AN ABSTRACT OF THE THESIS OF

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Title: Evaluation of the Boleyn Solar Home, Portland, Oregon

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Abstract approved:
David Philbrick, Milton Larson

The Boleyn home located in Portland Oregon (latitude 45°) is evaluated based on monitoring data taken from 1977 to 1982. The Boleyn home is a two-story (plus basement) frame home. It takes benefit of passive solar gains and is equipped with an active solar system. The active solar system consists of a 429 ft^2 (39.9 m^2) collector with 3750 gallons (14400 liter) of water for thermal storage. The active solar system and the monitoring equipment were installed by PGE (Portland General Electric Company). The performance of the building and of the active solar system and the validity of models predicting parameters of the home and of the solar system are evaluated.

Performance of the home: The Boleyn home is a very well insulated house with low infiltration rate and benefits from passive solar gains obtained from 96 ft^2 of glass area to the south. The Boleyn home is heated by four sources: passive solar gains, internal gains, active solar system, and backup system. Reduced transmission losses through the floor area to the basement heated by losses from the solar storage tanks contributes a significant amount of the overall gain from the active solar system.

Performance of the active system: The design goal of the solar system to meet 50% of the house heating requirements was exceeded. The performance of the Revere double-glazed collector did not deteriorate over time and matchs the manufacturer's data within 5%. A significant amount of heat was lost through the storage tanks because insulation was lacking on the tanks around penetrations and around the pipes. Heat loss due to thermosyphoning was present before installation of a backflow check valve in the collector loop. The overall efficiency of the system was improved by reducing the pump power in the solar collection loop and installation of an improved backup system. Installation of a domestic hot water preheat tank reduced the domestic hot water load by 73%.

Validity of predictive tools: The design heat loss calculated by using the ASHRAE method matched the experimentally evaluated design heat loss within 6%. The annual heating requirements predicted by the degree-day-method by ASHRAE and Calpas3 were accurate within 12% and 21% respectively. A large cooling load caused by passive solar gains predicted by Calpas3 did not occur at the Boleyn home. The Boleyns open the windows and accept higher indoor temperatures than predicted by Calpas3. The active solar fraction predicted by F-chart was 66.3%. The experimentally evaluated value is 74.5%. The heat loss from the solar storage tanks was 3.6 times higher than the prediction performed by PGE, which did not include losses from piping and uninsulated portions of the tank.

Evaluation of the Boleyn Solar Home, Portland, Oregon

by

Hans Ehm

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Professor of Mechanical Engineering in charge of major

Redacted for Privacy

Head of department of Mechanical Engineering

Redacted for Privacy

Dean of Graduate School

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By Hans Ehm

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1 INTRODUCTION

The Boleyn home is one of about 15 residences equipped and monitored by Portland General Electric Company (PGE). In 1975 at the height of the oil crises PGE started to research solar buildings in the Portland and Salem regions of Oregon. The Boleyn solar home is of great interest since it meets its heating requirements by both active and passive solar gains.

Monitoring took place from 1977 to 1982. Data are available both on magnetic tape and on printouts. The evaluation of the data in this paper is based on the printouts. Approximately four million datapoints were taken during the five years of monitoring, only a fraction of which were evaluated in this work. Not all recorded data are accurate. Therefore the evaluated data were selected by specified requirements stated for the purpose of evaluation.

Data were analyzed to determine the performance of the solar building and to empirically validate the results of different predictive tools. The validity of predictive tools like Calpas3 and F-chart is discussed.

Similarly the performance of the components of the active solar system are compared to design predictions. As a part of this effort, the performance of the solar collector is compared with the manufacturer's data and the losses from the storage tanks are compared with the predicted losses.

2 THE BOLEYN SOLAR HOME

2.1 Introduction

The Boleyn solar home is a two-story (plus basement) frame home, located in Gladstone 2 miles south of Portland, Oregon (latitude 45°).

The house was constructed in 1974 by the Homecraft Construction Co.. In 1975 Portland General Electric Company (PGE), a utility which serves the Portland Oregon area, installed the solar equipment and the monitoring equipment.

The house is owned and occupied by Douglas and Emily Boleyn. Two adults and two children live in the house. There are two floors, three bedrooms and two bathrooms.

The total floor area is 1790 ft^2 (166 m^2). The heated volume is 16220 ft^3 (459 m^3). The Boleyn home has an average 9 ft (2.7 m) ceiling height. If standard 8 ft (2.4 m) ceilings were assumed, the corresponding equivalent floor area to provide equivalent volume would be 2020 ft^2 (188 m^2).

The walls and the roof are insulated with R-11 and R-19 batts respectively. The basement is unheated and was initially uninsulated.

The overall glass window area is 240 ft^2 (22.3 m^2), with 96 ft^2 (8.9 m^2) facing south.

Drawings of the house from four directions and the basement and the first floor are given in Figures 2.1 through 2.6.

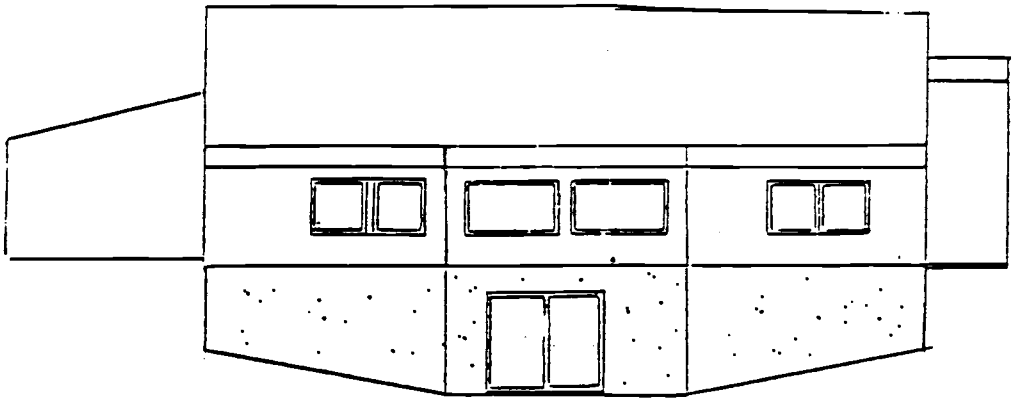

Fig. 2.1 South facing wall

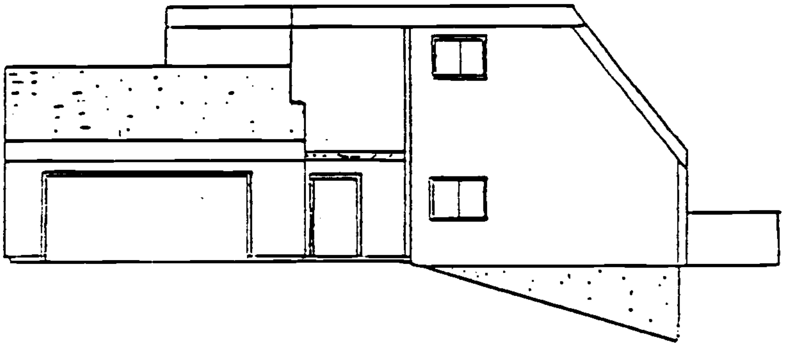

Fig 2.2 West facing wall

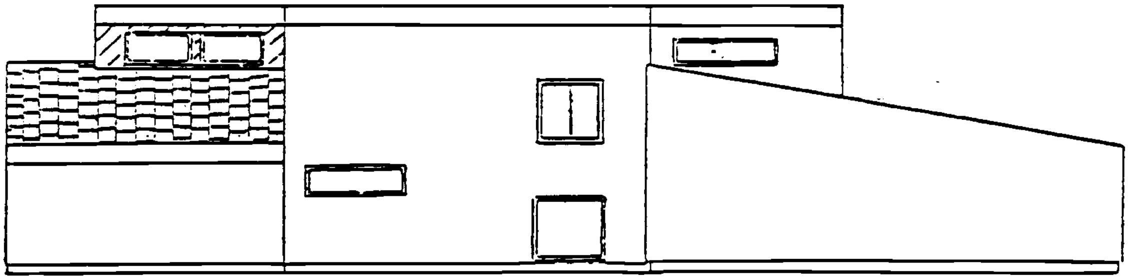

Fig. 2.3 North facing wall

Fig. 2.4 East facing wall

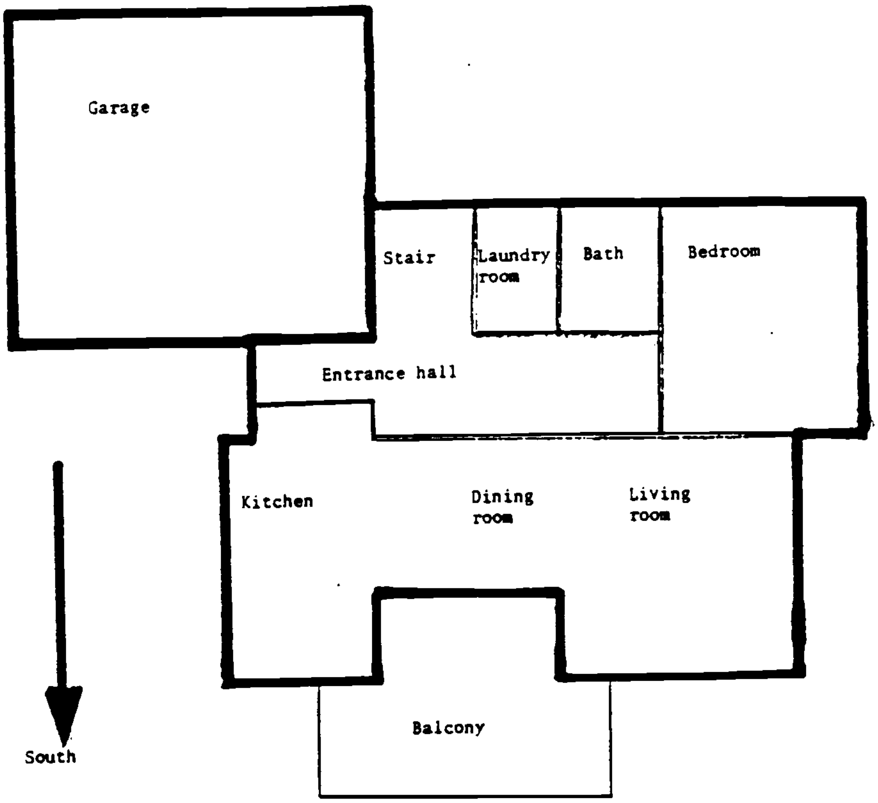

Fig. 2.5 Main floor

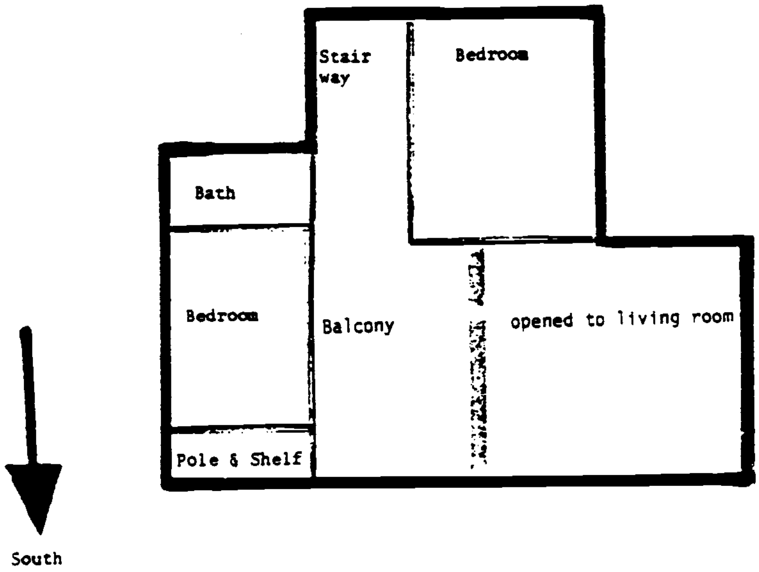

Fig. 2.6 First floor

2.2 The Solar System

Fig 2.7 shows the original solar system installed by PGE.

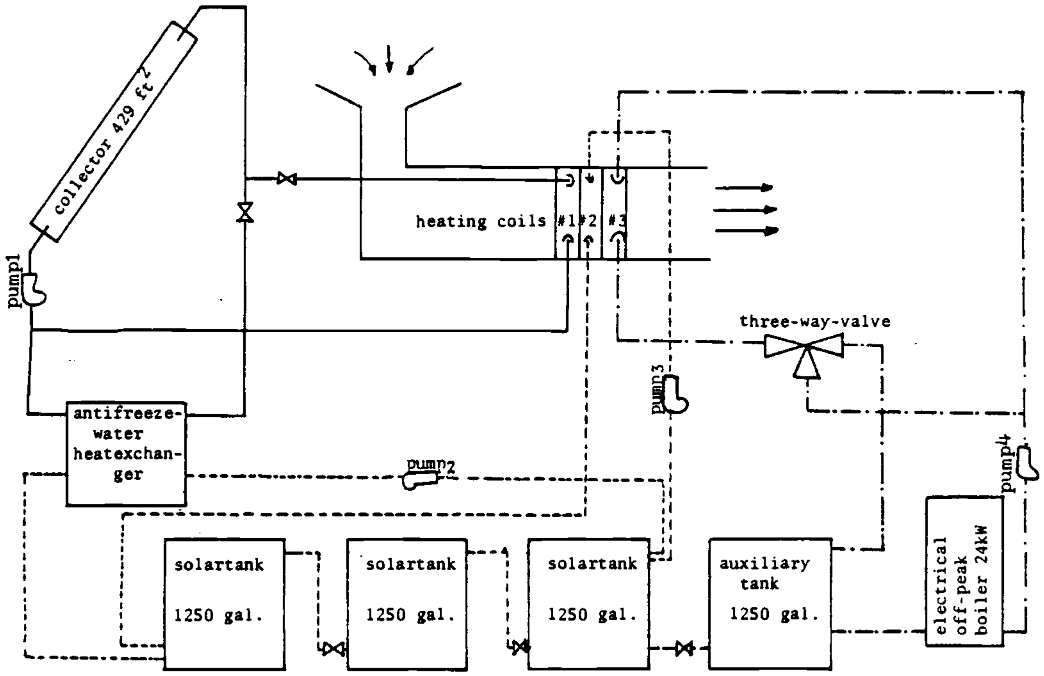

Fig 2.7 Original installed solar system

The solar heating system consists of 429 ft^2 (40 m^2) of Revere double glazed copper panels (22 panels). The collector is located on the 60 degree sloped south facing roof. The collector array piping scheme used is a three-segment, reverse-return, multiple-parallel arrangement with no more than 24 individual risers on any parallel circuit. This scheme is used in an attempt to avoid problems of uneven flow rates through the array.

The primary loop is filled with a 30% glycol-water solution as antifreeze. The pipes go down to the basement to a water-to-water heat exchanger which feeds the solar water storage system.

The collector heat exchanger loop is controlled by a thermostat that turns on the pump any time the collector outlet temperature exceeds the storage temperature by 20 F (11 ^oC) and turns off the pump when the temperature difference drops to 3 F (1.6 ^oC). This avoids heating the collector from the storage system and running the pumps unnecessarily.

The storage system consists of three 1250 gallon (4800 liter) fiberglass tanks. The walls of each cylindrical tank are insulated with R-19 fiberglass batt insulation. The tanks are inside an area insulated with R-11 to the basement.

There was an additional 1250 gallon (4800 liter) electrically heated storage tank for the backup system in the original design. This auxiliary boiler heating system was designed to heat the house during off-peak periods. PGE originally envisioned using the home to study means for minimizing variations in the load demands placed on their utility.

Three hot water heating coils (see Fig. 2.7) are located in the duct system: coil No.1 is fed directly from the collector, coil No.2 is fed from the solar storage system and coil No.3 is fed from the auxiliary system.

The system operates in the following manner. Whenever the indoor temperature drops below the 1st stage of the thermostat, it activates the fan and coil No.1 provides as much direct solar heat as possible. The 2nd stage of the thermostat (approximately 1 F lower) energizes pump #3 and provides heat from the solar storage system using hot water heating coil No.2.

If both of these stages still do not meet the heating requirements of the house the third stage of the thermostat (one F lower) is activated which energizes pump #4 from the auxiliary boiler storage tank to provide the necessary heating. Should all three stages not meet the requirements of the house, the boiler is electrically heated to feed hot water coil No.3 directly from the boiler.

One additional heat exchanger is located in the system. It is isolated from the space heating system and is used to preheat domestic hot water (see section 5.4.3).

2.3 Data Collection System

The instrumentation package consists of a datalogger (L 2.1) and a recorder. The datalogger was used to sample 30 parameters. The 30 points sampled include air and water temperatures in the system and in the home, water and air flowrates, and solar insolation on a horizontal surface and on a 60° tilted surface. The solar insolation data are measured with a pyranometer. Data are taken every 20 minutes and stored on magnetic tape. Printouts are available for hourly integrated data. A copy of the two page printout is given in Appendix A.

The datalogger is the Data Logger II from Datel Systems, Inc.. The specifications are given below.

No. of channels	32
Power supply	+14.75 V DC (Batteries)
Power used	@12 V 100 mA max. during motor stepping
System weight	20 lbs (9kg)
Dimensions	12"H * 12"W * 10"D 305 mm * 305mm * 254 mm
Temperature range	-20 $^{\circ}$C to +85 $^{\circ}$C
Sample time	150 s

Every measurement is converted into a voltage between -5 V and +5 V and then digitized in steps of 39 mV. One data word requires 8 bits.

The 30 used channels are occupied as follows

No.1	Energy to the boiler in kWh
No.2	Energy requirements of pump #3 and pump #4 (for solar and auxiliary heating)in kWh
No.3	Energy requirements of pump #1 and pump #2 (for collector, heat exchanger and fan) in kWh
No.4	Horizontal insolation in Btu/hrft^2
No.5	60° tilt insolation in Btu/hrft^2
No.6	Energy flow from the collector in Btu/hr 1)
No.7	Energy flow from the auxiliary storage tank in Btu/hr 1)
No.8	Energy flow from the solar storage tanks in Btu/hr 1)
No.9	Energy flow from the collector side of the heat exchanger in Btu/hr 1)
No.10	Energy flow from the storage side of the heat exchanger in Btu/hr 1)
No.11	Energy flow to the house in Btu/hr 1)
No.12-No.16	Collector absorber temperatures in F 2)
No.17-No.21	Solar tank temperatures in F
No.22	Auxiliary tank temperature in F
No.23	Collector outlet temperature in F
No.24	Collector inlet temperature in F
No.25	Ambient air temperature in F
No.26	Tank enclosure temperature in F
No.27	Basement temperature in F
No.28	Residence temperature in F
No.29	Supply air duct temperature in F
No.30	Return air duct temperature in F

1), 2) see pages 12 and 13

The Btu energy data (footnote 1) on page 11) are calculated by electrically multiplying the flowrate and the temperature difference (Fig. 2.8).

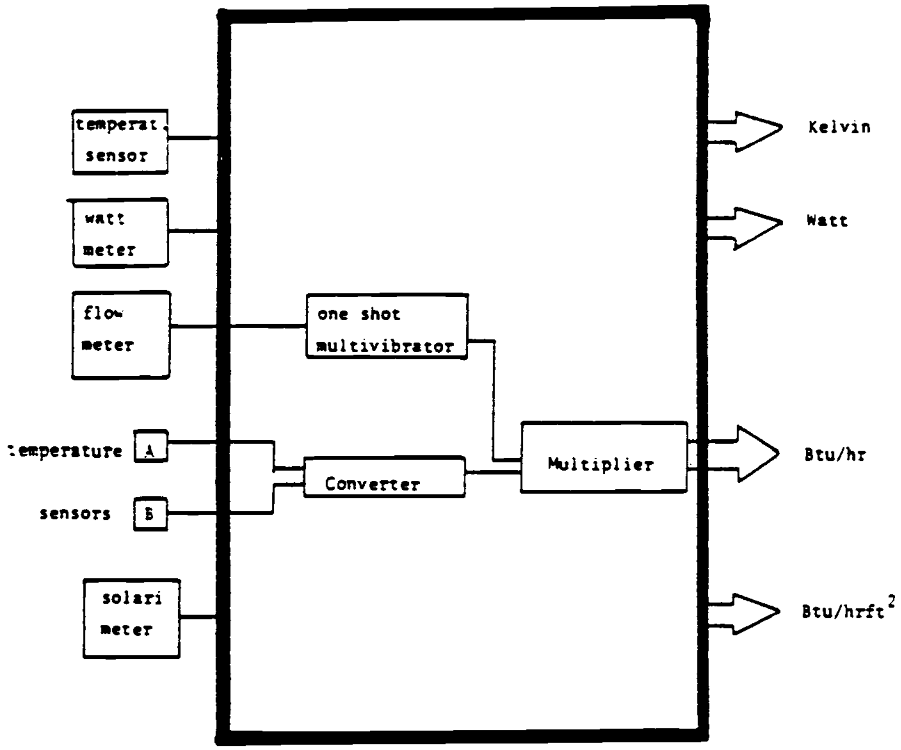

Fig 2.8 Measuring the energy to the house

The collector sensor locations (footnote 2) on page 11) are shown in Fig 2.9.

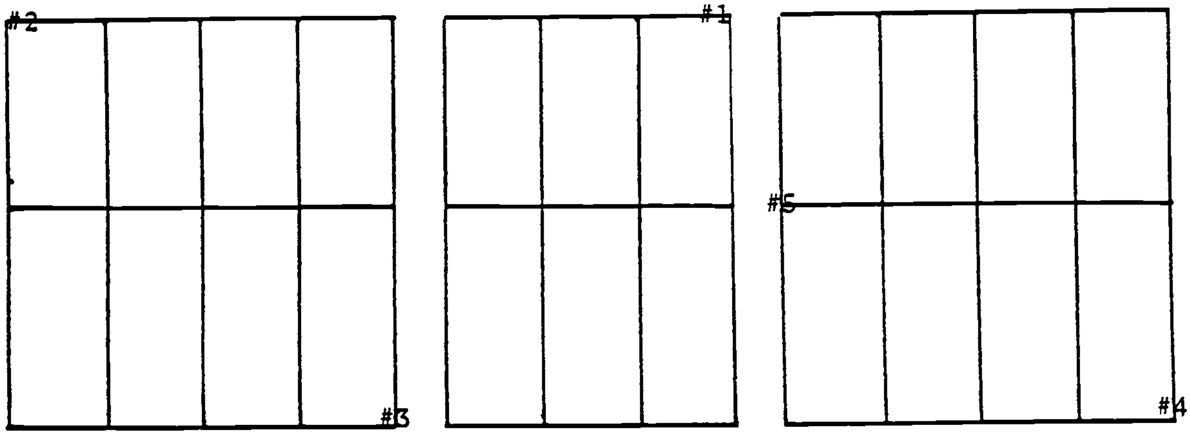

Fig 2.9 Collector sensor location

Data were taken continuously from 1976 to 1982 with short breaks. Since 1982 some very useful data were recorded by hand by Douglas Boleyn.

2.4 Data selection

The evaluation of the data is based on the data available on the printouts. Not all recorded data are accurate and not all recorded data are available on the printouts. In addition data were selected to make the large amount of data manageable. The selection criteria are: accuracy, availability over a large period of time and pupose of evaluation. Thus the evaluated data used in this paper are:

Temperature: ambient air, indoor, basement, enclosure, averaged collector, averaged solar storage tank, auxiliary storage tank, collector inlet

Insolation: value for 60° tilted surface

Energy: from collector to solar storage, from solar storage to air distribution system, from auxiliary storage to air distribution system, from air distribution system to the house

Specific selection criteria were necessary for the purpose of specific evaluations. Those selection criteria are stated whenever they were necessary.

2.5 Changes to the system

Improvements in the system occured during testing. This section describes the changes that were made and provides qualitative evaluation. A quantitative evaluation will be presented in a later section.

Auxiliary heating system

In June 1979 the 25-kW electric boiler heating a 1250 gallon (4800 liter) auxiliary tank were removed and replaced by a 10-kW electric resistance duct heater. This lowered the energy consumption drastically, because of heat loss through the storage tank walls (see section 5.4.1).

