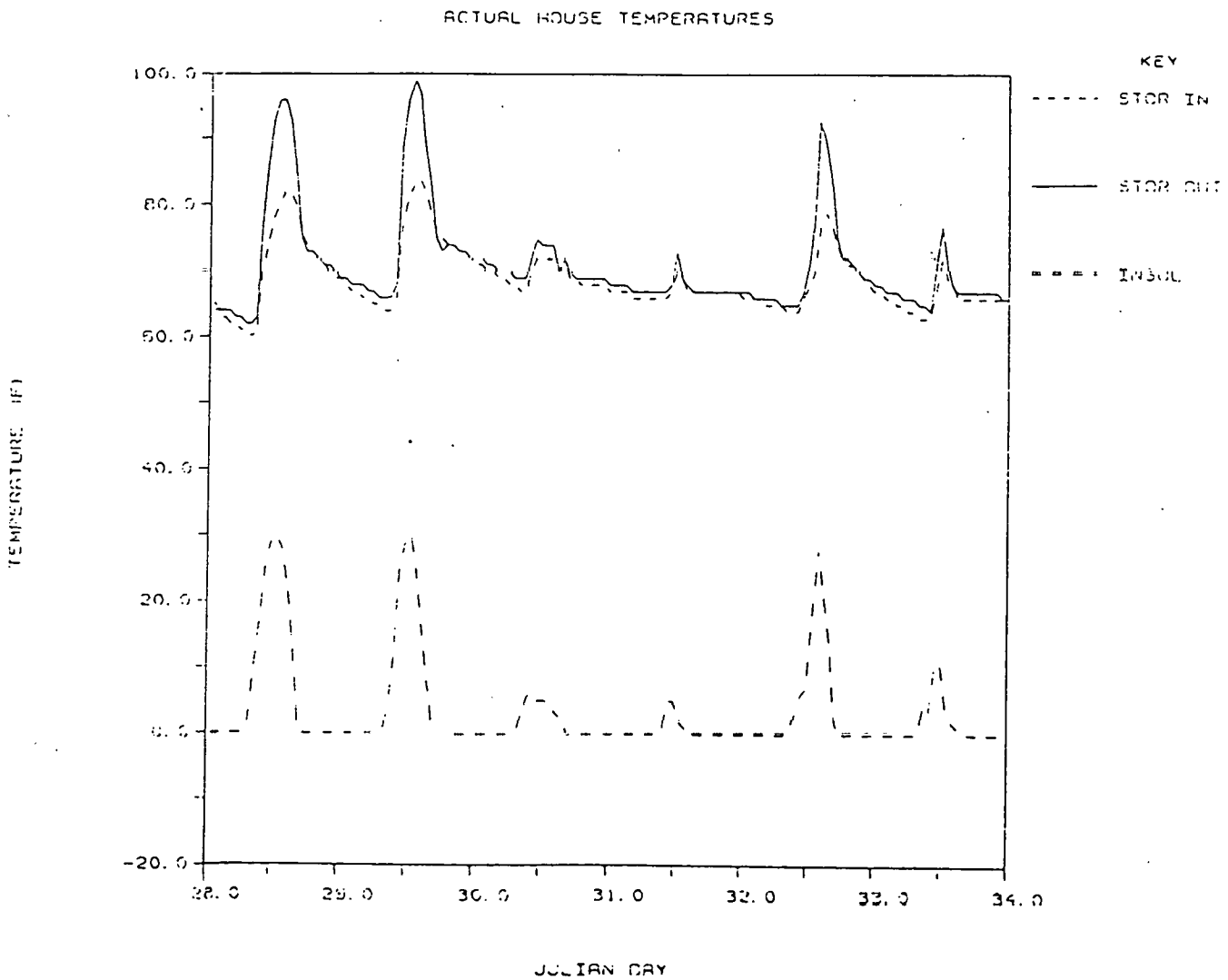

ACTUAL HOUSE TEMPERATURES
KEY
STOR IN
STOR OUT
INSUL
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
28.0
29.0
30.0
31.0
32.0
33.0
34.0
JULIAN DAY

