1977

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Socha, L. S. and McGowan, John G., "Instrumental and Initial Experimental Testing of Solar Habitat I" (1977). *Wind Energy Center Reports*. 18.
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UM-WF-TR-77-8

INSTRUMENTATION AND INITIAL EXPERIMENTAL TESTING OF SOLAR HABITAT I

Technical Report

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July 1977

Prepared for

THE U.S. ENERGY RESEARCH AND DEVELOPMENT
ADMINISTRATION UNDER CONTRACT NO. E(49-18)2365

NOTICE

ABSTRACT

This report presents a description of the analytical and experimental procedures used to determine the performance of all subsystems and models for Solar Habitat I. It includes a description of the instrumentation necessary for evaluating all subsystems and models and the corresponding test methods used. Experimental test data is presented and compared with the results based on previously developed analytical models.

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CHAPTER I

INTRODUCTION

1.1 Background

Solar Habitat I is located on top of Orchard Hill at the University of Massachusetts, Amherst Campus. The dwelling was designed and constructed by Professor Curtis Johnson of the University of Massachusetts Agricultural Engineering Department. The structure is a 32 ft by 48 ft well-insulated, prefabricated house. Originally, the design of Solar Habitat I was to be a single story, one family home with no basement. In 1975 a group of professors from the UMass Energy Alternatives Program began working with Professor Johnson to integrate an alternative heating system into Solar Habitat I. In order to incorporate and evaluate this energy system, a laboratory and provision for large thermal energy storage were required. Thus, a basement and five concrete water storage tanks ranging from capacities of 500 to 3500 gallons were added to the Solar Habitat I structure.

The alternative energy system under study at this location, called the New England Wind Furnace (NEWF) is designed to supply a large fraction of the residence's heating load via wind and/or solar thermal energy input. As described in Reference 1, this project, under the direction of Professor William E. Heronemus, has been sponsored principally by the U.S. National Science Foundation (NSF) and the U.S. Energy Research and Development Administration (ERDA), along with several private donors. A basic goal of this project was the construction and demonstration of a 32.5 foot diameter wind turbine generator (WTG). The WTG specifically developed for this project (2) is a three bladed, variable pitch, down wind machine rated at 25 kW in a 26 mph windspeed. The energy produced from the WTG is variable voltage, variable frequency electricity, and is utilized by either dissipating it through electric baseboard convectors or through immersion heaters placed in a water storage tank. In addition, Solar Habitat I has 200 ft^2 of vertical flat plate solar collectors as an energy source. The double glazed collectors deliver thermal energy to the storage tank via a small heat exchanger. An auxiliary heat source using a 60,000 BTU/hr. propane fired, forced hot air furnace is also provided. Additional details concerning the design of the heating system are discussed in Reference 3. A photograph of Solar Habitat I is shown in Figure 1. Analytical studies of this system (1,4,5) predicted that the WTG combined with the solar collectors will supply 80% of the annual heating load.

After the completion of the heating system in August 1976, the tasks of instrumentation and experimental testing of the Solar Habitat I system remained. It is the purpose of this work to discuss the implementation of these tasks, the experimental results, and how these results compare to those predicted from the initial analytical modeling.

1.2 Objectives

The primary objective of this project was to conduct preliminary tests to evaluate the performance of the subsystems and compare these results to analytical results. Before this goal could be achieved, there was a considerable amount of preparatory work that had to be accomplished. These tasks included installation and testing of the instrumentation needed to monitor the performance of the overall systems and all subsystems, purchasing and installation of a data acquisition system which would interface with the UMass time-sharing computer system, and documentation