Air distribution system

Between January 1976 and May 1979, there were two pumps used to distribute the heat into the fan coil unit. Pump #3 (Fig 2.7) with a 1/4 hp (horsepower) motor circulated water from the solar storage tanks through the water-air heat exchanger. Pump #4 (Fig. 2.7) with a 1/6 hp motor circulated electrically heated water from the backup storage tank through heating coil#3. In May 1979 the solar storage tank pump was replaced by a 1/20 hp unit and pump #4 was taken off the system as part of the conversion to a duct heater. Both lowered the electricity bill.

Solar collection pumps

In July 1980 the 3/4 hp (pump #1 see Fig. 2.7) and 1/6 hp (pump #2) solar collection pumps were replaced. Pump #1 was replaced by a 1/12 hp unit and pump #2 was replaced by a 1/20 hp unit (see section 5.4.2).

Domestic hot water

To simplify monitoring of the space heating system, the domestic hot water heating preheat tank was disconnected during the space heating season from 1976 through 1979. During this period the domestic hot water preheat tank was connected and provided savings only in those months in which space heating was not required: the summer months.

From March 1979 to the present the solar domestic hot water preheat tank has been continuously connected to the main storage tanks. Thus providing hot water preheating on a year-round basis. The domestic hot water system is discussed in more detail in section 5.4.3.

References

L 2.1 Datel Systems, Inc. Data Logger II (1975), Brochure from Datel Systems Inc. 1020 Turnpike Street, Canton Mass. 02021

3 HEATING LOAD OF THE HOUSE

This chapter presents an analysis of the effective UA-product for the building (including infiltration losses and internal gains during the operation of the building) and compares it with the values predicted by the ASHRAE design method (L 3.1). The effective UA-product multiplied by the design temperature difference determines the design heat loss.

In addition the results from a calculation made by PGE are shown and compared with the above results.

3.1 ASHRAE Method

The ASHRAE method predicts the design heat loss of a building and the annual heating requirements. The design conditions were assumed to be 15 F for the outside temperature and 70 F for the inside temperature.

The annual heating requirements are predicted with the degree-day-method.

The ASHRAE method accounts for transmission losses and infiltration losses as well as for internal gains from people and equipment.

3.1.1 Transmission losses

The transmission losses modeled after ASHRAE are performed in detail in Appendix B.

Table 3.1 gives a summary of all areas (taken from Fig. 2.1 to Fig. 2.6) and the corresponding U-values.

	South	East	West	North	U-values in Btu/hrft^{2}F
Wall (main floor)	369	474	467	671	.068
Glass area	96	79	41	24	.47
Doors (wood)	-	-	-	20	.43
Wall (basement)	320	275	360	275	.21
Roof	1576				.049
Floor	1125				.25

Table 3.1 Summary of the areas and U-values

The heat loss of walls, roof, floor, windows and doors is given in Table 3.2.

	$U_x*A_x*(T_i - T_o)$	Heatloss in Btu/hr
Walls	.068*1681*55	6287
Roof	.049*1576*55	4247
Floor	.25*1125*(70-42)	7875
Windows and Glass door	.47*240*55	6204
Wood door	.53*20*55	473
		25086

Table 3.2 Heat loss due to transmission

The total heat loss due to transmission calculated using the ASHRAE design method for the design temperatures for the Boleyn home is 25086 Btu/hr (6968 W)

3.1.2 Infiltration losses

Outdoor air coming into the house by infiltration has to be warmed to the indoor temperature. The heat required to warm up the cold air is given in EQ. 3.2.

$$H_i = c_p*Q*p*(T_i-T_o)$$

EQ. 3.2

H_i: Heat required to warm the air from 15 F to 70 F
Q: Volume flowrate of incom. air
c_p: Heat capacity of air .24 Btu/lbmF (1 kJ/kgK)
p: Density of standard air .075 lbm/ft^3 (1.15 kg/m^3)

The volume flowrate of the incoming air is a function of windspeed, wind direction, width of cracks and size of openings. However, it is also heavily influenced by traffic through doors and the habits of the people living in the house.

A convenient and frequently practiced way to estimate Q is the air change method (L 3.1).

$$Q = f_a*V$$

EQ. 3.3

f_a: Air change factor
V: Volume of the house 16220ft^3 (459 m^3)

According to the recommendations of ASHRAE (L 3.1) and considering that the Boleyn home is a fairly tight built house and that the windspeed is fairly low (about 7mph), f_a is assumed to be 3/4 air changes per hour. Using these assumptions and combining EQ. 3.2 and EQ. 3.3 yields:

$$H_i = .24*3/4*16220*.075*55 = 12043 \text{ Btu/hr } (3530 \text{ W})$$

3.1.3 Total heat loss

The total heat loss is the sum of infiltration and transmission heat losses reduced by gains from people and equipment.

The heat gain due to people can only be estimated, since it depends on the kind of work done and how long the people really stay in the house. An estimation based on "Heating Ventilating and Airconditioning" (L 3.2) assuming that 2 adults and 2 children stay (on the average) 15 hours a day in the house is:

$$H_p = 1000 \text{ Btu/hr} \qquad (290 \text{ W})$$

The equipment gains depend strongly on the lifestyle of the individual homeowners. According to ASHRAE (L 3.1) the electricity requirement for a family of four is:

$$H_e = 1000 \text{ Btu/hr} \qquad (290 \text{ W})$$

The total design heat loss is then approximately:

$$H_t = H_T + H_i - H_p - H_e$$

$$H_t = 25086 + 12043 - 1000 - 1000 = 35129$$

The total design heat loss including both transmission and infiltration losses and equipment and people gains calculated using the ASHRAE design method for the Boleyn home is

$$H_t = 35129 \text{ Btu/hr} \qquad (10294 \text{ W})$$

Annual heating requirements

In addition to the design heat loss, the annual heating requirements are of interest. They can be estimated by using the degree-day-method (L 3.4).

$$AHR' = \frac{H_t*DD*N_h}{DT_d}$$

AHR': Annual heating requirements without internal gains

H_t: Total heat loss not including internal gains 37129 Btu/hr (10880 W)

DD: Degree days for Portland 4635 DD_F (L 3.4)

DT_d: Design temperature difference 55 F (30 °C)

N_h: Number of hours when heating is required. The Number of hours are adjusted to account for thermostat setback and passive solar gains to calculate the true annual heating requirements. A reasonable assumption (L 3.3) is 17 hours a day.

$$AHR' = 53.19*10^6 \text{ Btu/yr} \quad (56.12*10^6 \text{ kJ/yr})$$

From this value the internal gains which are not temperature dependent have to be subtracted. The yearly total internal gains using the values from section 3.3 are: $2000*24*365=17.5*10^6$ Btu/yr. The annual heating requirements (AHR) including internal gains:

$$AHR = 35.69*10^6 \text{ Btu/yr} \quad (37.65*10^6 \text{ Btu/yr})$$

The computer program Calpas3 predicts the annual heating requirements as $31.15*10^6$ Btu. Calpas3 is discussed in section 4.7.1.

3.1.4 Summary

A quantity often used to describe the heating requirements of a house is the building performance index (BPI). The BPI is the yearly heat load per degree-day and per unit of house area:

$$BPI = AHR/(DD*A)$$

BPI: Building performance index

AHR: Annual heating requirements $35.69*10^6$ Btu/yr ($37.65*10^6$ kJ/yr) according to the prediction of the ASHRAE method. $31.15*10^6$ Btu/yr ($32.86*10^6$ kJ/yr) according to the prediction of Calpas3.

DD: Number of degree days 4635 DD_F for the ASHRAE prediction and 4546 DD_F for the Calpas3 prediction.

A: Equivalent floor area of the house assuming 8 ft ceiling 2020 ft^2 (188 m^2)

For the Boleyn home this would yield a BPI of 3.8 Btu/DD_Fft^2 according to the ASHRAE prediction and 3.4 Btu/DD_Fft^2 according to the Calpas3 prediction. The experimentally evaluated BPI of the Boleyn home (see section 4.8) is 4.3 Btu/DD_Fft^2. This shows that the ASHRAE method predicts the annual heating requirements of the Boleyn home within 12% and Calpas3 within 21%. Residences are usually in the order of 6 to 12 Btu/DD_Fft^2 (L 3.5). This shows that the Boleyn home is a well insulated house.

In general houses with smaller surface to volume ratios have smaller values of BPI. This results from the fact that transmission losses depend strongly on the skin surface.

Table 3.3 summarizes the performance of the Boleyn home as calculated using the ASHRAE method and indicates the section of this paper where the calculation was discussed.

	EE-Units	SI-Units	chapter
Transmission heat loss	25086 Btu/hr	7352 W	3.1.1
Infiltration heat loss	12043 Btu/hr	3530 W	3.1.2
Internal gains	2000 Btu/hr	586 W	3.3
Tot. heat loss	35129 Btu/hr	10295 W	3.3
Annual heating requirements	41.17 MBtu/yr	43.4 GJ/yr	3.3
BPI	3.8 $Btu/DDft^2$	79 kJ/DD_Km^2	3.5

Table 3.3 Summary of the design heat loss

3.2 Heating load predicted by PGE

Before the active solar system was installed the heat loss of the house was predicted by PGE using the NESCA Manual J Method. NESCA stands for National Enviromental Systems Contactors Association. This calculation used slightly different U-values and assumed only 1/2 air change per hour for infiltration losses.

The design heat loss from the calculations made by PGE is 31350 Btu/hr (9187 W). The result from the ASHRAE method is 34630 Btu/hr or 10% higher than the result given by PGE.

Based on the assumption of 1/2 air change per hour and EQ. 3.2 the infiltration losses are 4014 Btu/hr (1176 W) lower than for 3/4 air change per hour. With this lower infiltration value the ASHRAE method would come up with 30614 Btu/hr (8972 W), only 2.4% lower than the calculation performed by PGE.

3.3 Actual Load of the House

Analyses of the data from the Boleyn solar home provide an overall UA-factor. This is the ratio of the total heat to the house, from the heating system regardless of the source, divided by the temperature difference between indoor temperature and outside temperature. According to $Q=UA*(T_i-T_a)$

$UA = Q/(T_i-T_a)$

UA: Total house UA-factor
T_i: Indoor temperature
T_a: Ambient air temperature
Q: Total heat to the house

Selecting only nighttime data, one minimizes passive solar gains. The total heat to the house is measured by multiplying the air flowrate through the ductwork by the temperature difference before and after the heat exchanger. Data are available for this purpose for the years 1977,1978, and 1980 to 1982.

To get a realistic number from all the data the following procedure was used:

1) To eliminate warmup peaks, UA-values were sampled during nighttime hours only when heating was required over a large period of time. In addition it was checked to determine if the energy delivered through the duct system matches the energy delivered from the solar storage tanks plus the energy delivered from the auxiliary tank within 20%.
2) Only months with high heating requirements were selected since the error is larger for smaller Q and (T_a-T_i) values.

3) To eliminate passive solar gains carried into nighttime hours through the heat capacity of the house, days with high insolation values were not considered.
4) To avoid irregularities due to changes in the system only data were selected for years in which minimal changes were made.

A statistic method was used to calculate the overall UA-factor from the data at the Boleyn home. UA-values from October to March (because of criteria #2 in the list above) in 1977 and 1978 (because of criteria #4) at 1 a.m 2 a.m, and 3 a.m (because of criteria #1) were selected. From these 1000 values 200 were drawn by means of a random table.

From these 200 values only those were considered which satisfied all the requirements #1 to #4. Finally 60 values mainly (because of criteria #2 and #3) in November and December remained.

The mean of the 60 values is:

UA=462 Btu/hr (135 W)
with a standard deviation of 55 Btu/hr (16 W)

How does this compare with the predicted results

Multiplying the actual UA-value by the design temperature difference of 55 F (30 C^{O}) gives a heat loss of 25410 Btu/hr (7447 W). This value is 26% lower than the prediction made by ASHRAE and 19% lower than the prediction made by PGE.

However, this heat loss cannot be compared with the calculated heat loss immediately, since the design heat loss was calculated by assuming that the basement is an unheated space. However, during the data collection the basement was heated by the heat loss from the storage tanks to within ± 3F of the indoor temperature. Therefore essentially no losses occured through the floor to the basement. By adding to the 25410 Btu/hr the design heat loss through the basement of 7875 Btu/hr (see section 3.1) the comparable result is 33290 Btu/hr (9642 W).

A comparison to the predictions from the NESCA Manual J Method and the ASHRAE-Method is given in Table 3.4.

Actual losses corrected for heated basement	ASHRAE method	Calculation made by PGE
33290 Btu/hr	35129 Btu/hr	31350 Btu/hr
9642 W	10295 W	9186 W

Table 3.4 Comparison of actual and predicted design heat loss

The results summarized in Table 3.4 show that the predictions match the actual losses very well within 6% and are therefore a good tool for predicting design heat losses for residences.

Since the main difference in the calculation made by PGE compared to the ASHRAE approach was the infiltration rate, the actual data gives an indication that the infiltration rate is probably somewhere between .5 and .75 airchanges per hour.

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4 PERFORMANCE OF THE BOLEYN HOME

This chapter evaluates the contribution of the energy sources of the Boleyn home, gives the annual temperature profile of the home and compares the results with predictive tools and other monitored solar homes. The passive solar contribution is compared with the prediction made by the computer model Calpas3. The contribution of the active solar system is compared with the prediction made by the computer model F-chart.

4.1 Introduction

After evaluating the design heatloss in chapter 3 it is of interest to note where the Boleyn home gets the required energy. There are essentially 4 energy sources in the Boleyn home: passive solar gains, active solar system, internal gains and backup system.

1) Passive solar gains. The Boleyn home is built to take advantage of passive solar gains obtained from 96 ft^2 (8.9 m^2) of glass area to the south. To increase the passive solar gains the Boleyns added a sunspace in 1982.

2) Active solar system. The 429 ft^2 (40 m^2) of collector surface with 4500 gallons (17100 liter) of water storage tank was designed to meet annually 50% of the heating requirements (L 4.1).

The energy gain from the active solar system contains two components: the energy delivered from the solar storage tanks via the heat exchanger and the energy gain from the tank heated basement. The heated basement from the storage tanks is a unique energy source for the Boleyn home because the storage tanks are in the basement. Due to unexpected high losses the basement was heated by the storage tanks. When the active solar system was in operation the tank heated basement reduced the transmission losses via the floor area.

3) Internal gains. Internal gains due to people and equipment within the building contribute a significant energy source to the house. See section 3.3 for a discussion.

5) Backup system. The remaining heating requirement was met from 1977 to 1979 by an electically heated auxiliary storage tank. Due to its high heatloss the auxiliary storage tank was replaced by an electrical duct heater in 1979.

4.2 Methodology used to evaluate the energy sources of the Boleyn home

The performance of the house was evaluated on a year round basis by accounting for all four energy sources. A full year was chosen to make the results comparable with annual predictions. Five datapoints (Fig. 4.1) were necessary to calculate the four energy sources and the predicted heating requirement:

1) Ambient air temperature
2) Indoor temperature
3) Energy flow to the house *)
4) Energy flow from the solar storage tanks *)
5) Energy flow from the auxiliary storage tank *)

*) These energy flows are measured as outlined in Fig. 2.8.

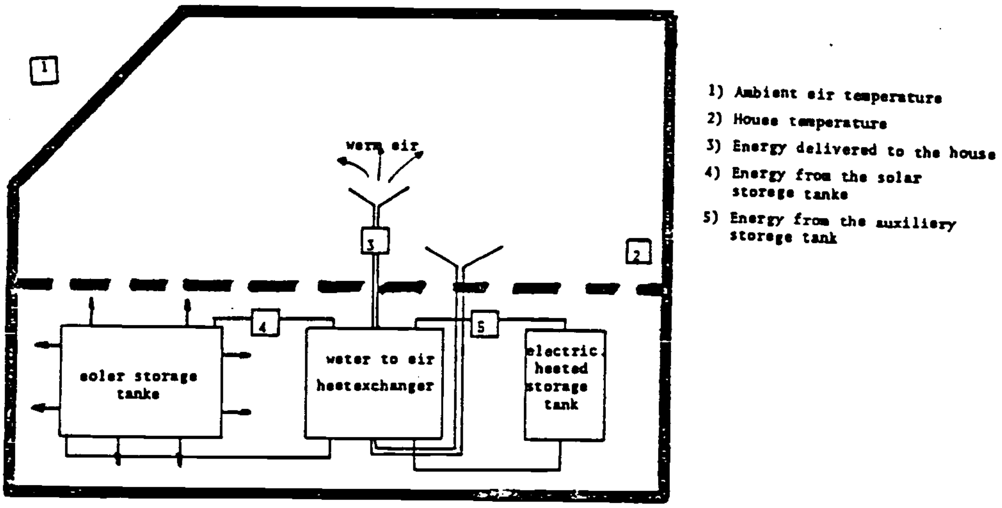

Fig. 4.1 Datapoints to evaluate the energy performance of the house

Some problems occured with the data from the measurement of the energy delivered to the house (#3 in Fig 4.1). This value was determined by digitally multiplying the temperature rise through the ductwork by the air flowrate (see Fig. 2.8). It was concluded that during the monitoring period the flowmeter malfunctioned because some of the energy values are illogical (e.g. zero over a long period of time when heating was required). In addition the flowmeter does not measure any energy delivered by natural convection, because it measures the flowrate only if the fan operates.

Most of the data show the sum of the energy from the solar storage tank (#4 in Fig. 4.1) plus the energy from the electrically heated storage tank (#5 in Fig 4.1) to be much higher than the energy delivered to the house (#3 in Fig. 4.1). See Appendix F for a discussion.

To avoid these irregularities the energy delivered to the house was taken as the sum of the energy from the solar storage tanks and the electrically heated storage tank. This was considered more accurate than the energy delivered to the house. The problems with the measurement of the energy delivered to the house is discussed in section 6.2.1 and Appendix F.

Because the electrically heated storage tank and therefore datapoint #5 in Fig. 4.1 was replaced in 1979 by a 10 kW electrical duct-heater data from 1977 and 1978 were prefered.

Neither of these years was completely monitored. In both years the month February has invalid results (some days were not monitored). However, 1978 was chosen as having the best data and missing data were taken from 1977 and 1980 (see Table 4.1) to make up an effective year of data.

For February 1980 the energy delivered from the auxiliary tank could not be used as a result of the replacement of the auxiliary tank with an electrical duct heater. Therefore datapoint #3 in Fig. 4.1 had to be used. The total energy to the house in February 1980 was calculated by taking the measured energy through the ductwork multiplying it with a correction factor (1.3). This correction factor is the average ratio from the energy from the tanks, as measured in #4 (Fig. 4.1) plus #5, divided by the energy to the house as measured in #3 on a monthly basis.

Six different energy terms were evaluated:

TOT	The total heatloss from the house to the surrounding
ACT.S	Energy delivered from the solar storage tanks via the heat exchanger
BAS.H	The energy gained by the heated basement
PAS.G	The energy gained by the passive system
INT.G	The energy gained by internal gains
REM	Energy delivered by the backup system (remaining heating requirements)

The evaluation of the energy terms is given on pages 35 through 37.

				Active solar G.				
Date	Heatloss	Passive G.	Internal G.	Via heatex.	Heated basem.	Backup	Ind. Temp.	Ambient Temp.
Jan/78	10.6	1.653	1.49	.23	2.51	4.7	62.0	38.4
Feb/80	9.84	2.311	1.34	2.51	2.33	1.35	63.2	39.0
Mar/78	8.30	3.055	1.49	1.84	1.97	—	64.8	46.3
Apr/77	7.49	1.979	1.44	2.30	1.77	—	70.0	52.8
May/77	7.85	2.767	1.49	1.75	1.84	—	68.7	51.2
Jun/78	4.85	2.112	1.44	.27	1.03	—	72.1	61.0
Jul/78	3.69	1.179	1.49	.21	.82	—	73.5	65.4
Aug/77	4.42	1.816	1.49	.15	.97	—	78.7	69.0
Sep/78	3.99	1.475	1.44	.20	.88	—	70.0	60.9
Oct/78	8.28	4.340	1.49	.55	1.90	—	68.5	50.3
Nov/78	11.76	2.507	1.44	3.46	2.79	1.56	65.0	37.9
Dec/78	13.14	2.188	1.49	2.03	3.11	4.32	64.5	35.3
eff. year	94.21	27.382	17.53	15.50	21.92	11.93		

Energy in 10^6 Btu
Temperature in F

Table 4.1 Energy balance of the Boleyn home

Total heat loss from the house to the surroundings

The total heat loss for a month is calculated by using EQ 4.1.

$$TOT = UA*(TH-TA)*N_h$$

EQ. 4.1

TOT: Total heat loss from the house to the surroundings

UA: Overall UA-factor from the house to its surrounding if it has an unheated basement. The numerical value is 605 Btu/hrF (320 W/^{o}C). This is the sum of the UA-factor for the house with a heated basement (462 Btu/hrF) as determined in section 3 plus the calculated losses through the floor to an unheated basement (7875 Btu/hr)/55 F = 143 Btu/hrF. This value is used to be able to isolate all energy contributions to the home.

TH: Indoor temperature

TA: Ambient air temperature

N_h: Number of hours in a month

Energy gained from the active solar system

The energy gain to the house from the active solar system contains two components: the energy flow from the solar tanks to the house (point 4 in Fig. 4.1) multiplied by the appropriate time interval and the energy gained by the heated basement from the solar storage tanks. During the data taking time the basement of the Boleyn home was always at about the same temperature as the main floor (3 F). This makes the basement a more comfortable space and reduces the transmission losses through the floor area of the house. The energy gain from the tank heated basement by the solar storage tanks can be approximated by

$$BAS.H = (H_{bd}/T_d)*(TH-TA)*N_h \qquad \text{EQ. 4.2}$$

BAS.H: Heat gained from the basement

H_{bd}: Design heat loss through the basement, 7875 Btu/hr (2300 W)

T_d: Design temperature difference, 55 F (30.5 ^oC)

TH: Indoor temperature

TA: Ambient air temperature

N_h: Number of hours in a month

Energy gained by internal gains

This item is an estimation rather than an exact calculated value because it depends on too many uncertainties such as lifestyle, habits, etc. As was indicated in section 3.3 the total internal gains (people plus equipment) is assumed to be 2000 Btu/hr (586 W). This value is an averaged value and assumed constant throughout the entire time period.

Passive gains

From the measured energy flow from the auxiliary storage tank to the house (#5 in Fig. 4.1) the energy from the backup system is known. With the already determined energy sources from the active system, the internal gains and the heated basement the passive solar gains can be evaluated by means of EQ. 4.3:

$$PAS.G = TOT - INT.G - ACT.S - BAS.H - HAUX \qquad \text{EQ. 4.3}$$

PAS.G:	Passive solar gains
TOT:	Total heat loss from the house to the surrounding
INT.G:	Internal gains
ACT.S:	Heat delivered from the solar storage tanks via the heat exchanger
BAS.H:	Heat gained by the heated basement
HAUX:	Energyflow to the house from the auxiliary tank (#5 from Fig 4.1)

It must be mentioned that the evaluation of the passive solar gains carry a large uncertainty (20-30%) largely because of the uncertainty associated with the estimation of internal gains.

4.3 Total heat loss from the house to the surroundings

Fig 4.2 shows the total heat loss from the house to the surroundings as a function of the month of the year. It also shows the heat loss divided into the five sub-parts as discussed in 4.2. The sub-parts are discussed in detail in sections 4.4 to 4.6.

As seen from Fig. 4.2 heat is lost from the building even in summer months. This is due to an building heated by internal gains and passive solar gains.