FIGURE 2.21

Table 2.17

Interior Temperature Histogram Data

House Temperature (Degrees F)	Frequency of Occurence
54	2
55	1
56	5
57	13
58	34
59	61
60	88
61	107
62	204
63	247
64	193
65	233
66	288
67	249
68	230
69	204
70	226
71	181
72	165
73	188
74	128
75	156
76	124
77	124
78	101
79	104
80	85
81	46
82	33
83	29
84	15
85	14
86	14
87	9
88	7
89	3
90	2
91	2

Table 2.18

Monthly Summary of Weather Inputs

Month	Degree Days (Base 65F) Actual Site Data	Burlington 1982-83	Burlington Long Term	Insolation (Btu/ft^2 day) Actual Data (60° Incline)	Actual Converted (Horiz)	Burlington Long Term (Horiz)
October	446*	455	502	1067*	809*	740
November	840	676	840	533	349	374
December	1184	1021	1314	603	324	283
January	1442	1356	1494	755	434	385
February	1242	1188	1299	1128	720	606
March	1059	983	1113	981	900	940
April	716	675	660	958	1060	1296
Season	6929	6354	7222			

*October was incomplete in actual measurements.

Note: All long term data is based on 1966-70.

TABLE 2.19

SUMMARY OF COLLECTOR PERFORMANCE

Month	Total Solar Input to Collectors (Btu x 10^6)	Measured Output from Collectors (Btu x 10^6)	Average Monthly Efficiency (%)
November	3.358	1.668	49.7
December	3.926	1.972	50.2
January	4.915	2.350	47.9
February	6.632	3.334	50.3
March	6.390	3.104	48.6
April	2.967	6.035	49.2

TABLE 2.20

SYSTEM PERFORMANCE SUMMARY
(All Values in Units of 1000 Btu)

	Heating Loads			Electrical Energy Input		
Month	Simple ASHRAE	Computer Model	Auxiliary Heating Energy	Pumping Energy	Appliance Energy	Total Electrical Input
November	3,830	2,038	41	177	505	723
December	5,423	3,447	653	123	522	1,298
January	6,576	4,472	859	143	522	1,524
February	5,664	3,655	251	164	471	886
March	4,824	2,742	0	182	522	704
April	3,259	1,409	0	188	505	693
Totals	29,576	17,763	1,804	977	3,047	5,828