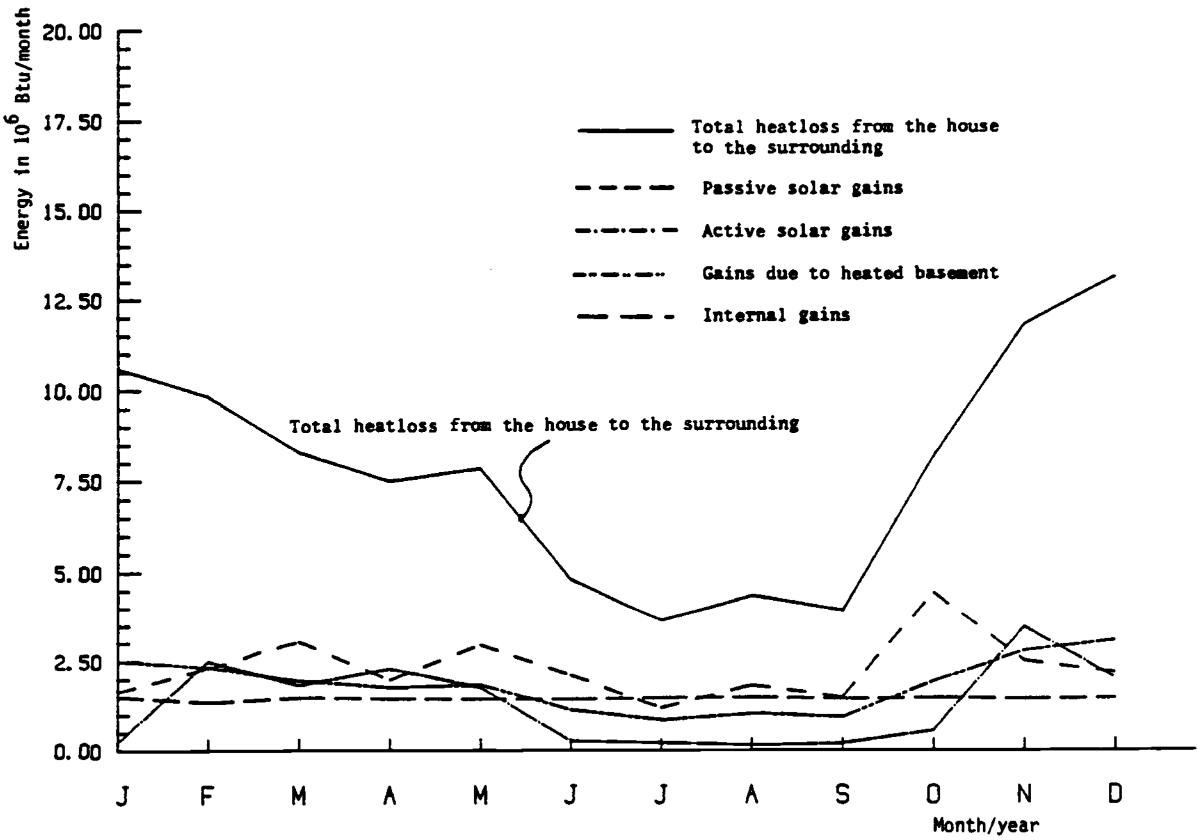

Fig 4.2 Total heat loss from the house to the suroundings

Fig. 4.3 shows the predicted heat loss versus the actual heat loss from the house to the surroundings.

The dashed line in Fig. 4.3 is calculated by using the design indoor temperature instead of the actual indoor temperature.

$$H_d = UA*(TD-TA)*N_h$$

H_d: Design heating load

UA: Overall UA-factor for the house 605 Btu/hrF (303 W/C°) as used in EQ. 4.1

TD: Design indoor temperature 70 F (21 °C)

TA: Ambient air temperature

N_h: Number of hours in a month

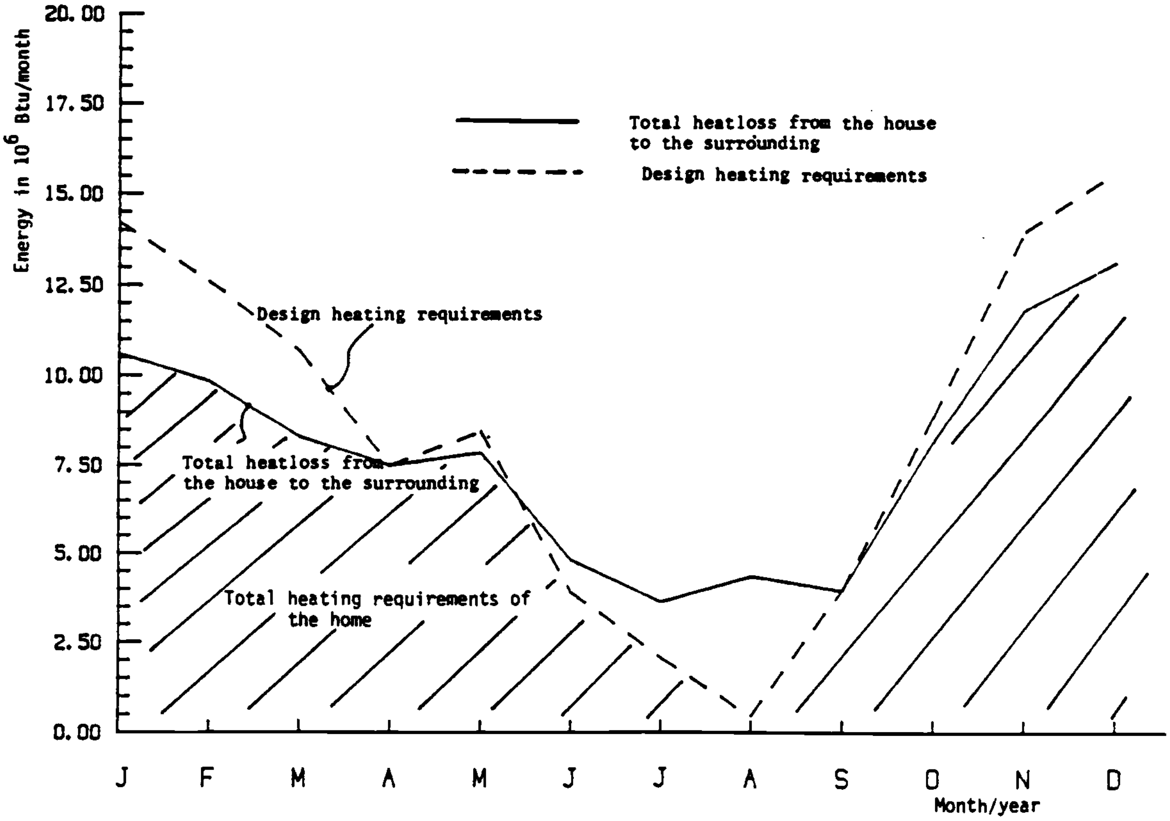

Fig. 4.3 Design heat loss of the house

The differences between the actual heat loss and the design heat loss in January, February, March, November and December reflect a responsible use of energy by the Boleyns resulting from a reduced thermostat during nighthours (Fig. 4.4). Because of this the Boleyns saved during the main heating period (from November to March) $10.4*10^6$ Btu ($10.9*10^6$ kJ) that amounts for 19% of the total heat load during this time.

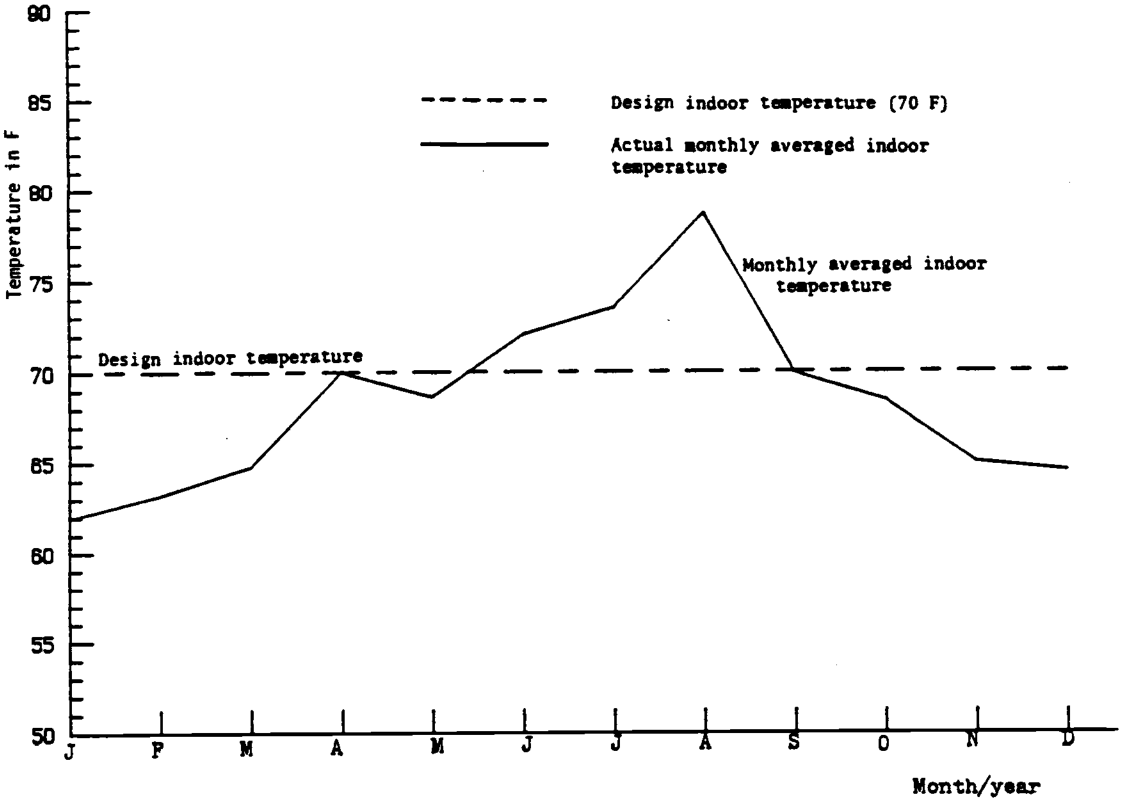

Fig. 4.4 Actual monthly averaged indoor temperature versus design temperature

Fig 4.4 shows that during the summer months the indoor temperature rises above the design indoor temperature. This reflects the disadvantage of the solar storage tanks in the basement, since the heatflux during the summer months can not be turned off.

Fig 4.4 shows also the reduced indoor temperature during the heating period. This is an effect of thermostat setbacks in the heating months.

4.4 Total heating requirements

In future discussions the term "total heating requirement of the house is used". The definition of this term is given here. The heating requirement of the Boleyn home is the total heat loss (solid line in Fig. 4.3) as long as the total heat loss is smaller than the design heat loss. However, if the total heat loss is greater than the design heat loss, the building is unnecessarily heated and the design heat loss represents the heating requirement of the house.

The annual total heating requirement of the Boleyn home (shaded part in Fig. 4.3) is $87.85*10^6$ Btu. The fraction of the four energy sources on a monthly basis to the Boleyn home were calculated by applying the following method. The annual fraction of each source is the sum of the monthly fractions.

Backup: The backup fraction is the ratio of the energy supplied by the backup system (see Table 4.1) to the total heating requirement of the home. Based on this assumption the annual energy delivered from the backup system is $11.93*10^6$ Btu. The backup fraction is 13.6%.

Internal gains: The internal gain fraction is the fraction of the useful internal gains to the total heating requirement of the home. Internal gains (as listed in Table 4.1) are considered to be not useful when the heating requirements of the home can be met by the heat delivered from the backup system plus the heat delivered from the solar storage tanks via the heatexchanger. Based on this assumption the annual useful internal gains are $16.39*10^6$ Btu. The internal gain fraction is 18.6%.

Passive gain: The passive gain fraction is the ratio of the useful passive solar gains to the heating requirements of the home. The passive solar gains are considered to be not useful when the heating requirements of the home can be met by the sum of: energy supplied by the backup system, energy supplied from the solar storage tanks via the heat exchanger and energy supplied by internal gains. Based on this assumption the annual useful passive solar gains are $24.85*10^6$ Btu. The passive gain fraction is 28.2%.
Active solar: The active solar fraction is the sum of the fraction of two components: energy delivered from the solar storage tanks via the heatexchanger and energy gain from the basement heated from the losses of the solar storage tanks. The fraction of the energy delivered from the solar storage tanks via the heatexchanger is the ratio of this energy term to the total heating requirements of the home. The annual energy delivered from the solar storage tanks via the heatexchanger is $15.5*10^6$ Btu. The fraction is 17.6%.

The fraction from the energy gain from the basement, heated from the losses of the solar storage tanks, is the ratio of the useful gain from this item to the total heating requirement of the home. The gain from the basement is considered to be not useful when the heating requirements of the home can be met by the sum of: energy suppplied by the backup system, energy supplied from the solar storage tanks via the heat exchanger, energy supplied by the passive solar gains, and energy supplied by the internal gains. Based on this assumption the annual useful gain from the basement heated by the losses from the solar storage tanks is $19.31*10^6$ Btu. The fraction is 22%.

Fig 4.5 shows the total heating requirements of the Boleyn home and the portion provided by the backup system.

The backup system is required from November to February, only. The backup supplies 13.6 % of the total heating requirements of the house.

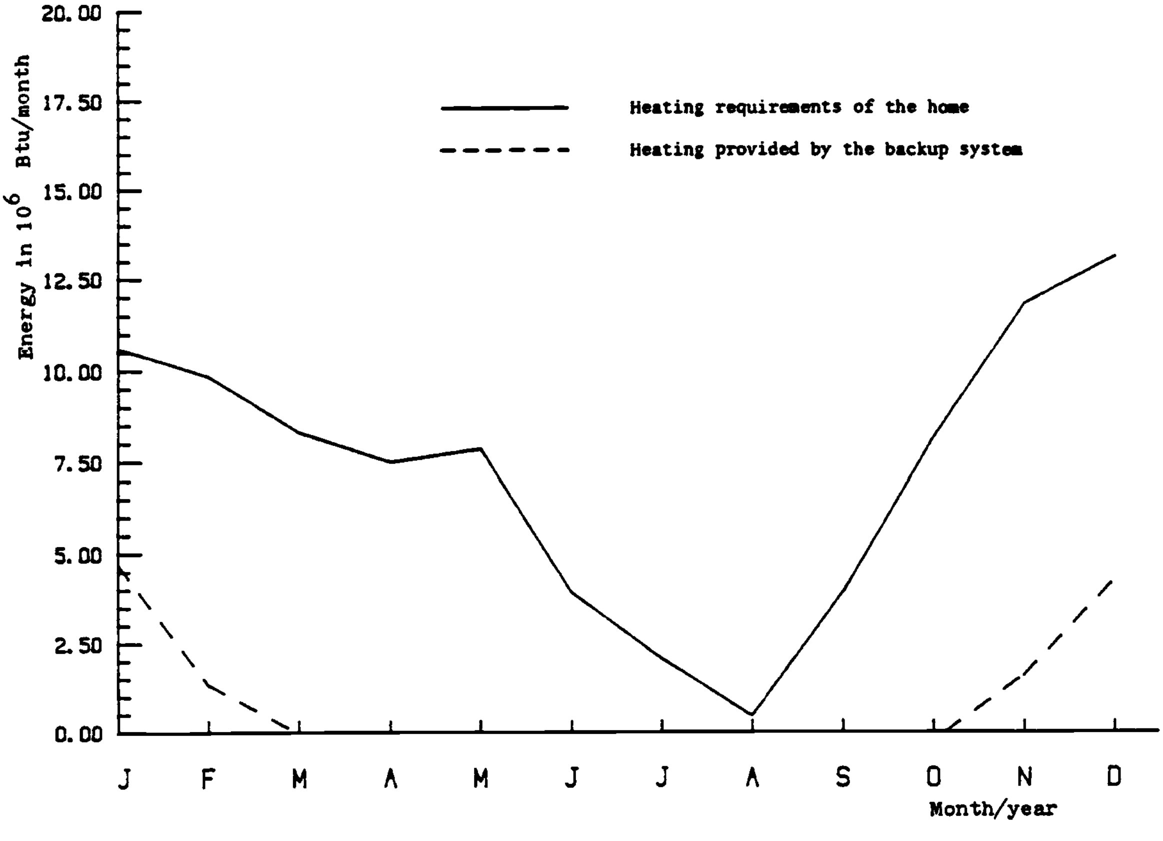

Fig. 4.5 Total heating requirements

4.5 Energy gain by the active solar system

Fig. 4.6 shows the participation of the active solar system on the total heating requirements of the house. In this plot the dashed line represents the energy delivered from the solar storage tanks via the heat exchanger plus the indirect gain due to the heated basement. The dash-dot line represents the heat delivered from the solar storage tanks, only (#4 in Fig. 4.1).

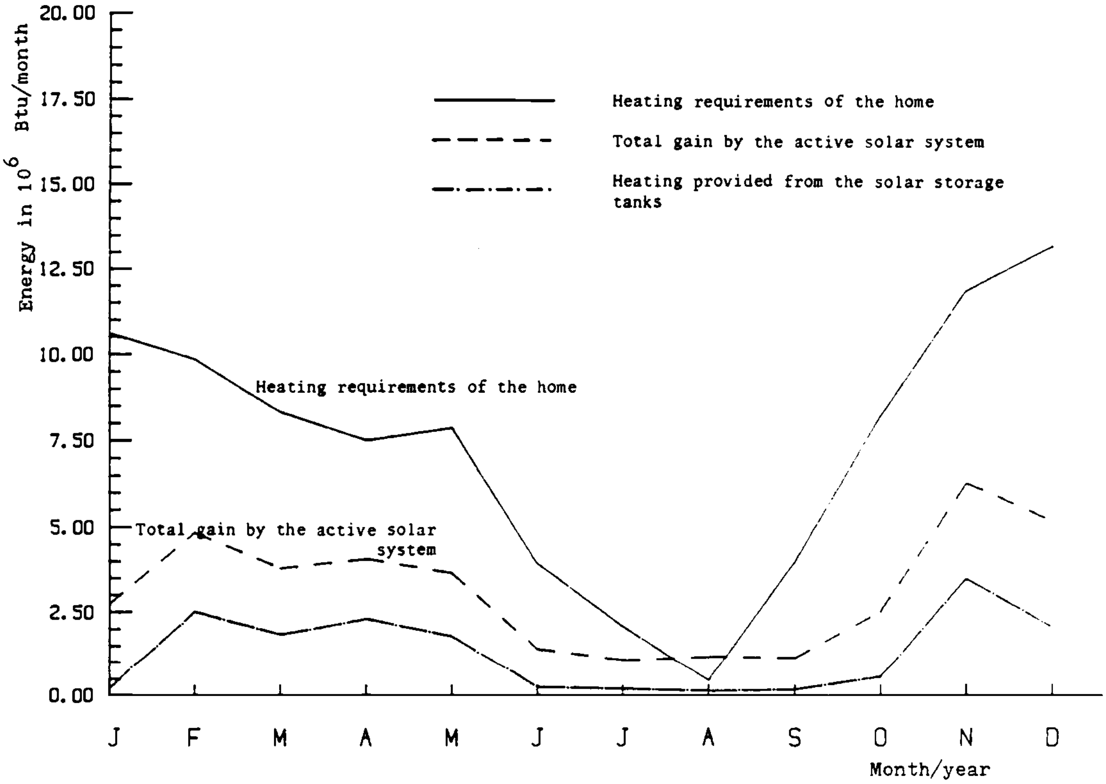

Fig. 4.6 Participation of the active solar system on the total heating requirements of the house.

The energy delivered from the solar storage tanks via the heat exchanger to the house meets 17.6% of the total heating requirements of the house. The reduced transmission losses through the floor to the storage tank heated basement supplies 22% of the total heating requirement of the house.

The annual heating requirements of the home without passive solar gains and internal gains are $46.7*10^6$ Btu. From these $34.8*10^6$ Btu (74.5%) is supplied from the active solar system.

The computer program F-chart was run for the Boleyn home using the specifications of the Boleyn solar system (Appendix D). F-chart is an interactive computer program available from the Solar Energy Laboratory, University of Wisconsin - Madison, which calculates solar heating system performance. For further information see Beckmann (L 4.1). According to F-chart the active solar system meets 66.3% of the heating requirements and the backup system 33.7%.

F-chart gives a good indication about the magnitude of the contribution of the active solar system. Specific variations, such as storage tanks located in the basement rather than outside are not considered.

The active solar system is particularly valuable from November to February when the heating requirements are high.

In December and January the decrease in the rate of the energy delivered from the solar storage tanks via the heat exchanger is due to low solar storage tank temperatures.

Some heat is delivered from the solar storage tanks to the house during the warmest months of the year. Although small in magnitude this heat is valuable since a conventional heating system operates inefficiently when only a small portion of energy is required.

4.6 Internal and passive solar gains

Fig 4.7 shows internal and passive solar gains as listed in Table 4.1 and the total heating requirements of the home.

The useful internal gains and the useful passive solar gains account for 46.8% of the total heating requirements of the house (Fig. 4.7).

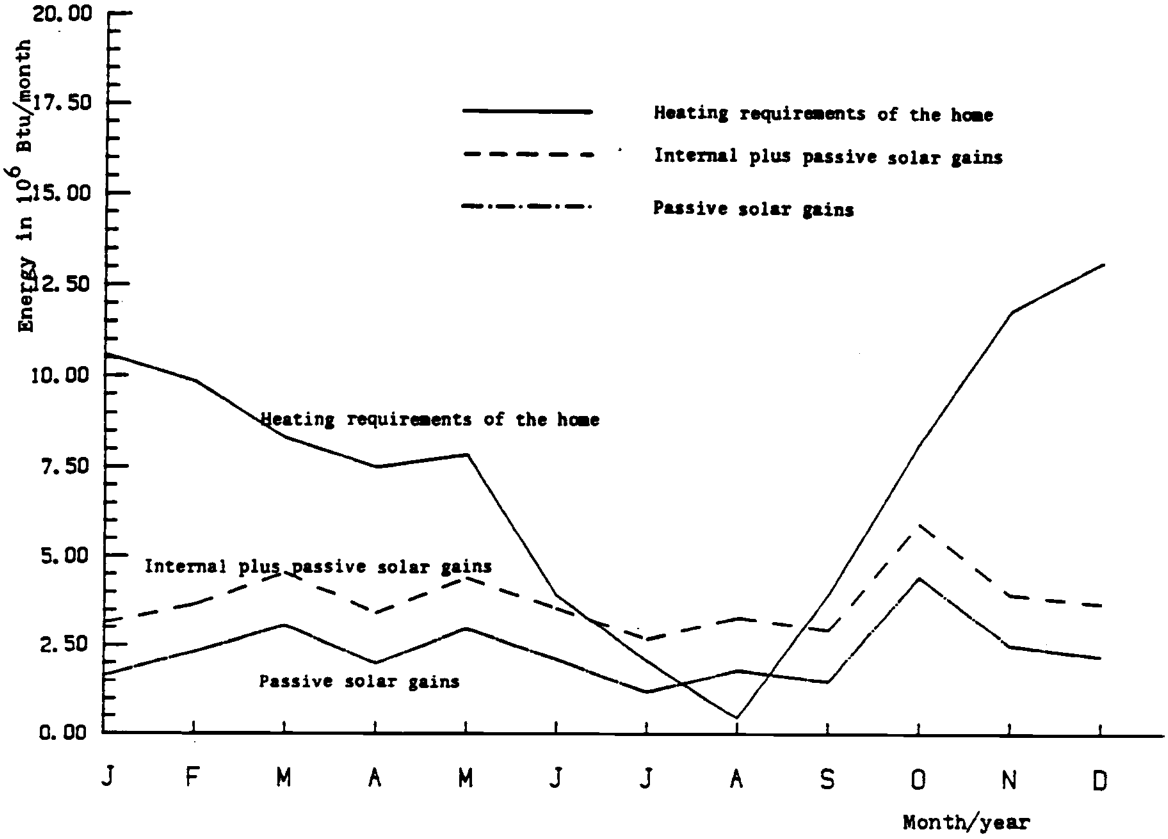

Fig. 4.7 Passive gains and internal gains

4.7 Passive solar gains

4.7.1 Calpas3 Predictions

Calpas3 is a computer program developed by the Berkeley Solar Group (BSG) (L 4.5). The heating load calculation are based on methods recommended by the California Energy Commission (CEC).

Input parameters for Calpas3 are the U-values for the wall, roof, window and door areas. Also specified are the infiltration rate and internal gains. There is an option to run Calpas3 on two zone structures: one zone of which can be a sunspace.

Output data provide the user with an overall house energy balance. The heat losses are subdivided into conduction and infiltration losses. Heat gains are subdivided into internal and passive solar gains. Three runs on the Boleyn home with different input parameters are given in Appendix C.

A summary of the passive solar gains as predicted by Calpas3 is given in Table 4.2. The largest solar gains are during the summer months when they are not needed (solid line in Fig. 4.8).

```
      Conduction   Infiltration                                          
MON   losses       losses          Solar   Internal    Cooling     Heating
---                                gains   gains       required'   required
JAN    -6716.0      -2330.5       945.78   1487.6            0     6613.1
FEB    -5250.0      -1904.7       1579.8   1343.6            0     4311.9
MAR    -5168.1      -2000.4       2538.3   1487.6            0     3606.5
APR    -4016.8      -1719.2       3094.0   1439.6      -111.15     2295.4
MAY    -2609.4      -1349.7       3531.9   1487.6      -745.99     1137.8
JUN    -1023.6      -859.68       3619.5   1439.6      -1325.9     293.54
JUL     332.45      -476.10       4044.1   1487.6      -3041.3     165.07
AUG    -439.99      -621.03       3566.0   1487.6      -1970.0     282.82
SEP    -1359.7      -820.99       3239.8   1439.6      -1308.0     414.77
OCT    -3447.1      -1381.4       2300.9   1487.6      -193.85     1845.3
NOV    -4798.3      -1718.2       1310.9   1439.6            0     3890.8
DEC    -6462.3      -2234.8       918.22   1487.6            0     6291.3

TOT     -40939       -17417        30689    17515      -8696.2      31148
```

Table 4.2 Output of the computer program Calpas3 (run with .75 air change/hour infiltration rate and the U-values as given in chapter 4). Energy values in kBtu

More of interest are the useful passive solar gains. They can be calculated from the output data from the Calpas3 run (Table 4.2). The evaluation is based on EQ. 4.4

$$G_{ap} = H_t + H_i - G_i - H_o$$
EQ. 4.4

Ga_p: Useful passive solar gains predicted by Calpas3
H_t: Transmission losses as listed in the Calpas3 output
H_i: Infiltration losses as listed in the Calpas3 output
H_o: Overall heating requirements, also listed in the Calpas 3 printout
G_i: Internal gains as listed in the Calpas3 output

The dashed line in Fig. 4.8 gives the useful passive solar gains for the Boleyn home. Calpas3 indicates that passive solar gains for the Boleyn home are most benificial from February to May and in October and November.

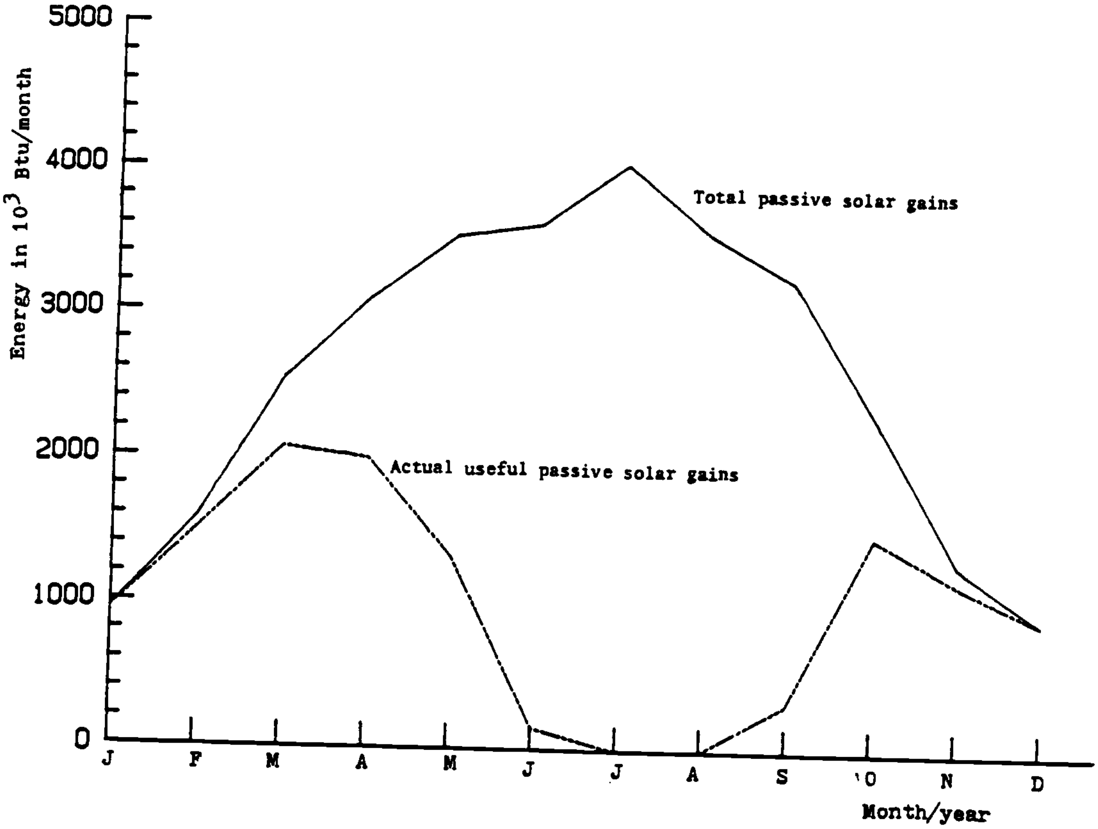

Fig. 4.8 Passive solar gains for the Boleyn home as predicted by the computer program Calpas3

The passive solar gains (solid line in Fig. 4.8) in the summer cause the computer program to predict a large cooling load during those months (fifth row in Table 4.2).

4.7.2 Measured passive solar gains

The useful passive solar gains at the Boleyn home are evaluated as outlined on page 43. The passive solar gains are considered to be not useful when the heating requirements of the home can be met by the sum of: energy supplied by the backup system, energy suplied from the solar storage tanks via the heat exchanger and energy suplied by internal gains.

Since the evaluated year at the Boleyn home had 5360 degree-days-F and Calpas3 uses a standarized weather file with 4546 degree-days-F based on data from the Portland Airport the total amount of the passive solar gains is not comparable.

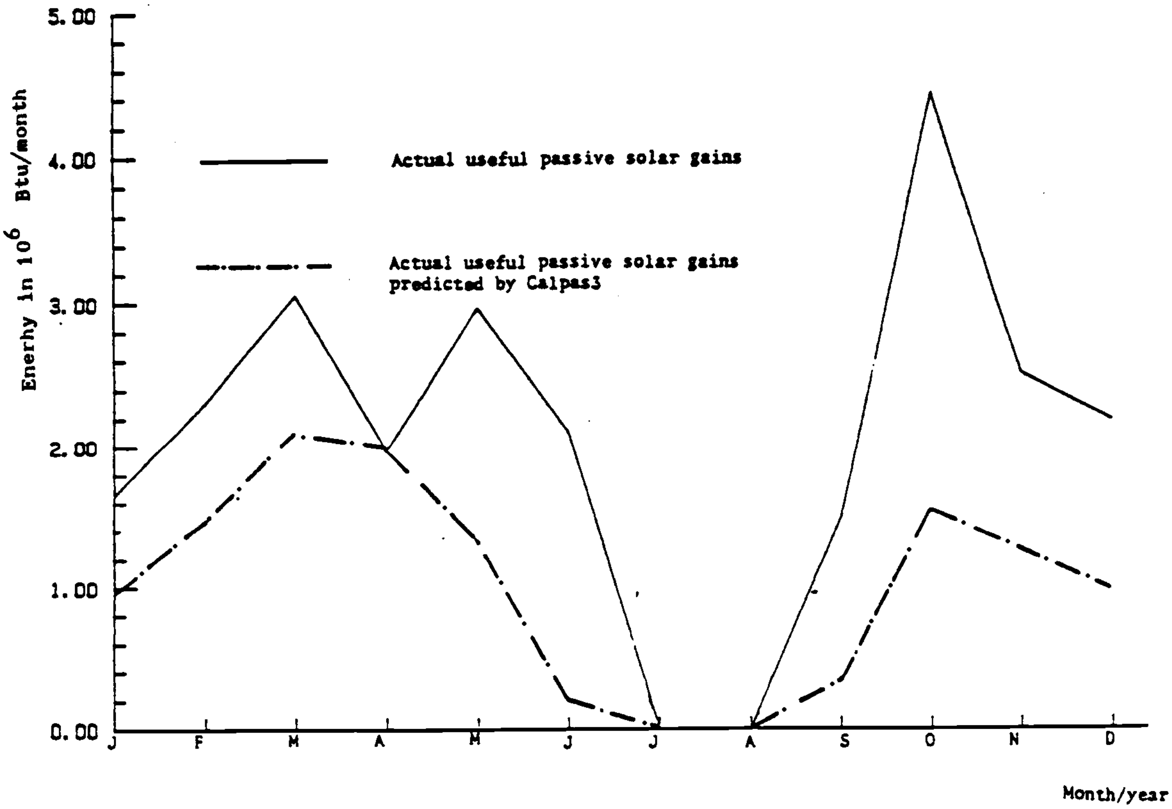

Fig. 4.9 Actual passive solar gains evaluated at the Boleyn solar home

4.7.3 Comparisons

The computer program Calpas3 predicts the largest useful passive solar gains from February to May and in October and November (see dashed line in Fig. 4.8). The same is true for the useful passive solar gains as evaluated at the Boleyn home (see Fig. 4.9). The trends are predicted very much the same.

Calpas3 predicts very high passive solar gains during the summer months (see solid line in Fig 4.8).

Due to the high predicted passive gain in the summer Calpas3 predicts a cooling load during the summer months of $8.7*10^6$ Btu ($9.2*10^6$ kJ). This cooling load does not exist at the Boleyn home. The Boleyns simply open the windows and live with the result. Because the climate is sufficiently mild this is not a major problem. They also accept higher indoor temperatures than predicted by Calpas3.

These results show that the passive solar gain predicted by Calpas3 may be misleading in mild climates where window opening may provide sufficient cooling.

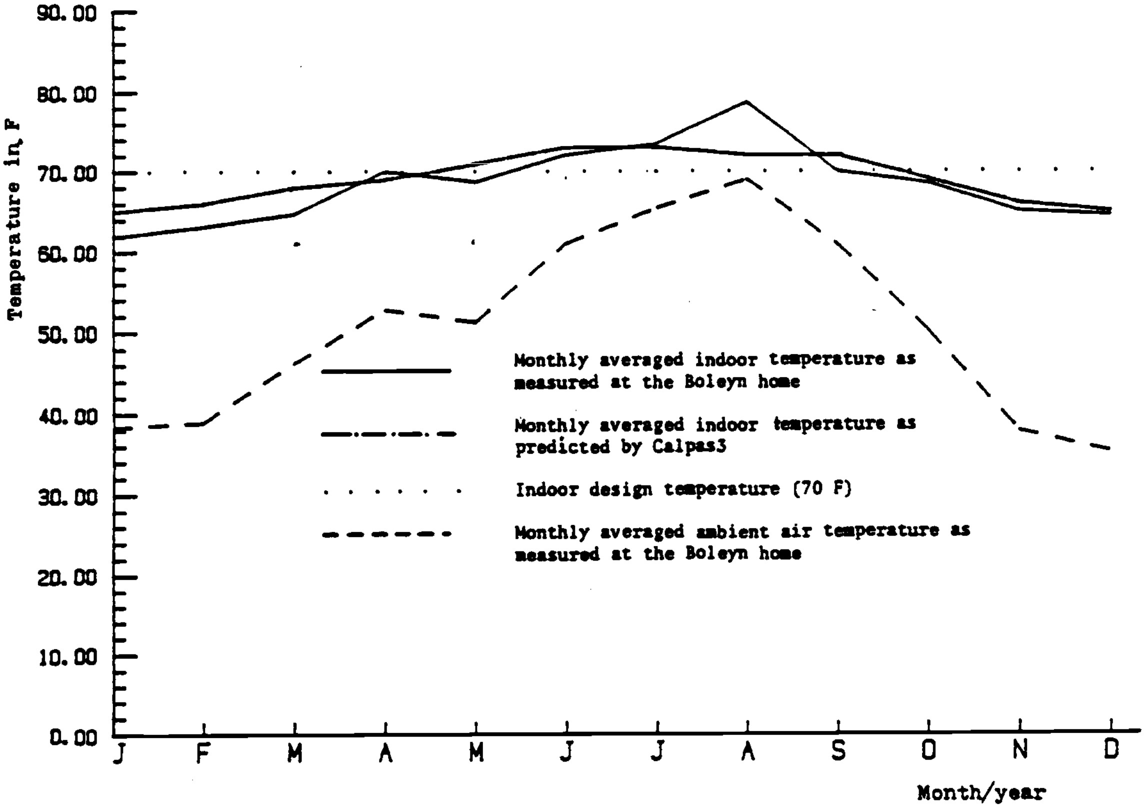

Fig.4.10 Indoor temperature as measured at the Boleyn home compared to various models

Fig 4.10 shows that the indoor design temperature calculated by Calpas3 approximates the measured internal temperatures at the Boleyn home well in all parts of the year except the warm months in summer. The temperature predicted by Calpas3 comes closer to the true temperature than the steady design temperature used in standard engineering design. Similar annual temperature distributions were found by other authors (see section 4.8).

4.8 Comparison with other houses

Performances of other houses can be found for example in Conference Papers of the 8th National Passive Solar Conference (L 4.2).

Mc. Kinstry (L 4.3) monitored 6 houses in Oregon from October 1982 to March 1983. He found that the indoor temperature varies from 60 F to 73 F (15.5 °C to 23 °C) during the heating season. The results from the Boleyn home also show that indoor temperatures below 70 F are acceptable.

J. N. Swisher (L 4.4) reports the result of 40 passive solar buildings in the USA monitored in the heating and cooling season 1982/83. He gives an average need of auxiliary heating for passive solar houses of 1.9 $Btu/F\text{-}day\text{-}ft^2$ (60 $kJ/{}^{o}C\text{-}day\text{-}m^2$). The auxiliary heating requirements for the Boleyn home can be calculated by using equation 4.6.

$$BPI = THL*(1-\eta)/(DD*A)$$
EQ 4.6

BPI: Building performance index in Btu/F-day-ft^2 (kJ/^{O}C-day-m^2)

THL: Total heating requirements for the Boleyn home in the monitored year (area under the solid line in Fig. 4.7: 87.85*10^6 Btu

η : Percentage of useful passive gains and internal gains: .468

DD: Degree days in the monitored year 5360 F-day

A: Equivalent floor area by assuming 8 ft (2.4 m) ceiling: 2020 ft^2 (188 m^2)

The BPI for the Boleyn home is according to EQ. 4.6 4.3 Btu/F-day-ft^2 (76 kJ/^{O}C-day-m^2). Conventional buildings typically need 6-12 Btu/F-day-ft^2 (120-240 kJ/^{O}C-day-m^2) (L 3.5). This shows that the Boleyn home performs somewhere between a passive solar building and a conventional house.

In fact the BPI is 28% lower than in the best conventional buildings. The design of a house with low infiltration values and large window areas to the south reduces the heating requirements significantly.

Swisher gives the average indoor temperature for the monitored buildings as 67.5 F (19.7 ^{O}C). The Boleyn home (Table 4.1) operates at an average indoor temperature of 66 F (19.2 ^{O}C).

The passive heating fraction for the monitored 40 buildings is averaged to 39.3%. The Boleyn home has 28.2%.

4.9 Summary

The Boleyn home is heated from four sources.

1) Energy from the active solar system
2) Energy from the passive solar gains
3) Internal gains
4) Backup heating

The total heating requirement during the monitored period was $87.85*10^6$ Btu by 5360 F-day. Fig. 4.11 shows the percentage of the four sources during the evaluated year.

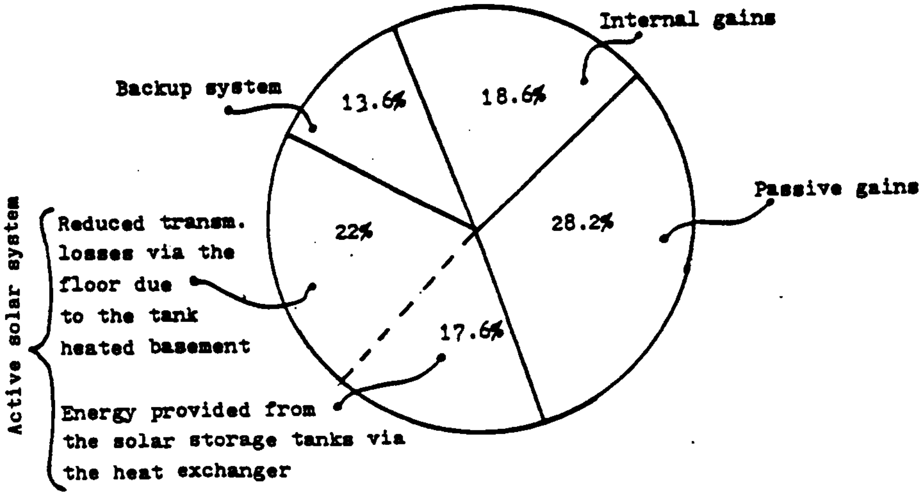

Fig. 4.11 Energy sources of the Boleyn home

The heating requirements without passive solar gains and internal gains are $46.7*10^6*10^6$ Btu/yr. From these $34.8*10^6$ Btu/yr (74.5%) are met by the active solar system. The computer program F-chart (Appendix D) predicts 66.3%. The difference between the actual gain from the active solar system and the predictions by F-chart can be explained F-chart does not account for the reduced transmission losses through the basement. The active solar system was designed to meet 50% (L 4.1) of the heating requirements of the home (without passive gains and internal gains). The active solar system performed better than expected.

The computer program Calpas3 predicted the variation of the passive solar gains during the winter months fairly well. The predicted large passive solar gains during the summer, causing a large cooling load, did not occur at the Boleyn home. The Boleyns handle the cooling load by opening windows.

References

L 4.1 Boleyn Douglas R.; Operating results from solar homes in the Pacific Northwest (1977), unpublished paper at PGE.

L 4.2 American Solar Energy Society, Inc; 8th National Passive Solar Conference (1983), Copyright 1983 by the American Solar Energy Society.

L 4.3 Kinstrey Mc. Mark; Heating season results from the Boneville Power Administration Class B Passive solar monitoring program (1983), puplished in 8th National Passive Solar Conference, Copyright 1983 by the American Solar Energy Society.

L 4.4 Swisher Joel N.; Measured Performance of 50 passive solar residences in the United States (1983), puplished in 8th National Passive Solar Conference, Copyright 1983 by the American Solar Energy Society.

L 4.5 Berkeley Solar Group; Calpas3 User manual (1982), Copyright Berkeley Solar Group 3140 Grove Street Berkeley, CA 94703

L 4.6 Beckman, Klein, Duffie; Solar Heating Design by the F-chart method (1977), John Wiley & Sons Inc.

5 PERFORMANCE OF THE COMPONENTS OF THE ACTIVE SOLAR SYSTEM

In this chapter all the major parts of the active solar system of the Boleyn home are discussed. The design prediction will be compared with the monitored performance. The predictions of the computer program F-chart are taken into consideration.

The performance of the solar collector over time is presented and the experimentally determined collector data are compared with the manufacturer's data. The predicted storage tank heat loss by PGE is compared with the storage tank heat loss during operation. The changes of the system are discussed and the improvements are evaluated.

The active solar system of the Boleyn home with its major parts is shown in Fig. 5.1.

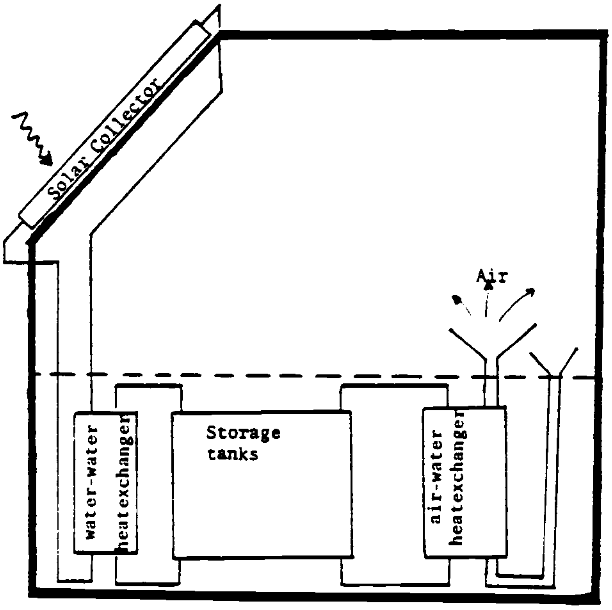

Fig. 5.1 Active solar system

5.1 The collector

The flat-plate collectors on the Boleyn home are Revere (L 5.1) double glazed collectors with a 30% glycol-water solution as collecting heat transfer media.

The efficiency of a collector is the fraction of the energy incident on the collector surface that is transfered to the transfer media. The efficiency depends on optical properties of the cover and on the heat transfer properties of the collector.

It is convenient to express the efficiency of a collector as a function of the incoming radiation, the temperature of the heat transfer media at the collector inlet, and the ambient air temperature. All parameters are then measurable. The collected energy can be found by using EQ. 5.1; the derivation of which can be found in Duffie & Beckman (L 5.2).

$$Q_u = A_c * F_r * [\ G_T * (\tau\alpha) - U_L * (T_{ci} - T_a)\ ]$$

EQ. 5.1

Q_u: Actual useful energy gain

Ac: Collector area

F_r: Heat removal factor accounts for the increasing collector fluid temperature along the collector and for the difference between the collector temperature and the collector fluid inlet temperature.

G_T: Total radiation perpendicular on the collector plate

$\tau\alpha$: Product of transmittance of the cover and absorptance of the absorber plate

U_L: Collector overall heat loss coefficient (accounts for conduction, convection and radiation losses of the top, bottom and the edges)

T_c: Collector fluid inlet temperature

T_a: Ambient air temperature

The collector efficiency can be calculated by dividing EQ. 5.1 by the total incoming radiation

$$= Q_u/(A_c * G_T) = F_r * (\tau\alpha) - [F_r * U_L] * [(T_i - T_o)/G_T]$$
$$x = B - A * y$$

EQ. 5.2

It is common to plot the efficiency versus $(T_i-T_o)/G_T$. The appropriate figure approaches a straight line with the y-intersection a function of the optical properties of a solar collector $F_r*(\tau\alpha)$.

F_r*U_L is the slope and represents the losses due to conduction, convection and radiation.

The next four plots (Fig. 5.2 to Fig. 5.5) give the performance of the Boleyn solar collectors as shown in EQ. 5.2.

The collector was evaluated based on data from 1978, 1980 and 1981. In each of these years about forty points selected randomly around the year were plotted. To get reliable data the following procedure was used:

1) Only hours with continuous collection were selected, to avoid irregularities in the collector flow rate.
2) Hourly integrated data were taken.
3) The collected data were taken near solar noon to avoid discontinuities resulting from thermal heat capacities.
4) Data were taken from each month in a year whenever possible.

Although the data were selected in the same way for each year, there are data with different characteristics: taken during different seasons of the year, during different length collection periods, and during different times of the day.

These were plotted separately to investigate whether there are some parameters not given in EQ. 5.2 that influence collector efficiency.

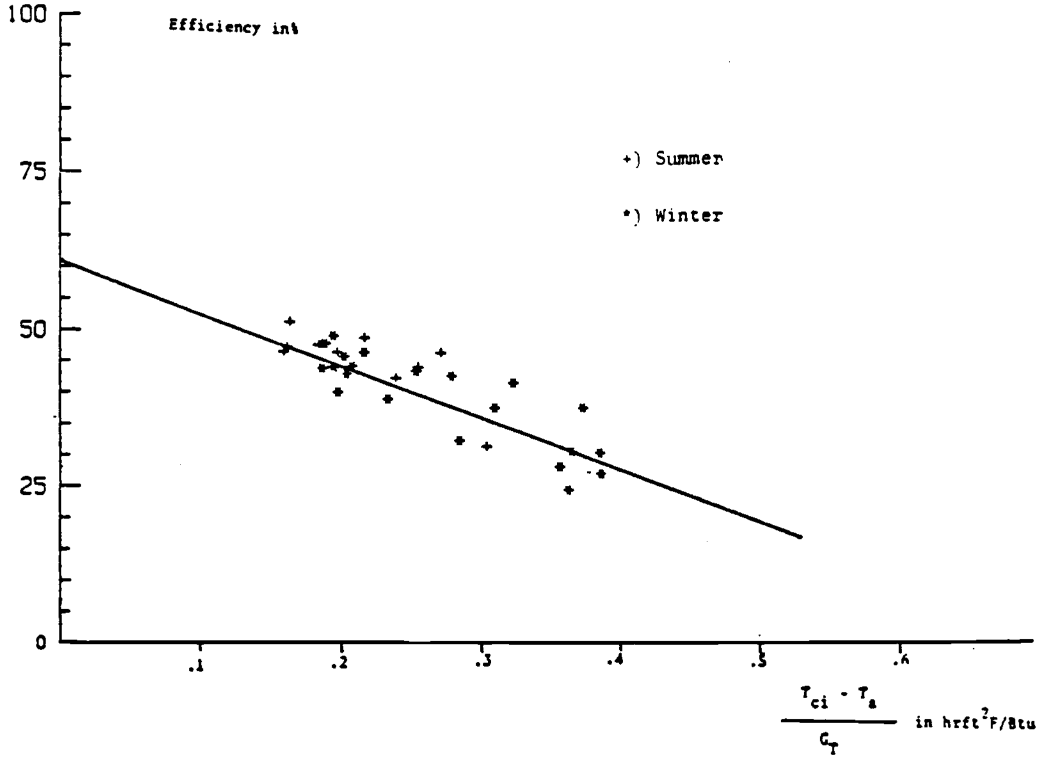

Fig. 5.2 Collector efficiency 1978

As seen from Fig. 5.2 there is no significant distinction between summer and winter collector efficiency.