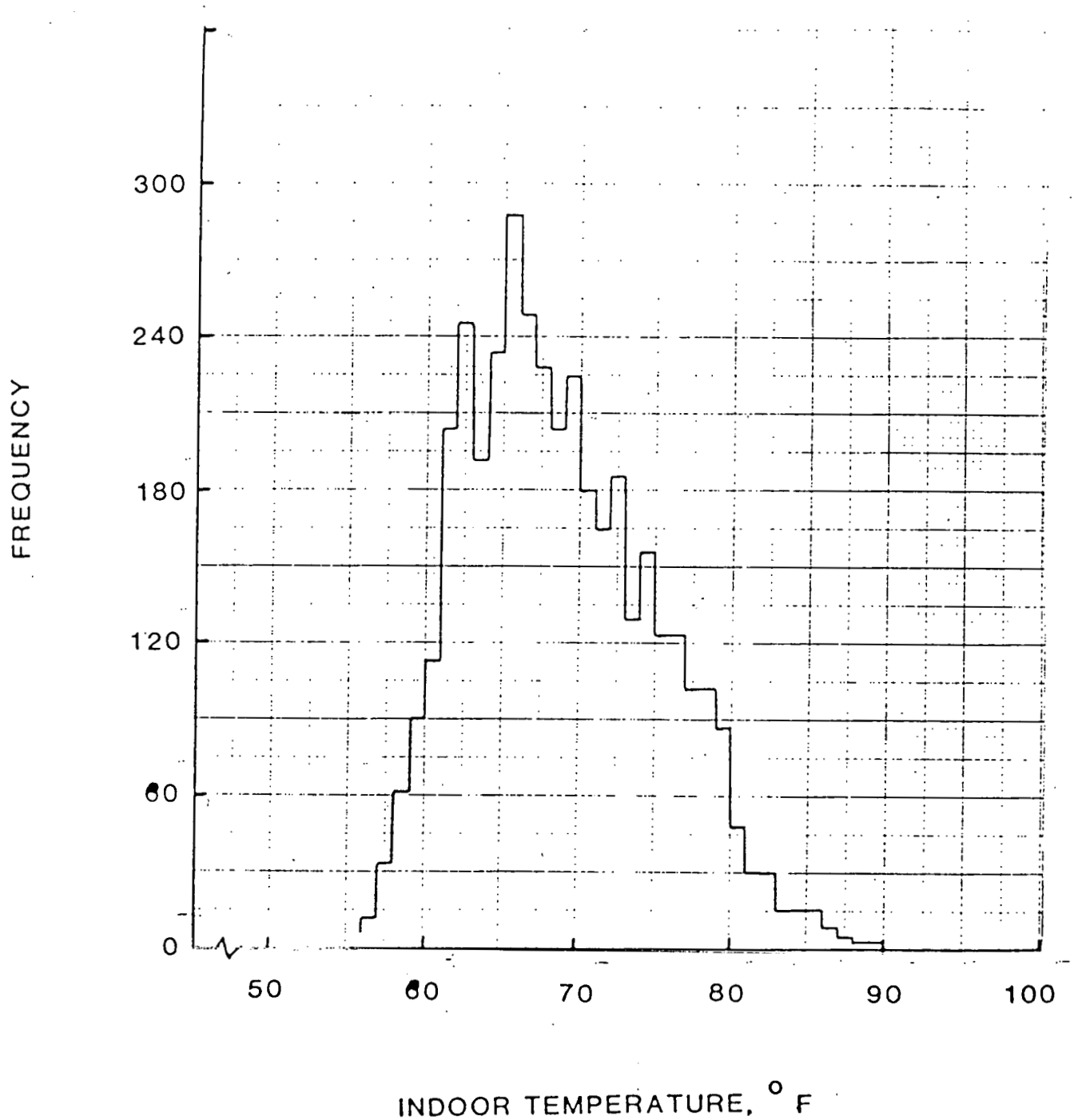

FREQUENCY
300
240
180
120
60
0
50
60
70
80
90
100
INDOOR TEMPERATURE, °F

FIGURE 2.22

than 60 °F or greater than 80 °F. This is an admirable performance record since the overheating protection (manual window opening) was not automatic. This data also indicates that there is sufficient thermal mass to absorb the collected energy.

b. Comparison of measured and long term weather inputs

The degree day total is good measure of the load of the house while the insolation is an indicator of the energy incoming to the system. In order to relate the system performance during the test period to an average year, these two weather inputs were compared to their long term averages from nearby Burlington, Vermont. Table 2.18 gives a tabulation of this comparison. The Degree Days measured at the residence were compared to those measured for the same period in Burlington, Vermont and the corresponding long term average (1956 - 70). The 1982-83 Burlington data was found to be 13.6 percent lower than the Burlington average, thus indicating a warmer heating season than usual. Thus, one might expect a long term average at the Lyndonville site of about 7875 Degree Days. This appears to be reasonable based on other available Vermont weather data (Reference 2.4) for nearby St. Johnsbury (at a lower elevation).