The best fitting straight line determined with linear regression has a y-intersection and a slope of:

$F_r*(\tau\alpha) = 61.08\%$

$F_r*U_L = .768$ Btu/hrft^{2}F (4.36 W/^{o}Cm^2)

The collector efficiency in 1978 given in English units can be represented by EQ. 5.4

$$= 61.08 - 76.8*[\ (Ti-T_a)/G_T\ ] \text{ in } \%$$

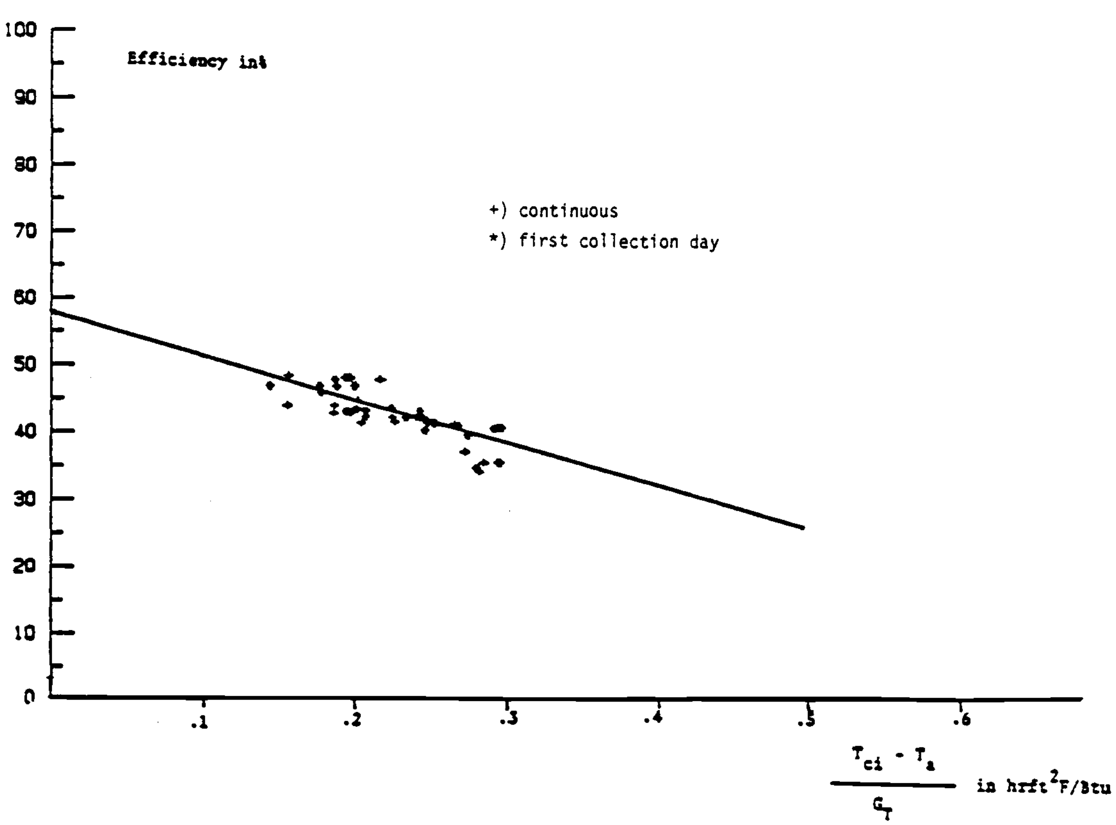

Fig. 5.3 Collector efficiency 1980

As seen from Fig. 5.3 there is no significant distinction between the first collection after a standby period and continuous operation. The internal heat capacities (pipe, heatexchanger) seem to be negligible.

The best fitting straight line determined with linear regression has a y-intersection and a slope of:

$F_r*(\tau\alpha) = 58.33\%$

$F_r*U_L = .636$ Btu/hrft^{2}F (3.62 W/^{o}Cm^2)

The collector efficiency in 1980 given in English units can be represented by EQ. 5.5

$$= 58.33 - 63.6*[\ (Ti-T_a)/G_T\ ] \text{ in } \%$$

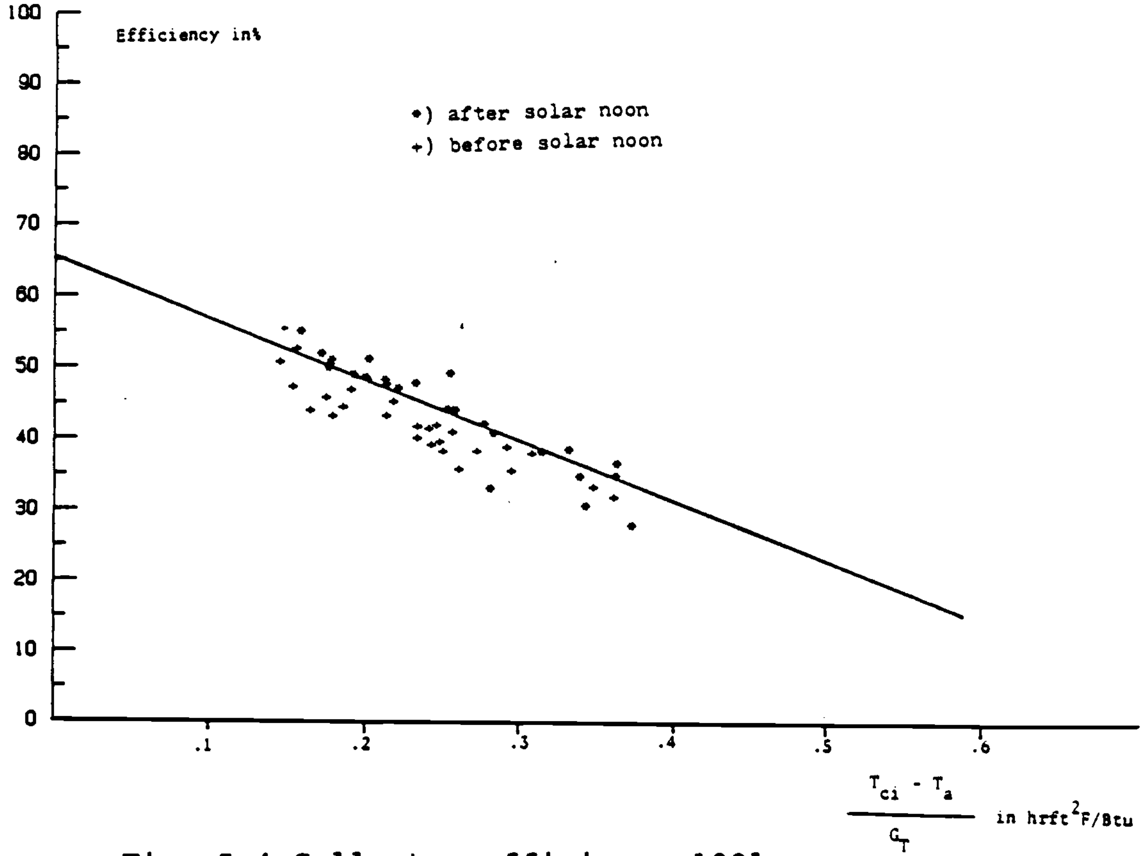

Fig. 5.4 Collector efficiency 1981

Fig. 5.4 does show a significant difference between the collector efficiencies collected shortly before solar noon and those collected shortly after solar noon. The efficiences after solar noon turn out to be about 3% higher than those before solar noon.

A reason could be that the temperature around the collector is higher than the measured ambient air temperature after hours of insolation. This is particularly likely at the Boleyn home because the ambient air temperature sensor is about 15 ft away from the nearest collecting surface and shaded partly by trees.

It would be of interest to study the temperature difference between the ambient air and the air temperature just above the collector as a function of the incoming radiation.

In 1981 the best fitting straight line determined with linear regression has a y-intersection and a slope of:

$F_r*(\tau\alpha) = 65.05\%$

$F_r*U_L = .841$ Btu/hrft^{2}F (4.53 W/^{o}Cm^2)

The collector efficiency in 1981 in English units can be represented by EQ. 5.5

$$= 65.05 - 84.1*[\ (Ti-T_a)/G_T\ ] \text{ in } \%$$

Summary of the Collector efficiency from 1978, 1980 and 1981

	Sample Criteria	$F_r*(\tau\alpha)$	F_r*Ul in Btu/hrft^{2}F
1978	Summer-winter	61.08	.768
1980	Periodic-contin.	58.33	.636
1981	before-after solar noon	65.05	.841

Table 5.1 Collector efficiency

Although the term and the F_r*U_L term differ up to about 20% the collector efficiency does not seem to be time dependent. Fluctuations within 20% are in good agreement given the variability of conditions at the site.

It should be noted here that the collectors were cleaned only once since they were installed in 1977. The rain in Oregon seems to maintain a highly transmittive cover.

Averaging the results from 1978, 1980 and 1981 the collector efficiency in this period of time in English units can be described by:

$$\eta = 61.44 - 74.8*[\ (Ti-T_a)/G_T\ ] \text{ in } \%$$

Comparison with the manufacturer's data

The manufacturer's data were taken from a brochure (L 5.2). The best fitting curve in English units determined by linear regression through the given data is:

$$\eta = 62.88 - 77.2*[\ (Ti-T_a)/G_T\ ] \text{ in } \%$$

Fig 5.5 shows that the data given from Revere (manufacturer) match the averaged actual performance very closely (within 5%).

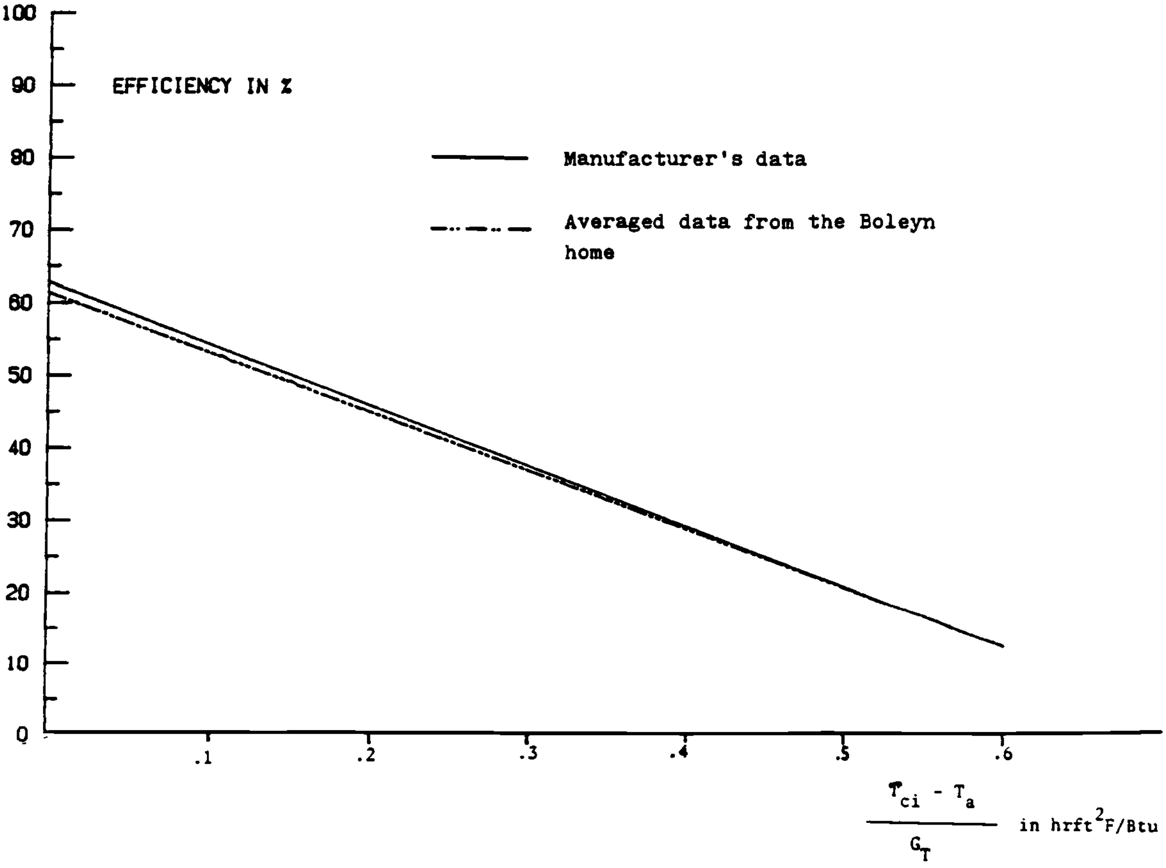

Fig. 5.5 Actual Collector efficiency versus manufacturer's data

5.2 Storage

The Boleyn home uses three 1250 gallon (4800 liter) water tanks as a storage unit. An auxiliary 1250 gallon (4800 liter) was included in the original design for the backup system.

The piping of the solar storage unit is shown in Fig. 5.6.

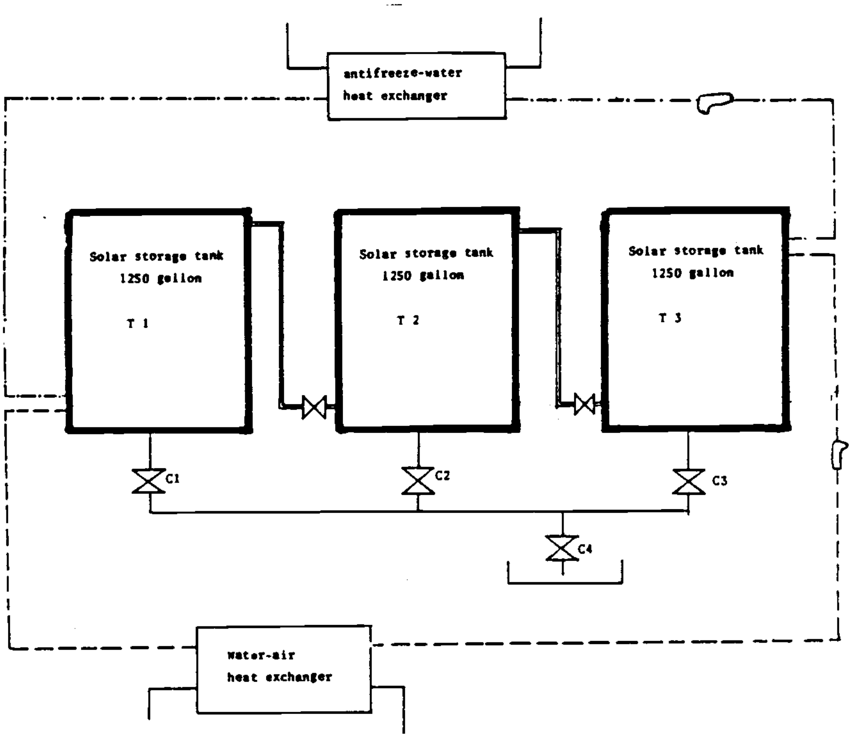

Fig. 5.6 Solar storage utility of the Boleyn home.

In the original design the storage tanks were built to take greatest advantage of temperature stratification. Therefore the coldest point of the warmest tank is connected with the warmest point of the next warmest tank and so on (see double lines in Fig. 5.6).

The large pressure drops in the pipes caused storage tank T3 to overfill and run over during the operation of the active solar system . Consequently the connection valves C1, C2 and C3 were opened. As a result most of the stratification was lost.

Table 5.2 summarizes the parameters associated with the solar storage of the Boleyn home

Number of tanks	3
Volume of each tank	1250 gallon (4800 liter)
Total heat capacity	$34*10^3$ Btu/F ($61*10^3$ kJ/^{o}C)
Insulation	R-19 batt insulation
Piping (solid line)	3/4" copper pipes
Piping (dashed line)	1" galvanized steel
Piping insulation	R-5 duct insulation (75% insulated)

Table 5.2 The solar storage utility

5.2.1 Losses from the storage tanks

Before the active solar system was in operation PGE calculated the storage tank losses. In these calculations only the losses from the insulated tanks were considered. Losses from pipes and uninsulated parts of the tanks were not calculated. The predicted results are compared with the losses that actually occured. Both calculations are outlined in Appendix E.

During the monitored period not all of the months have reliable data (see discussion in 6.1.2). Hence it was not possible to calculate a yearly performance figure.

The evaluated data given in Table 5.3 and Table 5.4 show that the actual losses are much higher than the predicted losses. For Table 5.3 and Table 5.4 a factor called Ratio was calculated by dividing the losses that actually occured by the design losses.

Table 5.3 gives the evaluation of months during 1977 where reliable data was available. Table 5.4 gives the evaluation for some randomly selected days.

Date	Predicted losses	Experimental evaluated losses	Ratio
FE	1.7E+005	4.7E+005	02.75
MA	5.5E+005	1.5E+006	02.67
MA	7.7E+005	3.8E+006	04.88
JU	8.9E+005	4.1E+006	04.64
JU	9.4E+005	2.8E+006	02.97
AU	9.3E+005	2.6E+006	02.74
SE	7.7E+005	3.3E+006	04.30
OC	7.9E+005	3.0E+006	03.72
NO	2.3E+005	3.7E+005	01.65

Table 5.3 Evaluation of the storage tank losses in 1977

Date	Predicted losses	Experimental evaluated losses	Ratio
3/18	5.6E+003	3.7E+004	06.58
3/17	3.7E+003	2.2E+004	06.08
3/16	4.3E+003	2.4E+004	05.54
3/15	3.4E+003	3.2E+004	09.31
3/14	3.8E+003	1.9E+004	05.09
4/7	7.8E+003	2.6E+004	03.27
4/6	1.3E+004	8.6E+004	06.70
4/11	9.3E+003	3.3E+004	03.57
5/27	1.1E+004	5.5E+004	05.07
5/26	1.4E+004	4.8E+004	03.46
11/23	2.7E+003	1.3E+004	04.71
11/22	2.0E+003	1.9E+004	09.34
11/21	3.2E+003	1.3E+004	03.94
11/17	3.4E+003	2.1E+004	06.37

Table 5.4 Evaluation of the storage tank losses of some randomly selected days

Comparisons: As indicated in Table 5.3 and Table 5.4 the actual losses are on the average 3.6 times higher than the design losses.

Higher storage tank losses can be explained in part by uninsulated portions of the tank and losses from the pipes. The calculated overall UA-factor, considering losses from uninsulated portions of the tank and losses from the pipes is 58 Btu/hrF (30.6 W/^{O}C). The calculation is outlined in Appendix E. Thus 63% of the tank losses can be explained by considering all convective losses from the solar system.

A major source of additional loss is natural convection through the two heat exchangers which are connected with the storage tanks.

From 1977-1978 some additional losses were caused by thermosyphoning. Thermosyphoning is heat transfer by natural convection. Fig. 5.7 shows that the absorber plate temperature is higher than the ambient air temperature during the hour from midnight to 1 a.m. in January 1978. Natural circulation of water in the loop kept the plate warmer than the air and hence losses occured.

The absorber plate temperature in 1978 is on the average 1.6 F (.9 ^{O}C) higher than the ambient air temperature.

In 1979 a backflow check valve was installed in the collector heat exchanger loop, to avoid thermosyphoning. Fig 5.8 shows that the absorber plate temperature after installation of the backflow check valve was 2.4 F cooler than the ambient air temperature. It is apparent that the check valve has reduced the thermosyphoning action.

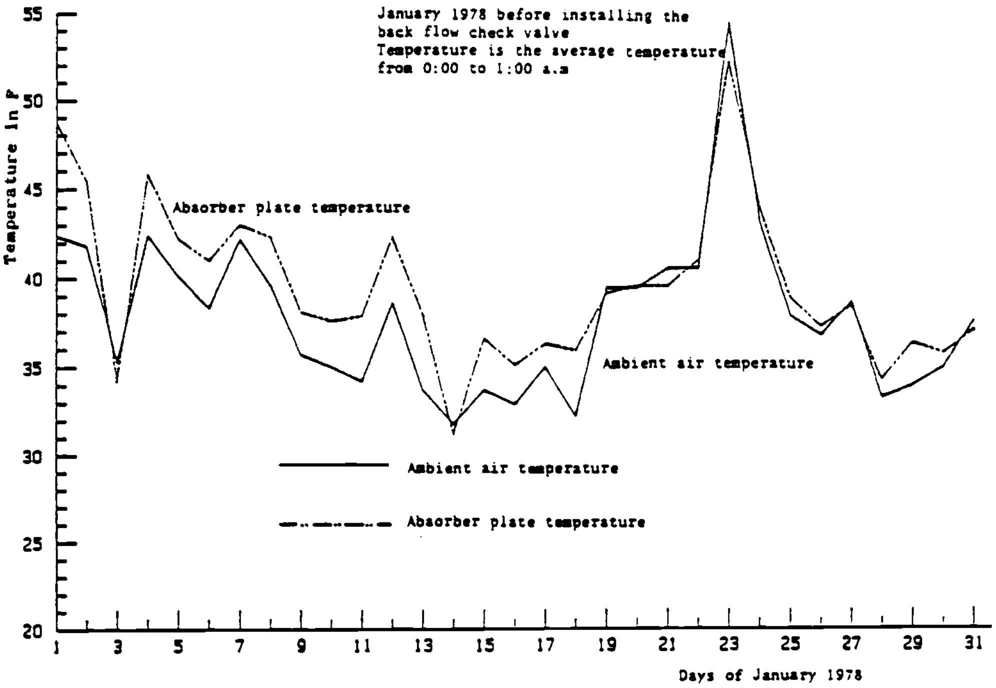

Fig. 5.7 Absorber plate temperature and ambient air temperature from January 1st to January 31st 1978

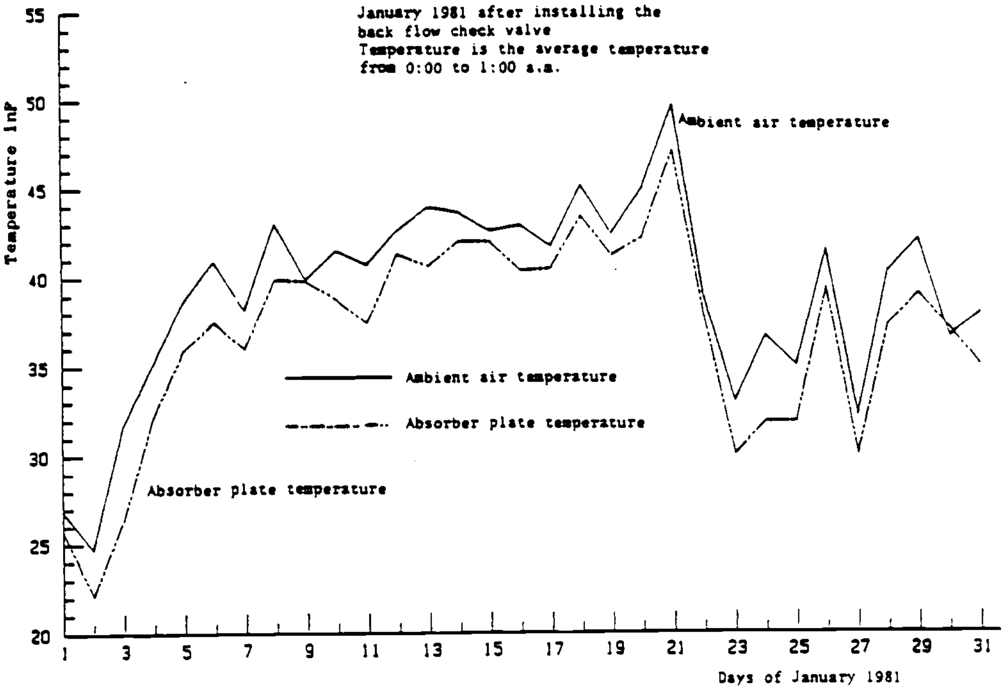

Fig. 5.8 Absorber plate temperature and ambient air temperature from January 1st to January 31st 1981.

Summary of thermosyphoning: Before the installation of the back flow check valve the absorber plate was warmer than the ambient air. This is strong indication that some heat from the storage tank heated up the absorber plate.

The absorber plate after the installation of the back flow check valve was cooler than the ambient air. This was due to radiation to the sky.

From these results the convection losses caused by thermosyphoning can be estimated.

$$Q_{ap} = U_{Lc}*A*(T_{ap}-T_a)*N_h$$

EQ. 5.12

Q_{ap}: Heat loss from the absorber plate

U_{Lc}: Total loss coefficient from the collector (see 5.1) .63 Btu/hrft^{2}F (3.6 W/m^2°C)

A: Collector area 429 ft^2 (40 m^2)

T_{ap}: Monthly averaged absorber plate temperature at 1 a.m.

T_a: Monthly averaged ambient air temperature at 1 a.m

N_h: Number of hours were the absorber plate temperature is 1.6 F above the ambient air temperaure. At the regarded month 5 hours a day or 155 hours a month

The total thermosyphoning loss from the absorber plate is approximately 67 000 Btu during monitoring in January 1978.

Conclusions losses from the storage tanks

The evaluation of storage tank heat loss by PGE (considering tank insulation only) underpredicts the heat loss by a factor of 3 to 4. Calculating losses from the uninsulated portions of the tank accounts for 63% of the losses. A significant amount of heat might be lost by natural convection and this amount has to be considered in estimating heat loss from storage tanks.

The installation of a backflow checkvalve at the Boleyn home successfully reduced the thermosyphoning action. In new systems checkvalves should be installed. Retrofitting such valves in existing systems should be considered whenever possible.

5.2.2 Impact of the storage tanks on the temperatures in the house

As already discussed in chapter 4 the tanks warm the basement and thereby reduce the overall heating requirements of the house.

The relation between the storage tank temperature, the ambient air temperature and the indoor temperature are discussed here. In addition the tank enclosure temperature is shown. The enclosure is an insulated room in the basement containing the storage tanks.

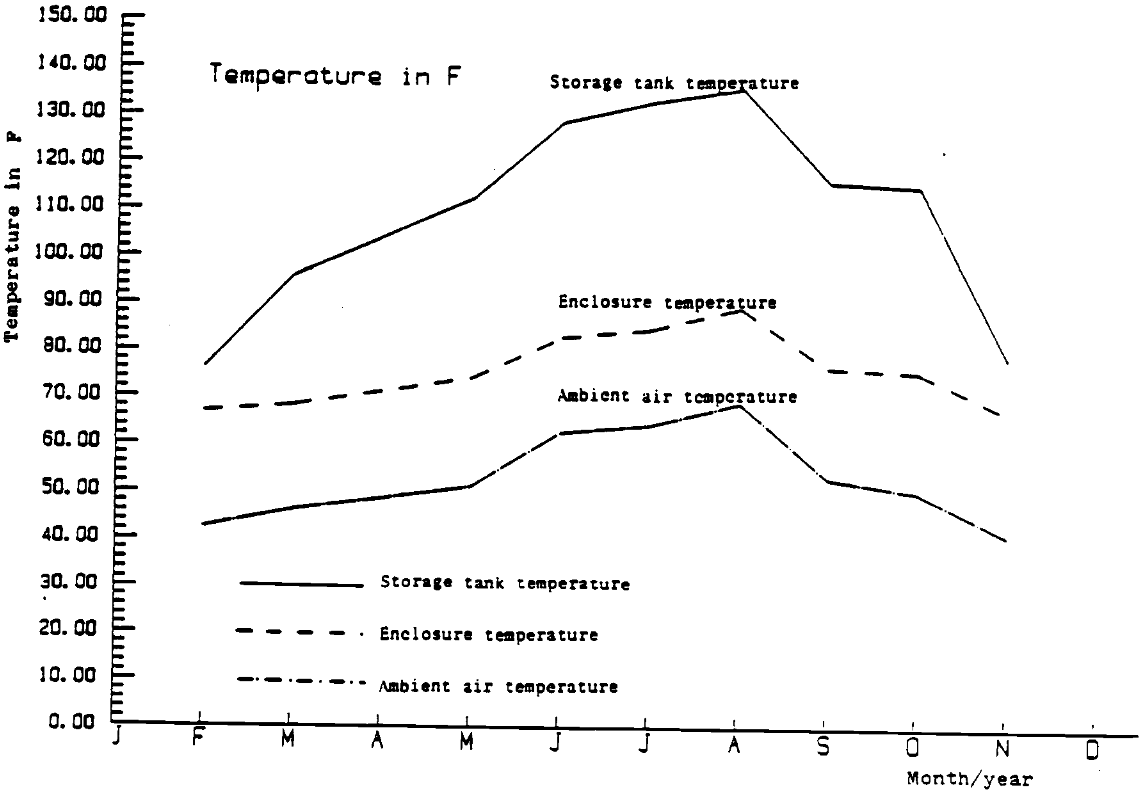

Fig. 5.9 Ambient air temperature, enclosure temperature and storage tank temperature

Fig 5.9 shows that the variation of the storage tank temperature is similar to that of the enclosure temperature and the ambient air temperature. The absolute temperature difference between storage tank temperature and ambient air temperature is higher during the summer months.

The enclosure temperature rises with the storage tank temperature. This has an impact on the basement temperature and on the indoor temperature of the house.

Fig 5.10 shows the indoor temperature and the basement temperature in 1978. The data are based on Table 4.1. From October to May the house is warmer than the basement. From June to September the tank heated basement is warmer than the house.

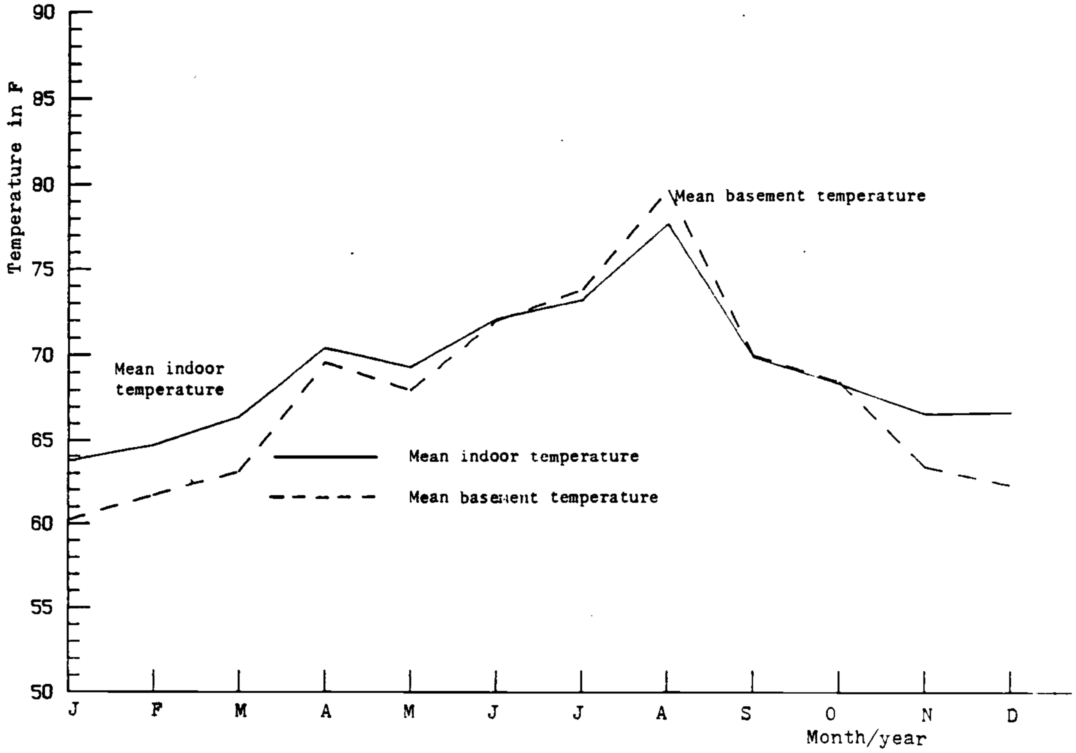

Fig. 5.10 Indoor temperature and basement temperature of the house

5.3 The heat exchangers

The active solar system of the Boleyn home has two heat exchangers (see Fig. 2.7). The water-water heat exchanger is in the collector storage tank loop and the water-air heat exchanger is in the storage tank air distribution loop.

1) Collector storage-tank heat exchanger: An energy balance of the heat exchanger in the collector storage tank loop shows more energy transfered to the storage tanks than received from the collector. This indicates that either the temperature measurements or the flowmeter malfunctioned. The monitoring equipment multiplies the flowrate digitally with the corresponding temperature difference (see Fig. 3.8). Thus the source of error could not be evaluated on the basis of the present data.
2) Air-water heat exchanger: The flow meter in the air flow loop records an energy flow only when the fan is working; All energy transported by natural convection are not recorded. Therefore the transfer of energy to the air is undervalued.

Both results are not satisfying, however a quantitative evaluation on the basis of the recorded data is not possible. Recommendations for future monitoring are given in section 6.1.2.

5.4 Changes to the system

5.4.1 The backup system

The primary backup system was a 1250 gallon (4800 liter) electrically heated auxiliary tank. PGE attempted to regulate the peak electricity requirements by installing electrically heated storage tanks, which are heated up during night time, an off peak period. The high losses from the tank motivated a change to a 10-kW duct heater.

The evaluation in 5.2 shows that the actual losses from the storage tanks are 3.6 times higher than originally calculated (see section 5.2.1).

For the auxiliary tank the actual U-factor is then $3.6*.05 = .18$ Btu/hrft^2 (.57 W/m^2). According to this the actual losses from the thermal stored energy are very high.

As an example the losses in January 1978 are calculated:

$$Q = [U*A*(T_{at}-T_e)]*N_h$$
EQ. 5.13

U: Actual U-factor .18 Btu/hrft^{2}F (1.0 W/m^2)

A: Surface area of the auxiliary tank 180 ft^2 (16.7 m^2) (see 6.2.1)

T_{at}: Averaged auxiliary tank temperature: 120 F (49.2 ^{o}C)

T_e: Tank enclosure temperature: 65 F (18.6 ^{o}C)

N_h: Number of hours in January 24*31=744 ($2.7*10^6$ s)

The total energy lost in January 1978 is $1.3*10^6$ Btu ($1.4*10^6$ kJ). The total heat delivered from the backup system in January 1978 was $4.7*10^6$ Btu ($4.95*10^6$ kJ). Thus the efficiency of the auxiliary storage tank was 72%.

January is one of the months where the heating requirements are fairly large. For months with lower heating requirements the efficiency is worse.

Due to the bad performance of the auxiliary heated storage tank an electrical duct heater was installed in 1979.

In Oregon a water-storage tank for energy storage is economically inefficient because the elecricity during off-peak hours is not cheaper.

Economic efficiency could be gained in other parts of the world (e.g. Europe) where the electricity during nighttime hours is much cheaper.

5.4.2 Reducing the pump power

The pumps originally installed were very large. The pump installed in the collector loop (pump #1 in Fig 2.7) was a 3/4 hp unit. The pump installed in the heat exchanger loop (pump #2 in Fig. 2.7) was a 1/6 hp unit. With these pumps the system annually required 1050 kWh (averaged value).

Due to the high electricity requirements both pumps were replaced in 1980 by smaller units (see section 2.4). The electricity required to collect the solar energy decreased to 480 kWh (54 % less).

The reduced pumping power caused a flowrate reduction from 18 gpm (1.1 kg/s) to 10 gpm (.6 kg/s) in the collector loop. The flowrate reduction in the heat exchanger loop was from 6 gpm (.38 kg/s) to 4 gpm (.25 kg/s).

The computer program F-chart (L 6.3) was run for both flow rates (see Appendix D). According to F-chart the solar fraction drops from 66.3% to 66.1%. This is insignificant compared to the savings in the parasitic electricity requirements. A reduction in the collector efficiency caused by the reduced flowrate was not observed experimentally.

5.4.3 Advancing the active solar system for hot water preheating

The active solar system was designed for space heating and domestic hot water preheating. However, to facilitate monitoring the space heating system the hot water preheat coil was disconnected in 1975.

Fig. 5.11 shows the solar system including the domestic hot water preheating.

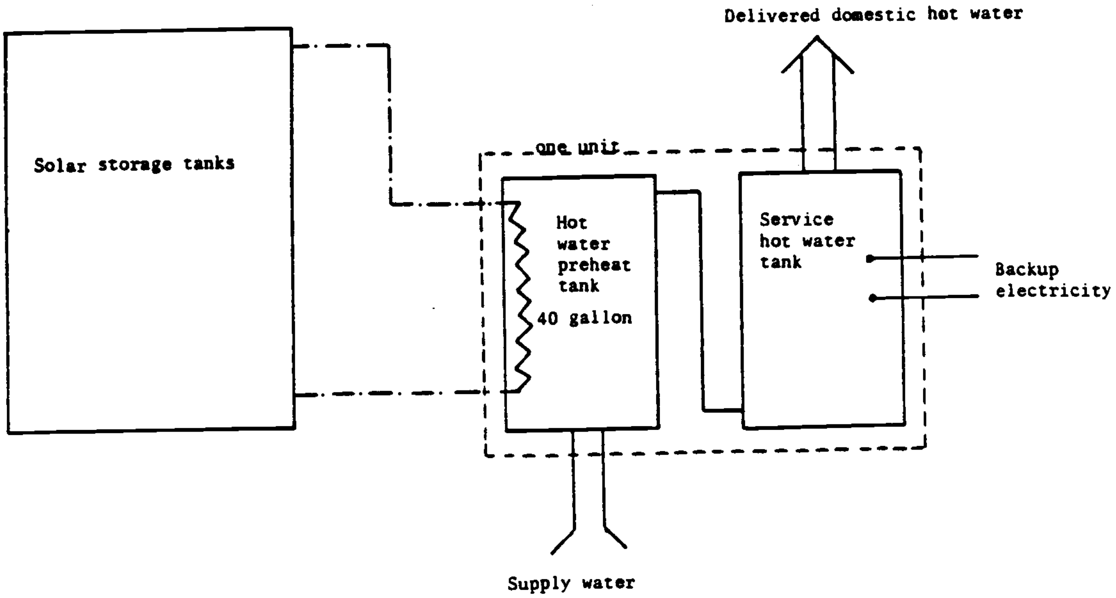

Fig 5.11 Solar system including the domestic hot water preheating

In 1975 the electricity required to deliver hot water to the house was 4209 kWh. It dropped in 1979, the first year when solar hot water preheating was supplied on a year round basis, to 1143 kWh.

Assuming no change in lifestyle the total savings are 3066 kWh ($10.5*10^6$ Btu).

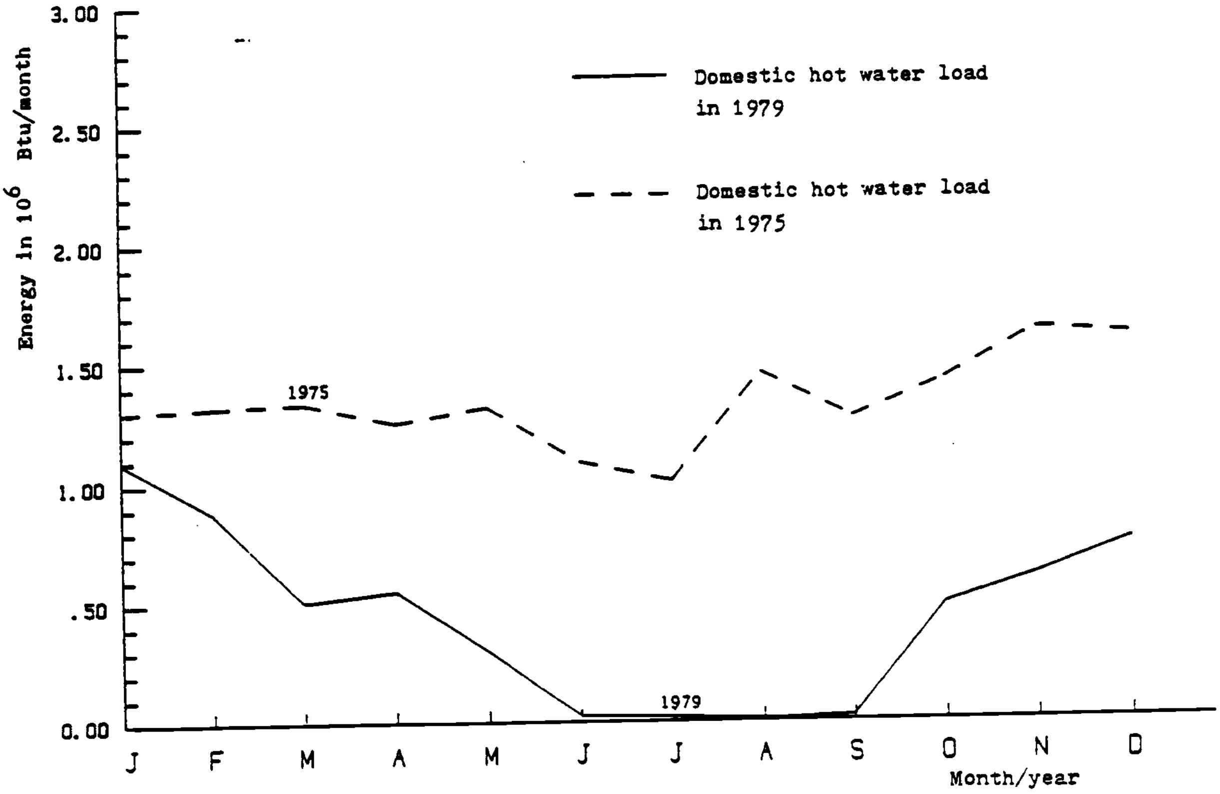

Fig. 5.12 Electricity required for domestic hot water before and after connecting the solar system

The gain from the active solar system due to space heating is on the order of $34.8*10^6$ Btu/year (4690 kWh/year) (see section 4.4). Thus the gain from the domestic hot water load amounts to 23% of the total gain from the active solar system.

References

L 6.1 Revere; The Revere Solar Energy Collector (no year); brochure from Revere

L 6.2 Duffie & Beckman; Solar Thermal Processes (1983), John Wiley & sons Inc.

L 6.3 Beckman, Klein, Duffie; Solar Heating Design by the F-chart method (1977), John Wiley & sons Inc.

6 RECOMMENDATIONS FOR FUTURE STUDIES

During the evaluation of the data observations were made, which raised new questions which require further work and studies to resolve.

6.1 Data Preparation

6.1.1 Availability of data

Between 1977 and 1982 approximately 4 million measurements were taken at a rate of 30 every 20 minutes. They were stored initially on a Phillips-type tape casette and later converted to a 800 BPI 1/2" Kennedy Tape Drive for an IBM computer. Each month requires one tape. All data together account for 60 tapes.

A first attempt to transfer the data to the OSU Cyber system was not succesful. The codes on the two tape drives are not compatible. Before evaluating the data over a larger period of time or to compare additional variables computer access should be obtained to the magnetically stored data.

If the data are successfully entered it is not suggested that the huge amount of data be analyzed at once. It would occupy too much storage space and the data manipulation would be very slow. To reduce the amount of data to a more manageable amount, some kind of averaging should be used.

Simple arithmetic averaging is not recommended since some of the data are obviously inaccurate. To eliminate obviously false data the recorded measurements should first be checked for validity (Fig. 6.1). This could be carried out by checking to be sure the values fall within a feasible range. For example ambient air temperature should almost always fall between 20 F and 90 F. Random jumps in measured values should be ignored. For example temperature changes of 20 F or more in 20 minutes for the storage tank temperature cannot be regarded as correct.

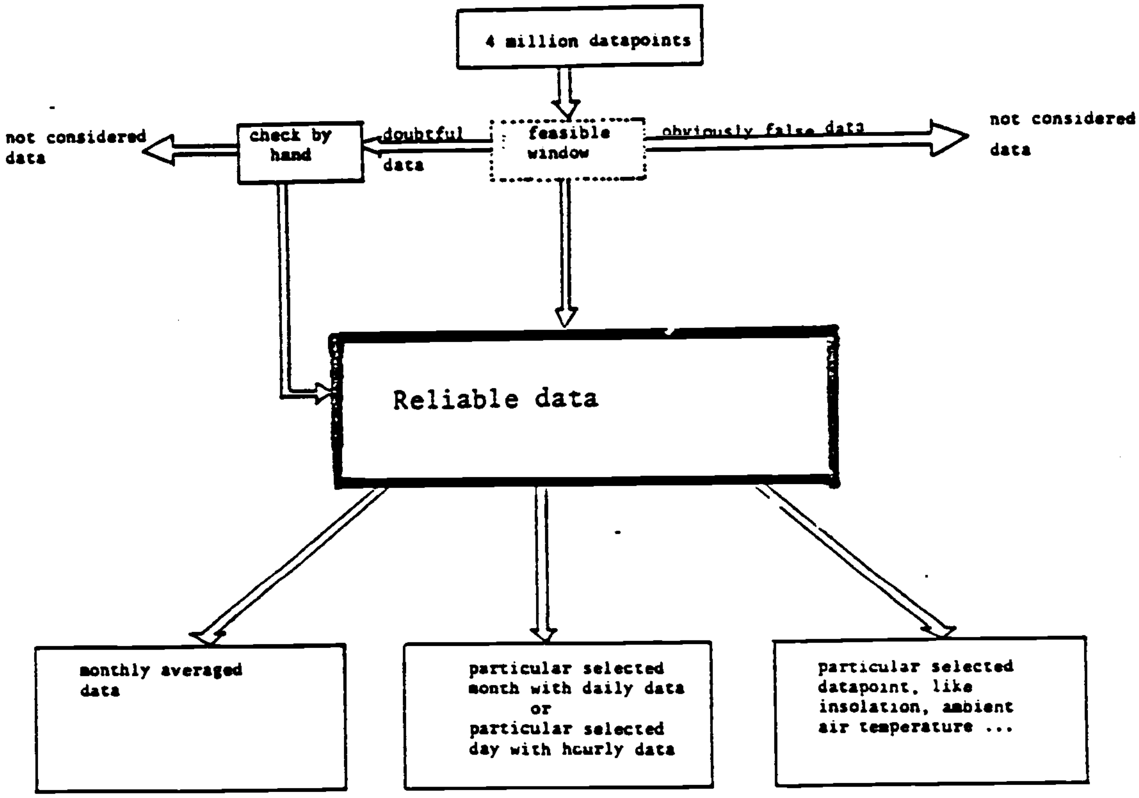

Fig. 6.1 Possible program to prepare the data

It is important that only accurate data be included in the averaging step. For example from the printouts of the monitored data none of the monthly averaged energy data could be used without first checking its validity.

Some data points were collected when the sensor was disconnected. Unfortunately these values are not always obviously erroneous. Some are in the correct order of magnitude but they can be identified because they do not change over time (e.g. 233 Btu from the auxiliary storage tank was measured constantly for 24 hours).

The reviewed data can then be averaged on a hourly, daily and monthly basis.

6.1.2 Reliability of the data

Not all of the sampled data make sense. If possible, these should be corrected before proceeding with further analysis. Problems occured particularly in the energy data.

Energy data: The energy data are calculated by elecronically multiplying the flowrate with the measured temperature difference before and after the heat exchanger (Fig. 6.2 and Fig. 2.8). Both the flowmeter and the temperature sensors have to be checked and calibrated to avoid illogical results.

For example it is not reasonable that the energy delivered to the storage tank is on the average 3% greater than the energy coming from the collector. Some hourly integrated datapoints show a difference of 20%.

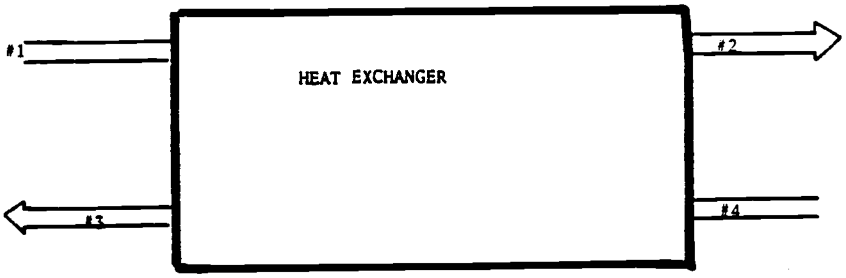

Fig 6.2 Temperature sensors at the heat exchangers

One easy check would be to switch the temperature sensors 1 and 2 with 3 and 4. If the energy delivered to the storage tanks is still higher, then the flowmeter is probably giving unreasonable results. It should also be possible to check the temperature sensors with a calibrated source (water at known temperature, ice-water ...).