The insolation measured at 60° at the house was transformed to horizontal insulation by the method of Liu and Jordan (Reference 2.5) and compared to the long term average year's insolation in Table 2.18. A comparison of the actual data (converted to the horizontal) and the long term Burlington data indicates that the solar insolation during the test period was close to normal.

c. Solar collector performance

Using the actual insolation data, as summarized in Table 2.18, and the delivered energy from the collectors, as measured by the ISTA Btu Meter, it is possible to calculate an average monthly efficiency for the solar collector system. The results of this calculation for the full data months of November through April are given in Table 2.19. As can be seen, the average collector efficiency (defined as the measured output from the collectors divided by the total solar input) is close to 50% during the entire heating season.

d. Summary of residence heating performance

Figure 2.23 shows the response of the residence (via slab and inside temperatures) to the outside temperature and solar collector input for six days in January. As shown, the interior is maintained at a reasonable comfort level despite wide fluctuations and low ambient temperatures.

Table 2.20 gives a summary of the system performance on a month-by-month and seasonal basis. The heating loads using the simple ASHRAE technique were based on the UA product of the residence times the measured monthly degree days. The computer model results, as will be discussed in the next section, used the same UA product, but calculated the hourly energy inputs of the test residences accounting for solar gains from the windows, night window shade effects, and inside residence temperature set back control. The applicance electrical energy inputs were based on a measured value of 4.932 kwhr per day for all the applicances inside the test residence (primarily the test instrumentation) and the pumping energy inputs were measured by a separate electrical meter. The auxiliary