Another source of error could be the location of the temperature sensors. If the convective and conductive resistance of all four thermosensors, to the item which is measured, is not the same illogical results are possible.

For further monitoring it is recommended not to digitally multiply the data. The pure measured data should be always saved. The energy flow through the ductwork for example could be evaluated later if the original measured datapoints (temperature and flowrate are available). Access to these data would be helpful in analyzing different hypotheses as to why the energy from the solar system is higher than the energy delivered to the house.

6.2 Measuring the infiltration rate

The infiltration rate was assumed in section 3 to be 3/4 air changes per hour according to the conditions at the site and the recommendations of ASHRAE (see section 3.1.3). A calculation performed by PGE assumed 1/2 air changes per hour (see section 3.1.4) and the heat loss measured at the Boleyn home indicates that the infiltration rate is somewhere between 1/2 air changes per hour and 3/4 air changes per hour.

A measurement of the infiltration rate at the Boleyn home could clarify the question whether the assumptions made for infiltration rate are valid.

6.3 Evaluation of weather data

Both insolation and ambient air temperature data are considered.

Insolation: The insolation data should be compared with the Portland airport data. This comparison will help to indicate the validity of computer programs like F-chart or Calpas3 at locations far from the location of the used weather file. The Portland Airport data are used as the standarized weather file in F-chart and Calpas3 for the Boleyn home (L 6.2).

In addition the University of Oregon monitored 7 locations in Oregon from 1978 to 1979 (L 6.3). A comparison could improve the knowledge of solar insolation distribution in Oregon.

Weather: The ambient air temperature measurements indicate that the ambient air temperature at the Boleyn home is below the ambient air temperature measured at the Portland Airport. Whether this is a true observation or an accidential observation caused by a improperly calibrated sensor can not yet be determined.

The calibration of the temperature sensor should be checked.

Comparisons could also be made to the ambient air temperatures measured at other solar houses monitored by PGE.

6.4 Later changes in the system

Sunspace: In 1983 a sunspace in the southfacing wall was added to the house (Fig 6.3).

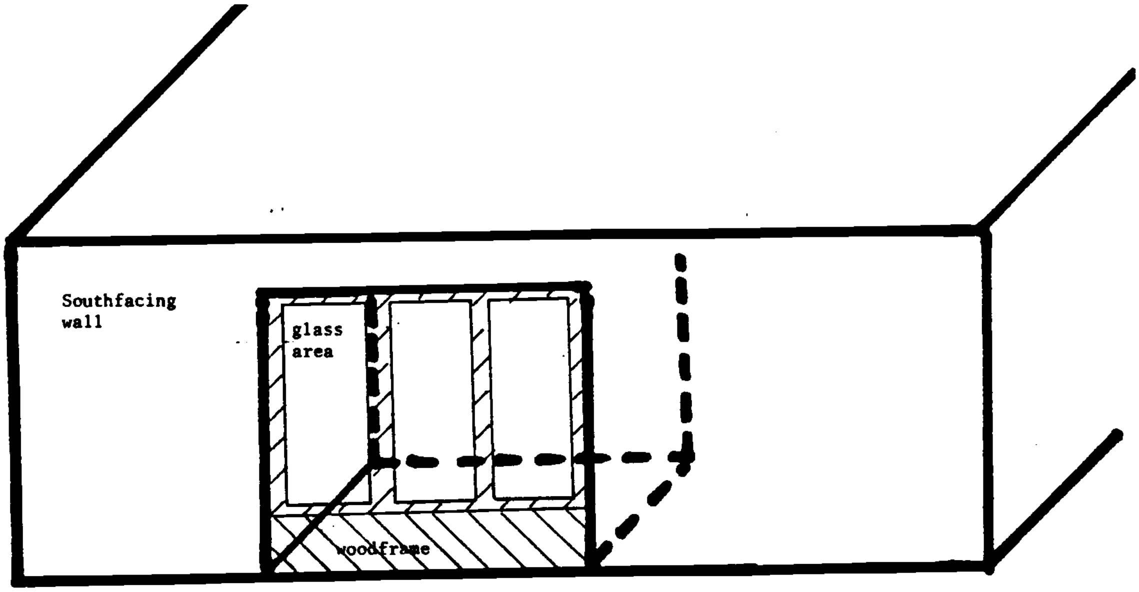

Fig. 6.3 Added sunspace

Calpas3 was run for the house including the sunspace. According to Calpas3 the heat load of the house with the sunspace decreases by 4.5%.

The sunspace had to be modeled as having a 1" layer of concrete, since 1" was the minimum required input value for the thermal mass. However, the sunspace of the Boleyn home has a wood floor. By taking the energy data for the Boleyn home from 1983 and later the actual savings could be compared with the predicted savings.

Heat pump: In 1981 a heat pump was added to the system (Fig. 6.4) to reduce the overall elecricity requirements of the home.

Data were recorded by hand by Douglas Boleyn showing the reduced energy consumption. The evaluation of the savings by adding a heat pump should be done in connection with an economic analysis.

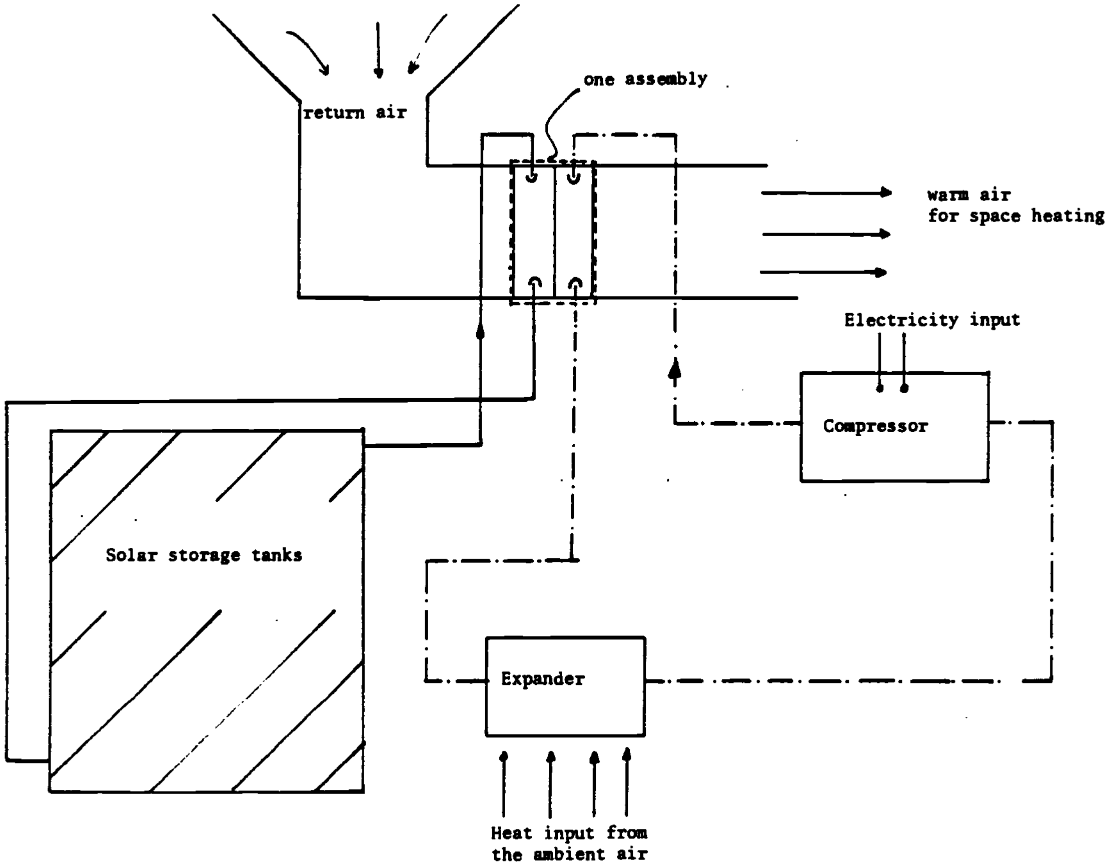

Fig. 6.4 The heating system after installing the heat pump

6.4 Economic analyses

The dollar counts in the real world. Therefore the economic analysis is very important.

A rough estimation shows that the passive solar gains are extremely beneficial and have low investment costs. Essentially they only require a good design.

The active solar system seems to be much less cost effective given the high capital costs. However, during bad weather periods where passive gains are not available the active solar fraction is more valuable than the passive gains.

The greater benefits of the active solar fraction has to be taken into consideration by applying an economic analysis.

References

L 7.1 Balcomb J. Douglas; Passive Solar Design Handbook Vol 2 (1980), Copyright U.S. Department of Energy

L 7.2 Berkeley Solar Group; Calpas3 User manual (1982), Copyright Berkeley Solar Group 3140 Grove Street Berkeley, CA 94703

L 7.3 University of Oregon; Solar Radiation Data (1981), unpublished Solar Radiation Monitoring Group

7 FINDINGS AND CONCLUSIONS

The Boleyn home was evaluated based on the monitoring data taken from 1977 to 1982. The performance of the building and of the components of the active solar system was evaluated and compared with the design predictions. This chapter summarizes the results from the previous sections.

7.1 Performance of the home

The Boleyn home is a very well insulated house with low infiltration rate that benefits from passive solar gains obtained from 96 ft^2 of glass area to the south. The building performance index (BPI) of the house during the evaluated effective year was 4.3 Btu/DD$_F$ft^2.

Thermostat setback during the heating season (November to March) reduced the heating requirements of the home significantly by 19%, indicating that indoor temperatures below 70 F are acceptable.

The Boleyn home is heated by four sources. The contribution during the evaluated effective year was:

Passive solar gains	28.2%
Internal gains	18.6%
Active solar system	
Energy delivered from the solar storage tanks via the heatexchanger	17.6%
Reduced transmission losses via the floor to the tank heated basement	22.0%
Backup	13.6%

Validity of predictive tools:

Design heat loss

The experimental evaluated design heat loss is 26% lower than the predictions made by the ASHRAE method. However, during operation the basement of the home was heated by the solar storage tanks located in the basement. The design heat loss evaluated at the Boleyn home including the correction for the unheated basement matches the ASHRAE predictions within 6%.

If all influencing factors are considered, the ASHRAE method is a good tool to estimate the design heatloss of a building.

Annual heating requirements

The annual heating requirements were evaluated at the Boleyn home and predicted by the degree-day-method by ASHRAE and by the computer program Calpas3. The BPI is compared to account for the different degree-days used in each calculation. The BPI is 12% underpredicted by the ASHRAE method and 21% underpredicted by Calpas3. These are acceptable results considering the various assumptions needed to predict annual heating requirements.

Passive solar gains

Calpas3 predicted a large cooling load at the Boleyn home. This did not occur at the Boleyn home. The Boleyns handle the cooling load by opening windows and they accept higher indoor temperatures than predicted by Calpas3.

Calpas3 predicted the main trends of the passive solar gains throughout the year.

7.2 Performance of the active solar system

Active solar fraction

The active solar fraction evaluated over the "effective" year at the Boleyn home (without passive gains and internal gains) is 74.5%. F-chart predicted the active solar fraction to be 66.3%. F-chart is a valuable tool in predicting the active solar contribution of a building but there is no option to consider heat gains from tank losses of storage tanks located inside the building.

The active solar system was designed to meet 50% of the heating requirement of the home. This design goal was exceeded.

Collector:

The optical properties and the heat loss properties of the Revere-double-glazed collector were constant over the four year period of evaluation. They match the manufacturer's data within 5%. The collector efficiency after solar noon was higher than the collector efficiency before solar noon. A reason could be that the temperature above the collector is higher than the ambient air temperature. This is likely in this case due to the location of the ambient air sensor and heating of the collector.

Storage tank:

The heat loss from the storage tanks was 3.6 times higher than the predicted losses by PGE. The additional losses could be explained partly by uninsulated parts of the tanks and losses from the piping.

The installation of a backflow checkvalve in the collector heat exchanger loop reduced thermosyphoning. The installation of backflow check valves in new systems and existing systems is recommended.

Heat loss from the storage tanks in the basement kept the house warmer than desired in the summer and made the basement a more comfortable space in the winter.

Pumps:

The pumps in the collector loop were replaced by smaller units. This reduced the parasitic electricity requirements to collect the solar energy by 54%. A reduction in the collector efficiency caused by the reduced flowrates was not observed experimentally or anticipated by F-chart.

Domestic hot water preheat tank (DHW):

The connection of the DHW reduced the electricity requirements for the domestic hot water preheating from 4209 kWh to 1143 kWh. The benefit of the DHW amounts to 23% of the total gain of the active solar system (space heating and domestic hot water preheating).

The DHW improved the system. It should be part of new systems whenever possible.

7.3 Other findings

The monitoring system:

The temperature and insolation data were monitored properly.

Problems occured with the energy flow data because of the way the monitoring equipment was set up. Invalid results from the heat exchangers could not be analyzed because the temperature data and the flowrate data were not recorded. For future monitoring digitally multiplying of flowrate data with temperature data is not recommended because the temperature data and the flowrate data are lost.

Weather data:

The ambient air temperature measurements at the Boleyn home indicate that the temperature at the Boleyn home is below the temperature at the Portland Airport. The Portland airport weather data are used in standarized weatherfiles for F-chart and Calpas3. The weather data measured at the Boleyn home could be compared with the standarized weatherfiles to give more information about the validity of those standarized weatherfiles.

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Appendix

APPENDIX A PRINTOUTS

Fig A.1 and Fig A.2 show the daily printouts. It includes hourly integrated temperature and energy data.

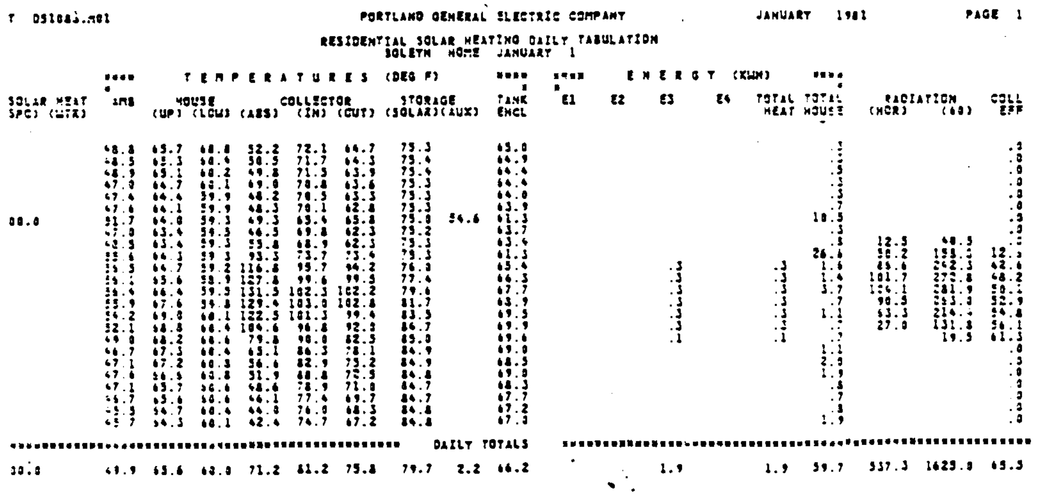
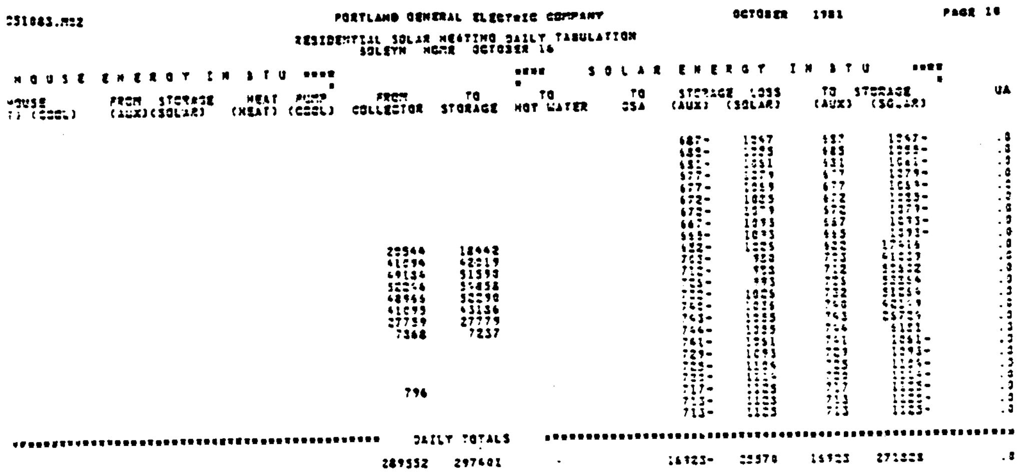


Fig A.1 Daily printout (temperatures)



```
PORTLAND GENERAL ELECTRIC COMPANY          OCTOBER   1981          PAGE 10
RESIDENTIAL SOLAR HEATING DAILY TABULATION
SOLEYN  HOME  OCTOBER 16

H O U S E   E N E R G Y   I N   B T U

          FROM  STORAGE     HEAT  PUMP     FROM        TO
          (AUX)(SOLAR)    (HEAT) (COOL)  COLLECTOR  STORAGE

S O L A R   E N E R G Y   I N   B T U

   TO         TO     STORAGE  LOSS     TO  STORAGE         UA
HOT WATER     SSA    (AUX)  (SOLAR)   (AUX)  (SOLAR)

                                DAILY TOTALS
                            289552   297401
```

Fig. A.2 Daily printout (energy balance)

APPENDIX B TRANSMISSION LOSSES OF THE BOLEYN HOME

The transmission heat loss for the Boleyn home is calculated by using the heatflux through the walls, windows, doors, roof, and floor. The thermal conductivities (U-values) are taken from the ASHRAE Handbook of Fundamentals (L 4.1) pp 360-369.

Fig B.1 to B.3 and Table B.1 to B.3 show the construction detail and the U-values of the floor, roof and wall.

Wall

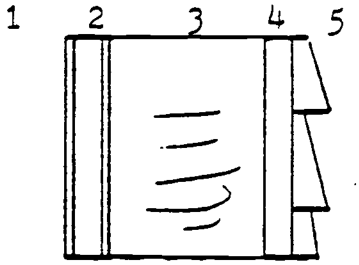


Fig. B.1 Wall of the main floor

R-values in $hrft^2F/Btu$

1	Surface still air	.68
2	1/2" Gyp. Board	.45
3	7/2" Fiberglass Batts	11
4	1/2" Ext. Plywood	.62
5	1/2 * 8 Tight Knot Bevelled constr. side	1.22
		14.65

Table B.1 R-values of the wall

The U-value is given by 1/R

U_w = .068 $Btu/hrft^2F$ (.39 W/m^2C^o)

Roof

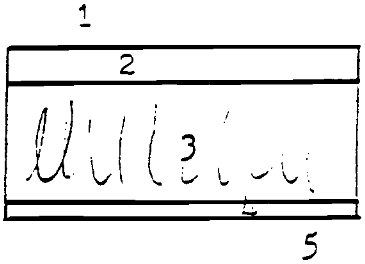


Fig B.2 Roof of the Boleyn home

1	Outside surface (15 mph wind)	.17
2	Built-up roofing	.33
3	6" Fiberglass batts	19
4	Gyp. wallboard	.45
5	Inside surface	.61
		20.56

Table B.2 R-values of the roof

The U-value is given by 1/R

U_r = .049 Btu/hrft^{2}F (.28 W/m^{2}C^o)

Floor

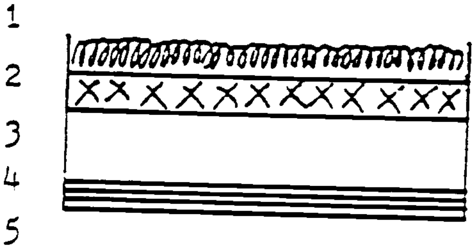


Fig. B.3 Floor of the Boleyn home

1	Still air	.61
2	Carpet & Pad	1.23
3	Underlayment	.82
4	Subfloor	.94
5	Still air	.61
		4.21

Table B.3 R-values of the floor

The U-value of the floor is 1/R and R is taken to be 4.0 since only about 75% of the floor is carpeted

U_f = .25 Btu/hrft^{2}F (1.4 W/m^{2}C^o)

Basement wall

Essentially the same wall as in the main floor but instead of the R-11 insulation batts a 7/2" airspace with R=.97 $hrft^2F/Btu$ is considered.

$$U_b = .21\ Btu/hrft^2F \qquad (1.23\ W/m^2C^o)$$

Windows and glass doors

The glass area is made of double glazed thermopane glass with 1/2" min. air space. The U-value is taken from "Heating Ventilating and Airconditioning" (L 4.2).

$$U_g = .47\ Btu/hrft^2F \qquad (2.66\ W/m^2C^o)$$

Wood door

The 2" wood door on the westside has a U-value of (L 4.2).

$$U_{wd} = .53\ Btu/hrft^2F \qquad (2.44\ W/m^2C^o)$$

Table B.4 gives an overview of all areas (taken from Fig. 3.1 to Fig. 3.6) and the corresponding U-values

	South	East	West	North	U-values in $Btu/hrft^2F$
Wall (main floor)	369	474	467	671	.068
Glass area	96	79	41	24	.47
Doors (wood)	-	-	-	20	.43
Wall (basement)	320	275	360	275	.21
Roof	1576				.048
Floor	1125				.25

Table B.4 Summary of the areas and U-values

Heat loss equation

The basic equation for the heat losses by transmission through any surface is given by:

$$H_l = A*U*(T_i-T_o)$$

EQ. B.1

H_l: Heatloss
A: Area
U: Coefficient of transmiss.
T_i: Indoor design temperature
T_o: Outdoor design temperature or temp. of adj. unheat. space

The indoor design temperature is stated to be 70 F (21 C^o). The outside design temperature to 15 F (-10 C^o). That corresponds to a design temperature difference of 55 F.

Since the basement is an unheated space the basement equilibrium temperature has to be calculated. An energy balance gives:

$$A_f*U_f*(T_i - T_b) = A_b*U_b*(T_b - T_o)$$

Therefore:

$$T_b = \frac{A_f*U_f*T_i + A_b*U_b*T_o}{A_f*U_f + A_b*U_b}$$

The constants are given as follows:

A_f: Floor area 105 m^2
A_b: Base. wall area 119m^2
T_i: Indoor design temp. 294 K (70 F)

U_f: U-floor 1.42 W/m^2C^o
U_b: U-base. 1.25 W/m^2C^o
T_o: Outdoor design temp. 278.7 K (15 F)

The equilibrium basement temperature at design conditions turns out to be 278.7 K (42 F).

Now the heat loss equation (EQ. B.1) can be used to determine the transmission losses through walls, windows, doors, basement and roof. The heat loss of each of them is given in Table B.5.

	$U_x * A_x * (T_i - T_o$	Heatloss in Btu/hr
Walls	.068*1681*55	6287
Roof	.049*1576*55	4247
Floor	.25*1125*(70-42)	7875
Windows and Glass door	.47*240*55	6204
Wood door	.53*20*55	473
		25086

Table B.5 Heat loss due to transmission

The total heat loss due to transmission at design temperatures for the Boleyn home is 25086 Btu/hr (26470 kJ/hr)

APPENDIX C INPUT AND OUTPUT DATA FOR CALPAS3

The computer program Calpas3 was run for the Boleyn home with different input parameters. Table C1 to Table C3 show the three runs with 1/2 air change/hour, 3/4 air change/hour and 3/4 air change/hour plus added sunspace. The constant input parameters are listed in Table 4.1. The conduction losses given in Table C1 to C3 are the product of an UA-factor and the temperature difference between the temperature of the outer surface of the wall and the indoor temperature. The outer temperature of the wall is determined by a network calculation accounting for passive solar gains which heats the wall. For further information it is refered to the Calpas User manual (see bibliography).

```
Title Boleyn
Site Location=Portland
House FLRAREA=1125
Roof Area=1576 UVAL=.048
Wall Name=North Area=371 AZM=180 UVAL=.068
Wall Name=East Area=474 AZM=-90 UVAL=.068
Wall Name=South Area=369 AZM=0 UVAL=.068
Wall Name=West Area=467 AZM=90 UVAL=.068
Wall Name=Floor Area=1125 AZM=0 TILT=180 UVAL=.048
Wall Name=Doors Area=20 AZM=90 UVAL=.43
Glass Name=North Area=24 AZM=180 NGLZ=2 UVAL=.47 XRFLCT=.22
Glass Name=East  Area=79 AZM=-90 NGLZ=2 UVAL=. 7 XRFLCT=.22
Glass Name=South Area=96 AZM=0   NGLZ=2 UVAL=.47 XRFLCT=.22
Glass Name=West  Area=41 AZM=90  NGLZ=2 UVAL=.47 XRFLCT=.22
INFIL ACBASE=.75
INTGAIN INTGAIN=14.06
END
```

```
MONTHLY HOUSE ENERGY BALANCE     (kBtu; + into house)
---------------------------------------------------------

     GAINS & LOSSES                                      TRANSFERS
     ==============================================      ===============================
MON    COND    SHCND    INFIL     SLR    INT   STRG      RE+SS    VENT     COOL    HEAT
---  -------  -------  -------  ------ ------ -----    ------- -------  ------- ------
JAN  -6716.0           -2330.5  945.78 1487.6  0.00                  0        0 6613.1
FEB  -5250.0           -1904.7  1579.8 1343.6 -0.00            -80.587        0 4311.9
MAR  -5168.1           -2000.4  2538.3 1487.6  0.00            -463.80        0 3606.5
APR  -4016.8           -1719.2  3094.0 1439.6  0.00            -981.86  -111.15 2295.4
MAY  -2609.4           -1349.7  3531.9 1487.6  0.00            -1452.1  -745.99 1137.8
JUN  -1023.6           -859.68  3619.5 1439.6 -27.8            -2115.6  -1325.9 293.54
JUL   322.45           -476.10  4044.1 1487.6  6.44            -2538.3  -3041.3 165.07
AUG  -439.99           -621.03  3566.0 1487.6 -5.38            -2300.0  -1970.0 282.82
SEP  -1359.7           -820.99  3239.8 1439.6  9.44            -1614.9  -1308.0 414.77
OCT  -3447.1           -1381.4  2300.9 1487.6  17.0            -629.47  -193.85 1645.3
NOV  -4798.3           -1718.2  1310.9 1439.6  0.26            -125.02        0 3890.8
DEC  -6462.3           -2234.8  918.22 1487.6  0.00                  0        0 6291.3

TOT   -40939            -17417   30689  17515  0.00             -12301  -8696.2  31148
```

Table C1 Calpas3 with 3/4 air change/hour infiltration rate

```
Title Boleyn
Site Location=Portland
House FLRAREA=1125
Roof Area=1576 UVAL=.048
Wall Name=North Area=371 AZM=180 UVAL=.068
Wall Name=East Area=474 AZM=-90 UVAL=.068
Wall Name=South Area=369 AZM=0 UVAL=.068
Wall Name=West Area=467 AZM=90 UVAL=.068
Wall Name=Floor Area=1125 AZM=0 TILT=180 UVAL=.048
Wall Name=Doors Area=20 AZM=90 UVAL=.43
Glass Name=North Area=24 AZM=180 NGLZ=2 UVAL=.47 XRFLCT=.22
Glass Name=East  Area=79 AZM=-90 NGLZ=2 UVAL=.47 XRFLCT=.22
Glass Name=South Area=94 AZM=0   NGLZ=2 UVAL=.47 XRFLCT=.22
Glass Name=West  Area=41 AZM=90  NGLZ=2 UVAL=.47 XRFLCT=.22
INFIL ACBASE=.5
INTGAIN INTGAIN=14.06
Sunspace Flrarea=60 Vol=720
SSwall Name=South Area=15 AZM=0 Uval=1.1
SSwall Name=Easth Area=40 AZM=-90  Uval=.068
SSwall Name=West  Area=40 AZM=+90  Uval=.068
SSwall Name=North Area=54 AZM=180  Uval=.068
[illegible]
SSGlass Name=South Area=81 AZM=0 NGLZ=1 UVAL=1.1 XRFLCT=.22
SSGlass Name=North Area=40 AZM=180 NGLZ=2 UVAL=.47
SSinfil Acbase=1.5
SScoupling UATAHS=22.5 Vent=Natural Arealow=15
END
M O N T H L Y   H O U S E   E N E R G Y   B A L A N C E     (kBtu; + into house)
--------------------------------------------------------

      GAINS & LOSSES                                           TRANSFERS
      ================================================         ===============================
MON      COND    SHCND    INFIL      SLR      INT   STRG       RB+SS     VENT     COOL   HEAT
---   -------  -------  -------  -------  -------  -----     -------  -------  -------  -----
JAN   -6733.6  -216.16  -1557.5   945.78   1487.6   0.00       8.904        0        0 6065.0
FEB   -5295.9  -153.18  -1280.0   1579.8   1343.6  -0.00      10.330  -116.26        0 3911.5
MAR   -5230.9  -124.13  -1347.6   2538.3   1487.6   0.00       8.822  -561.75        0 3229.7
APR   -4089.3  -85.903  -1162.2   3094.0   1439.6  -2.20       5.954  -1103.3  -122.42 2025.7
MAY   -2679.8  -34.164  -915.42   3531.9   1487.6   1.81      12.073  -1584.5  -771.07 951.45
JUN   -1096.0    3.320  -589.18   3619.5   1439.6  -28.1      24.335  -2202.9  -1392.3 221.82
JUL    301.79   51.719  -328.64   4044.1   1487.6   6.84      52.448  -2667.7  -3062.6 114.47
AUG   -496.67   30.547  -426.59   3566.0   1487.6  -6.00      50.136  -2405.5  -2004.0 204.51
SEP   -1428.8    5.105  -562.66   3239.8   1439.6   8.99      21.611  -1700.1  -1341.6 318.05
OCT   -3517.6  -73.954  -936.54   2300.9   1487.6   15.9       7.409  -706.74  -197.71 1620.7
NOV   -4834.4  -154.82  -1153.5   1310.9   1439.6   2.73       6.709  -152.21        0 3535.0
DEC   -6485.4  -211.75  -1495.0   918.22   1487.6   0.00      14.077        0        0 5772.3

TOT    -41587  -963.37   -11755    30689    17515  -0.00      222.81   -13201  -8891.7  27970


M O N T H L Y   S U N S P A C E   E N E R G Y   B A L A N C E  (kBtu; + into SS)
--------------------------------------------------------------

      GAINS & LOSSES                              TRANSFERS
      ====================================        =======================================
MON     TCOND    INFIL     SLR     INT  STRG          RB       HS     VENT    COOL   HEAT
---   -------  -------  ------  ------ -----     -------  -------  -------  ------  -----
JAN   -1106.1  -187.05  624.99       0  0.00                -8.904        0       0 677.06
FEB   -1051.3  -174.85  1026.2       0 -0.40               -10.330  -50.531       0 261.27
MAR   -1338.5  -216.17  1574.6       0 -4.21                -8.822  -166.42       0 159.68
APR   -1269.8  -204.71  1763.9       0 -13.5                -5.954  -306.98       0 37.509
MAY   -1196.5  -190.18  1870.4       0  0.74               -12.073  -472.84       0  0.435
JUN   -894.79  -144.27  1851.9       0 -12.5               -24.335  -775.60       0      0
JUL   -769.21  -123.56  2026.9       0 -2.13               -52.448  -1079.5       0      0
AUG   -806.02  -128.77  1965.9       0  2.45               -50.136  -983.52       0      0
SEP   -873.94  -139.45  1968.1       0  5.10               -21.611  -938.38       0 19.267
OCT   -994.76  -160.87  1496.5       0  7.13                -7.409  -360.06       0 159.50
NOV   -829.33  -143.07  887.83       0  17.0                -6.709  -85.703       0 592.20
DEC   -1029.6  -175.85  626.98       0  0.30               -14.077        0
                                                                           
TOT    -12160  -1988.8   17684       0 -0.04               -222.81  -5219.5       0 1906.9
```

Table C2 Calpas3 with 1/2 air change/hour infiltration rate including sunspace

```
 1     Title Boleyn
 2     Site Location=Portland
 3     House FLRAREA=1125
 4     Roof Area=1576 UVAL=.048
 5     Wall Name=North Area=371 AZM=180 UVAL=.068
 6     Wall Name=East Area=474 AZM=-90 UVAL=.068
 7     Wall Name=South Area=369 AZM=0 UVAL=.068
 8     Wall Name=West Area=467 AZM=90 UVAL=.068
 9     Wall Name=Floor Area=1125 AZM=0 TILT=180 UVAL=.048
10     Wall Name=Doors Area=20 AZM=90 UVAL=.43
11     Glass Name=North Area=24 AZM=180 NGLZ=2 UVAL=.47 XRFLCT=.22
12     Glass Name=East  Area=79 AZM=-90 NGLZ=2 UVAL=.47 XRFLCT=.22
13     Glass Name=South Area=96 AZM=0   NGLZ=2 UVAL=.47 XRFLCT=.22
14     Glass Name=west  Area=41 AZM=90  NGLZ=2 UVAL=.47 XRFLCT=.22
15     INFIL ACBASE=.75
16     INTGAIN INTGAIN=14.06
17     Sunspace Flrarea=60 Vol=720
18     SSwall Name=South Area=15 AZM=0 Uval=1.1
19     SSwall Name=Easth Area=40 AZM=-90  Uval=.068
20     SSwall Name=West  Area=40 AZM=+90  Uval=.068
21     SSwall Name=North Area=54 AZM=180  Uval=.068
[illegible]
23     SSGlass Name=South Area=81 AZM=0 NGLZ=1 UVAL=1.1 XRFLCT=.22
24     SSGlass Name=North Area=40 AZM=180 NGLZ=2 UVAL=.47
25     SSinfil Acbase=1.5
26     SScoupling UATAHS=22.5 Vent=Natural Arealow=15
27     END
M O N T H L Y   H O U S E   E N E R G Y   B A L A N C E     (kBtu; + into house)
---------------------------------------------------------

      GAINS & LOSSES                                         TRANSFERS
      =============================================          =================================
MON       COND    SHCND    INFIL      SLR      INT   STRG     RB+SS      VENT      COOL   HEAT
---   -------- -------- -------- -------- -------- ------   -------  --------  -------- ------
JAN    -6718.5  -215.66  -2331.3   945.78   1487.6   0.00    12.701         0         0 6819.4
FEB    -5251.8  -151.48  -1905.3   1579.8   1343.6   0.00    20.219   -81.407         0 4446.3
MAR    -5166.0  -121.21  -1999.7   2538.3   1487.6   0.00    15.284   -459.22         0 3705.0
APR    -4013.1  -82.239  -1718.0   3094.0   1439.6  -0.00    10.834   -973.98   -111.48 2354.4
MAY    -2614.1  -31.555  -1351.3   3531.9   1487.6  -0.00    21.576   -1458.9   -735.20 1149.9
JUN    -1035.5    5.888  -863.65   3619.5   1439.6  -28.0    32.563   -2121.7   -1331.1 282.35
JUL     329.35   52.564  -483.79   4044.1   1487.6   6.54    60.123   -2569.8   -3070.3 143.62
AUG    -462.80   31.680  -628.62   3566.0   1487.6  -5.58    58.028   -2320.9   -1984.5 259.09
SEP    -136[illegible].3    7.782  -824.18   3239.8   1439.6   9.71    27.918   -1618.5   -1320.8 407.95
OCT    -3445.1    0.365  -1380.7   2300.9   1487.6   16.9    11.614   -627.18   -195.09 1901.5
NOV    -4798.3  -153.33  -1718.2   1310.9   1439.6   0.44    11.191   -124.83         0 4032.6
DEC    -6465.6  -211.23  -2236.0   918.22   1487.6  -0.00    20.746         0         0 6486.3

TOT    -4101[illegible]  -939.17   -17441    30689    17515   0.00    302.80    -12356   -8748.5  31988


M O N T H L Y   S U N S P A C E   E N E R G Y   B A L A N C E   (kBtu; + into SS)
-----------------------------------------------------------------

      GAINS & LOSSES                                TRANSFERS
      ==================================           =========================================
MON     TCOND    INFIL      SLR     INT  STRG         RB       HS      VENT     COOL   HEAT
---   -------  -------   ------  ------ -----     ------  -------   -------   ------ ------
JAN   -1103.9  -186.68   624.99       0  0.00             -12.701         0        0 678.26
FEB   -1046.6  -173.97   1026.2       0 -0.38             -20.219   -48.063        0 263.02
MAR   -1334.6  -215.23   1574.6       0 -4.19             -15.284   -166.00        0 160.85
APR   -1267.1  -203.83   1763.9       0 -13.4             -10.834   -306.26        0 37.899
MAY   -1190.1  -188.94   1870.4       0  0.85             -21.576   -471.20        0  0.502
JUN   -890.06  -143.27   1851.9       0 -12.6             -32.563   -772.98        0      0
JUL   -764.68  -122.82   2026.9       0 -2.26             -60.123   -1076.9        0      0
AUG   -801.14  -127.95   1965.9       0  2.52             -58.028   -981.40        0      0
SEP   -870.37  -138.59   1968.1       0  5.06             -27.918   -936.46        0      0
OCT   -992.82  -160.12   1496.5       0  7.19             -11.614   -358.89        0 19.546
NOV   -826.21  -142.44   887.83       0  16.9             -11.191   -85.422        0 160.05
DEC   -1025.7  -175.25   626.98       0  0.30             -20.746         0        0 594.37

TOT    -12113  -1979.1    17684       0 -0.04             -302.80   -5203.6        0 1914.5
```

Table C3 Calpas3 with 3/4 air change/hour infiltration rate including sunspace

APPENDIX D F-CHART

F-chart was run for the active system for the Boleyn home with gpm 6 gpm (.38 kg/s) and 4 gpm (.25 kg/s) as the minimum flowrate. A problem occured with the input value for the heat capacity of the solar storage tanks. The solar storage tanks have a heat capacity of 1790 kJ/^{o}C and m^2 of collector area. F-chart checks prior to the run the validity of the input values. The value of 1790 kJ/^{o}Cm$^2{}_c$ was regarded as too high and the therefore the runs were performed with 999 kJ/^{o}Cm$^2{}_c$. A check with 1200 kJ/^{o}Cm$^2{}_c$ (the highest acceptable value) showed that the efficiency of the active solar system does not increase significantly with heat capacities greater than 1000 kJ/^{o}Cm$^2{}_c$. Thus the given efficiences can be regarded as valid.

Table D1 and Table D2 gives the input and output parameters of F-chart for the Boleyn home. The input parameters for the collector efficiency and the heat exchanger efficiency were based on the data given from the producer. For further information it is refered to Beckman, Klein, Duffie; Solar Heating Design by the F-chart method (1977), John Wiley & sons Inc.

```
CODE        VARIABLE DESCRIPTION                              VALUE UNITS

  1 AIR SH+WH=1,LIQ SH+WH=2,AIR OR LIQ WH ONLY=3.         2.00
  2 IF 1,WHAT IS (FLOW RATE/COL.AREA)(SPEC.HEAT)?        12.23 W/C-M2
  3 IF 2,WHAT IS (EPSILON)(CMIN)/(UA)?...........         5.00
  4 COLLECTOR AREA...............................        39.90 M2
  5 FRPRIME-TAU-ALPHA PRODUCT(NORMAL INCIDENCE)..          .63
  6 FRPRIME-UL PRODUCT...........................         3.54 W/C-M2
  7 INCIDENCE ANGLE MODIFIER (ZERO IF NOT AVAIL.)          .00
  8 NUMBER OF TRANSPARENT COVERS.................         2.00
  9 COLLECTOR SLOPE..............................        60.00 DEGREES
 10 AZIMUTH ANGLE (E.G. SOUTH=0, WEST=90)........          .00 DEGREES
 11 STORAGE CAPACITY.............................       999.00 KJ/C-M2
 12 EFFECTIVE BUILDING UA........................     14500.00 KJ/C-DAY
 13 CONSTANT DAILY BLDG HEAT GENERATION..........     50000.00 KJ/DAT
 14 HOT WATER USAGE..............................       300.00 L/DAY
 15 WATER SET TEMP.(TO VARY BY MONTH,INPUT NEG.#)        60.00 C
 16 WATER MAIN TEMP(TO VARY BY MONTH,INPUT NEG.#)        11.00 C
 17 CITY CALL NUMBER.............................       132.00
 18 THERMAL PRINT OUT BY MONTH=1, BY YEAR=2......         2.00
   TYPE IN CODE NUMBER AND NEW VALUE
 ? 17
 ? 183
   TYPE IN CODE NUMBER AND NEW VALUE
 ? R
  PORTLAND        OR   45.60

  ****THERMAL ANALYSIS****
   TIME PERCENT INCIDENT HEATING WATER DEGREE AMBIENT
          SOLAR    SOLAR    LOAD  LOAD  DAYS    TEMP
                   (GJ)     (GJ)  (GJ) (C-DAY)  (C)
   YR     66.3    173.73   23.62 22.48  2662.
```

Table D1 F-chart with 6gpm as minimum flowrate

```
 TYPE IN CODE NUMBER AND NEW VALUE
? 3
? 3
 TYPE IN CODE NUMBER AND NEW VALUE
? R
 PORTLAND        OR   45.60

 ****THERMAL ANALYSIS****
  TIME PERCENT INCIDENT HEATING WATER DEGREE AMBIENT
         SOLAR    SOLAR    LOAD  LOAD  DAYS    TEMP
                  (GJ)     (GJ)  (GJ) (C-DAY)  (C)
  YR     66.1    173.73   23.62 22.48  2662.
```

Table D2 F-chart with 4gpm as minimum flowrate

APPENDIX E CALCULATIONS OF TANK LOSSES

E1 Calculated design losses

The losses of the storage tank is given by EQ. E.1. In this approach losses from the piping are not considered.

$$Q = U*A*(T_t-T_e)$$
EQ. E.1

Q: Design heat loss from the storage tanks
U: Overall U-factor=1/R. R is 19 hrft^{2}F/Btu plus 1 hrft^{2}F/Btu for the outside surface. Therefore U is .05 Btu/hrft^{2}F (.28 W/m^2°C).
A: Total surface area of all three tanks. Each tank is 6 ft in diameter and 6 ft tall. Thererfore total area $\pi/2 *6^2+\pi *6*6=170$ ft^2. The top is atually spherical shaped and by considering some thickness for the insulation A is taken to be 180 ft^2 (16.7 m^2). For all three tanks A is 510 ft^2 (47.4 m^2)
T_t: Averaged tank temperature.
T_e: Enclosure temperature.

The design losses of the storage tanks are then a function of the enclosure temperature and the tank temperature, only.

Equation 6.8 gives the relation

$$Q = 25.5*(T_t-T_e)$$
EQ. E.2

E2 Actual losses

All the energy flowing to the storage tanks and all the energy leaving the storage tanks are known. Futheremore the temperature of the storage tank is known. Hence the losses can be determined.

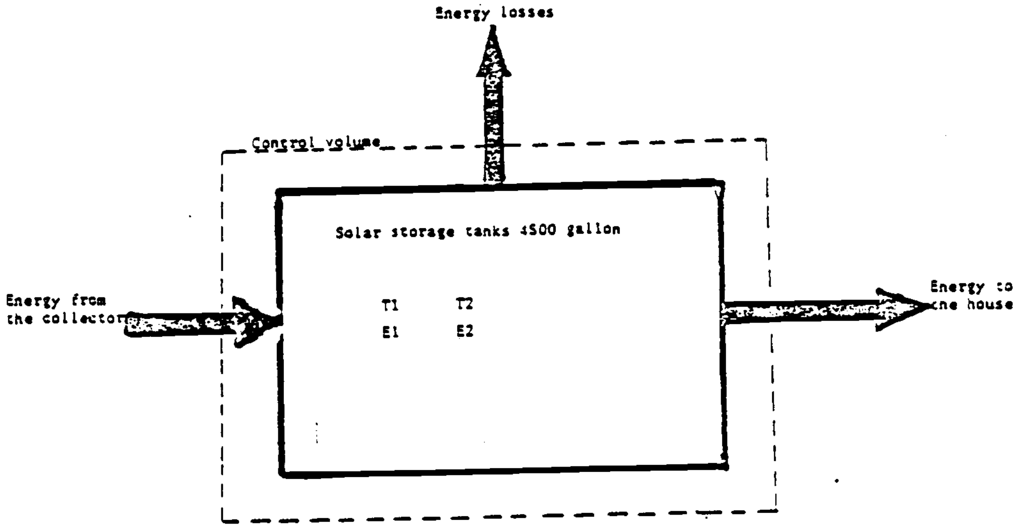


Fig. E.1 Actual losses from the solar storage tanks

Taking the storage tank as a a control volume (Fig. E.1) the change in internal energy can be calculated by equation E.3:

$$E_2-E_1 = BTS-BTH-BA$$

EQ. E.3

E_2: Internal energy of the tanks at time 2 and temperature 2
E_1: Internal Energy of the tanks at time 1 and temperature 1
BTS: Energy to the storage tanks from the collector during the time interval
BTH: Energy from the storage tanks to the house during the time interval
BA: Actual occuring losses from the solar storage tanks during the time interval

If all pressure changes in the system are neglected the final and initial state of the tanks are a function of the temperature only.

$$E_2-E_1 = c_w*p*V*(T_{t2}-T_{t1})$$
EQ. E.4

c_w: Specific heat capacity of water 1 Btu/lbmF (4.18 kJ/kg°C

p: Density of water 62.4 lbm/ft^3 ($1*10^3$ kg/m^3)

V: Volume of the three tanks 501.3 ft^3 (14.2 m^3)

T_{t2}: Tank temperature at time 2

T_{t1}: Tank temperature at time 1

By combining EQ. E.3 and EQ. E.4 the actual losses from the solar storage tanks are given by:

$$BA = BtS - BTH - 31280\ Btu/F * (T_{t2}-T_{t1})$$
EQ. E.5

E3 Losses including the pipes and lacking insulation

$$UA_{tot} = UA_{ti} + UA_{tb} + UA_{pi} + UA_{pb}$$
EQ. E.6

UA_{tot}: Total UA-factor

UA_{ti}: UA-factor of the insulated tank as calculated in section 6.1: 25.5 Btu/hrF (13.45 W/^{o}C)

UA_{tb}: UA-factor of the uninsulated portions of the tank = 1/R. The resistance is the serial resistance of the tank and the outside surface. The tank resistance can be neglected compared to the convective term of the outside surface. The U-value for the outside convection is between 1 and 5 Btu/hrft^{2}F (L 6.1). Since the tank room is mostly closed and almost no draft occurs U is chosen to be 2 Btu/hrft^{2}F (11 W/m^{2o}C). The total UA-factor is then 2*11 = 22 Btu/hrF (11.6 W/^{o}C) because 11 ft^{2} are uninsulated.

UA_{pi}: UA-factor for the insulated part of the pipes.30 ft of pipes with 1" in diameter and 75% of R-5 duct insulation gives an overall UA of 30*2*pi*1/12*1/5*.75 = 2.4 Btu/hrF (1.3 W/^{o}C)

UA_{pb}: UA-factor for the uninsulated part of the pipes. The same U-value as for the not insulated part of the tanks 2 Btu/hrft^{2}F. The UA-factor turns out to be: 30*2*pi*1/12*2*.25 = 7.9 Btu/hrF (4.2 W/^{o}C)

The calculated overall UA-factor, considering the losses from the tank, from lacking insulation and from the pipes is 58 Btu/hrF (30.6 W/^{o}C).

Appendix F ENERGY DATA

Appendix F gives the justification that in section 4 the energy from the solar storage tanks (#4 in Fig. 4.1) plus the energy from the auxiliary storage tank (#5 in Fig 4.1) was used for the energy delivered to the house rather than the energy through the air duct system (#3 in Fig. 4.1). The flowmeter in the air duct system recorded an airflow correctly only when the fan was run over a period of time.

Hour	To the house	From aux.	From solar
00			
01			
02			
03			
04			
05			
06			
07			
08	14893	4668	16807
09	15684		15640
10	12121		12605
11	6760		700
12			
13			
14			
15			
16			
17			
18			
19			
20	2108	3968	3735
21	3688	233	5835
22	5758		8637
23	3342		4201

Table F1 Hourly integrated energy data

Table F1 shows a hourly printout during a heating period in February 1977. The sum of the energy from the solar storage and the auxiliary storage at the beginning of the heating period was much larger than the energy measured through the air duct work. After the fan was run for a time the energy through the air duct work approached the sum of the auxiliary tank and the solar storage tank.

In addition flowrates in the water system can be determined more accurately than flowrates in the air system.