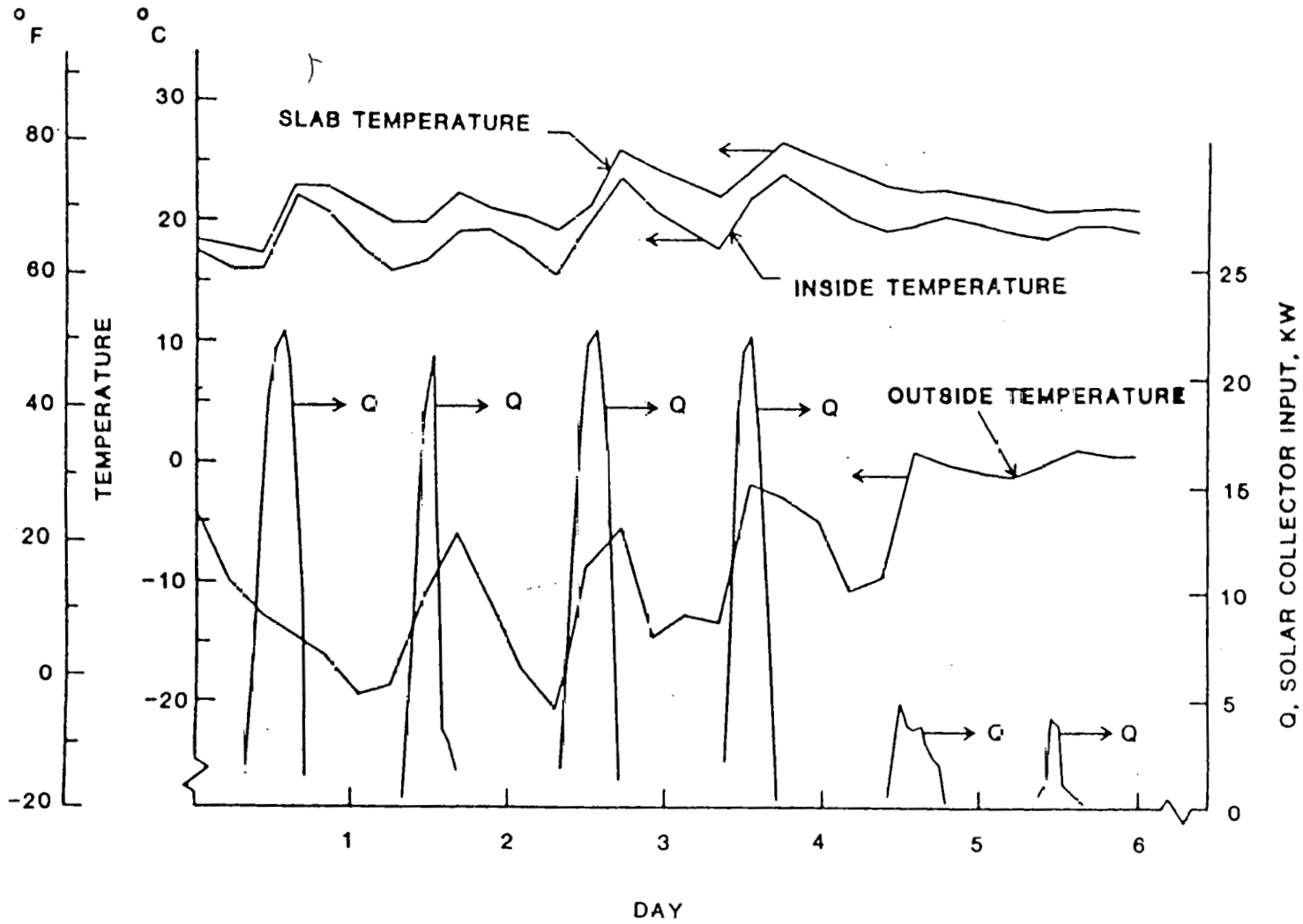

°F
°C
80
60
40
20
0
-20
30
20
10
0
-10
-20
TEMPERATURE
SLAB TEMPERATURE
INSIDE TEMPERATURE
OUTSIDE TEMPERATURE
Q
Q
Q
Q
Q
Q
25
20
15
10
5
0
Q, SOLAR COLLECTOR INPUT, KW
1
2
3
4
5
6
DAY

FIGURE 2.23

energy requirements were determined by subtracting the applicance energy and pumping energy from the total (measured) electrical energy input. Counting all the electrical energy input as useful auxiliary heat and based on the more realistic heating loads predicted by the computer model, it can be seen that the solar system provided about 67% of the test residence's heating requirements during the 1982-83 heating season.

Figure 2.24 shows, on a daily basis, the solar insolation, heating load (from the computer model) and auxiliary energy input for the month of January 1983. As shown by the low total electrical energy input to the system (1.524×10^6 Btu) and relatively constant inside temperature (see Figure 2.10-2.15), the thermal storage capabilities of the slab/gravel bed tend to damp out inside temperature fluctuations. Also, the thermal performance of the system is demonstrated in the highest heating demand month (1442 actual degree days) since the solar system provided about 66% of the heating requirements for this month.

It should also be noted that if, either on a monthly or heating season basis, the performance of the residence were to be based on the controlled electrical input (auxiliary energy only) as related to the computed heating requirement, its performance would appear to be much greater.

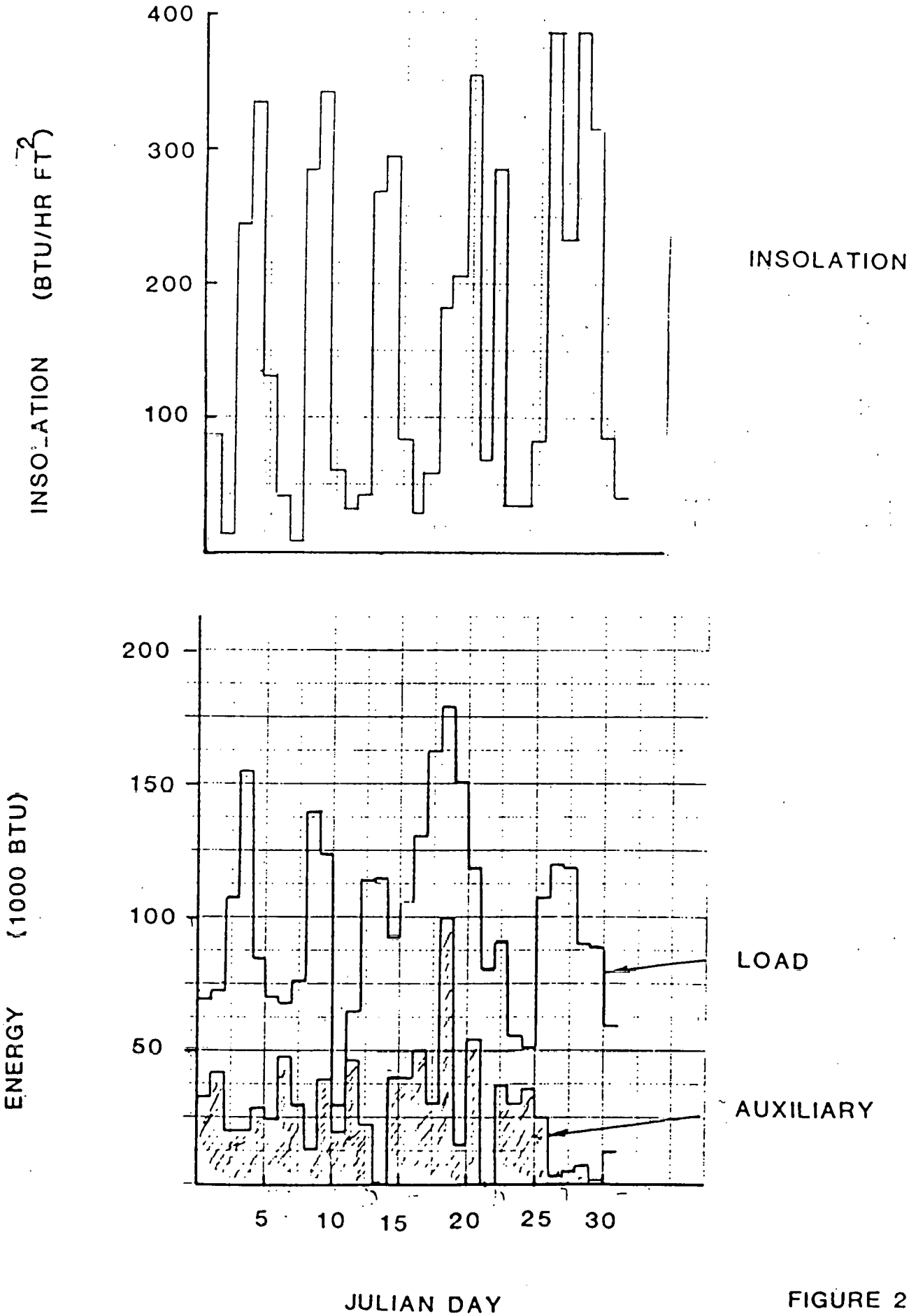

400
300
200
100
INSOLATION (BTU/HR FT^{-2})
INSOLATION
200
150
100
50
ENERGY (1000 BTU)
LOAD
AUXILIARY
5
10
15
20
25
30
JULIAN DAY

FIGURE 2.24

REFERENCES

2.1 ASHRAE Handbook of Fundamentals, American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., Atlanta, GA, 1977.

2.2 Duffie, J.A. and Beckman, W.A., Solar Engineering of Thermal Processes, Wiley, New York, 1980.

2.3 Handbook of Chemistry and Physics, Chemical Rubber, Co., Cleveland, Ohio, 1967.

2.4 "Climatography of the United States No. 60 - Vermont," NOAA, May 1977.

2.5 Liu, B.Y.H and Jordan, R.C., "The Inter-relationship and Characteristic Distribution of Direct, Diffuse and Total Solar Radiation," Solar Energy, 4,3(1960).

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2.1 ASHRAE Handbook of Fundamentals, American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., Atlanta, GA, 1977.

2.2 Duffie, J.A. and Beckman, W.A., Solar Engineering of Thermal Processes, Wiley, New York, 1980.

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2.5 Liu, B.Y.H and Jordan, R.C., "The Inter-relationship and Characteristic Distribution of Direct, Diffuse and Total Solar Radiation," Solar Energy, 4,3(1960).

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