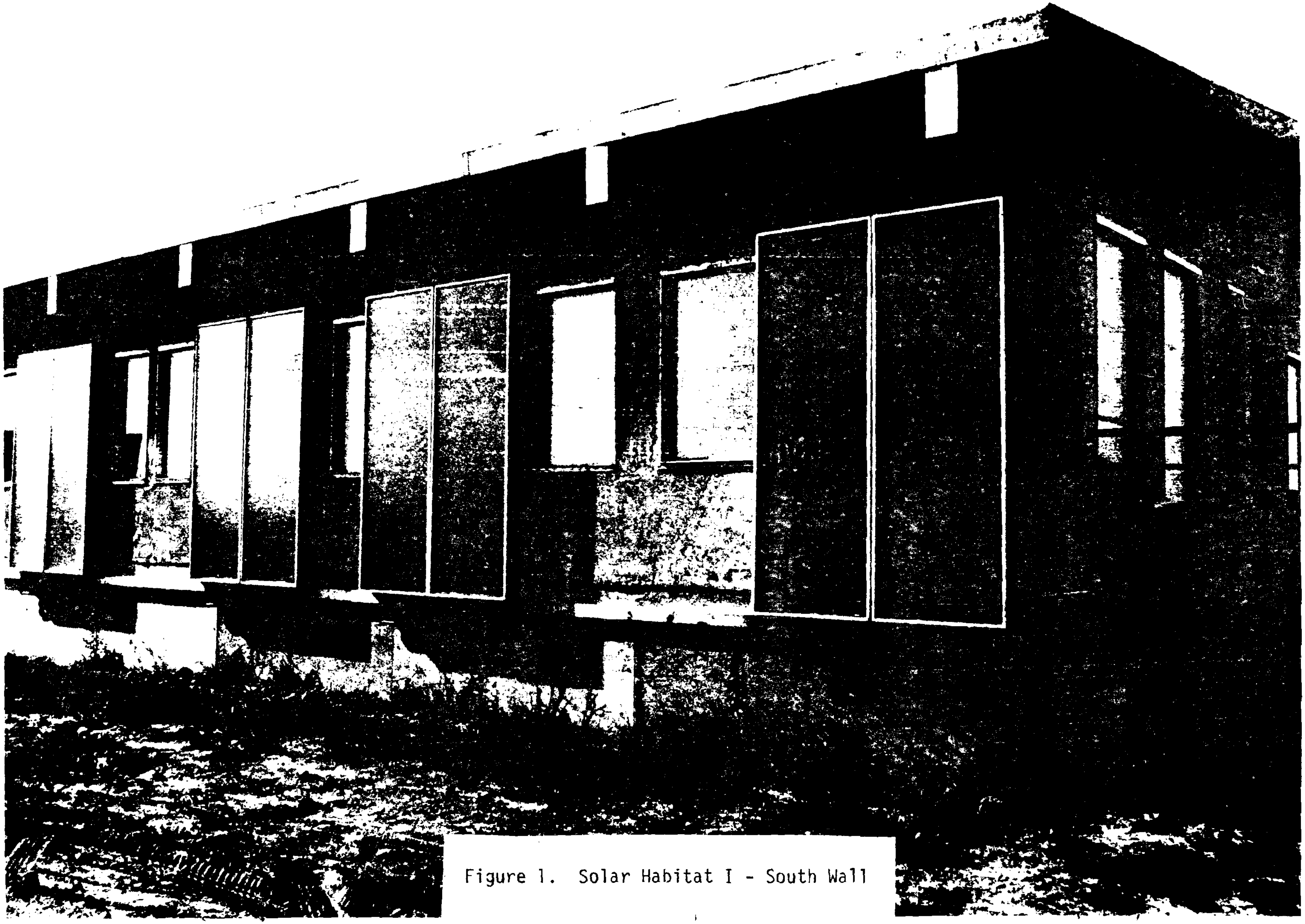


Figure 1. Solar Habitat I - South Wall

of all test methods to be used for the experimental tests. After these preparations were completed, the necessary tests were conducted and the data summarized using appropriate data reduction programs. The reduced data could then be compared to previous analytical work.

CHAPTER II

HEATING SYSTEM DESIGNS

2.1 Descriptive Summary of Models

The New England Wind Furnace concept is focused on the use of a 32.5 foot diameter, horizontal axis wind turbine generator (WTG). The basic principle is to change the energy from the wind into thermal energy. As mentioned earlier, the wind energy is first changed to variable frequency, variable voltage electricity. This electrical energy is changed to thermal energy by dissipating the electricity through electric baseboard convectors or immersion heaters placed in large water storage tanks. Future designs are proposed where the wind energy is changed directly to thermal energy by means of a mechanical churn, thus eliminating the creation of electricity. A plot of the heating demand for an "Average" New England home showing the available solar energy for 200 ft^2 of vertical surface, and the amount of energy which can be produced from a 32.5 ft diameter WTG using Bradley Field (Hartford, Conn.) wind data as a function of the time of year is illustrated in Figure 2 (1,4). From this graph it can be seen that the potential energy which can be captured from the wind and sun is large enough to pursue further investigation of the Wind Furnace concept. To determine how this concept can be utilized in the most effective manner, several heating system configurations have been proposed. Four of these models, each installed in Solar Habitat I (3) are described in the succeeding paragraphs.

2.1.1 Model 1A.

In Model 1A (Figure 3) the electricity generated from the WTG is fed to a load controller in the basement of

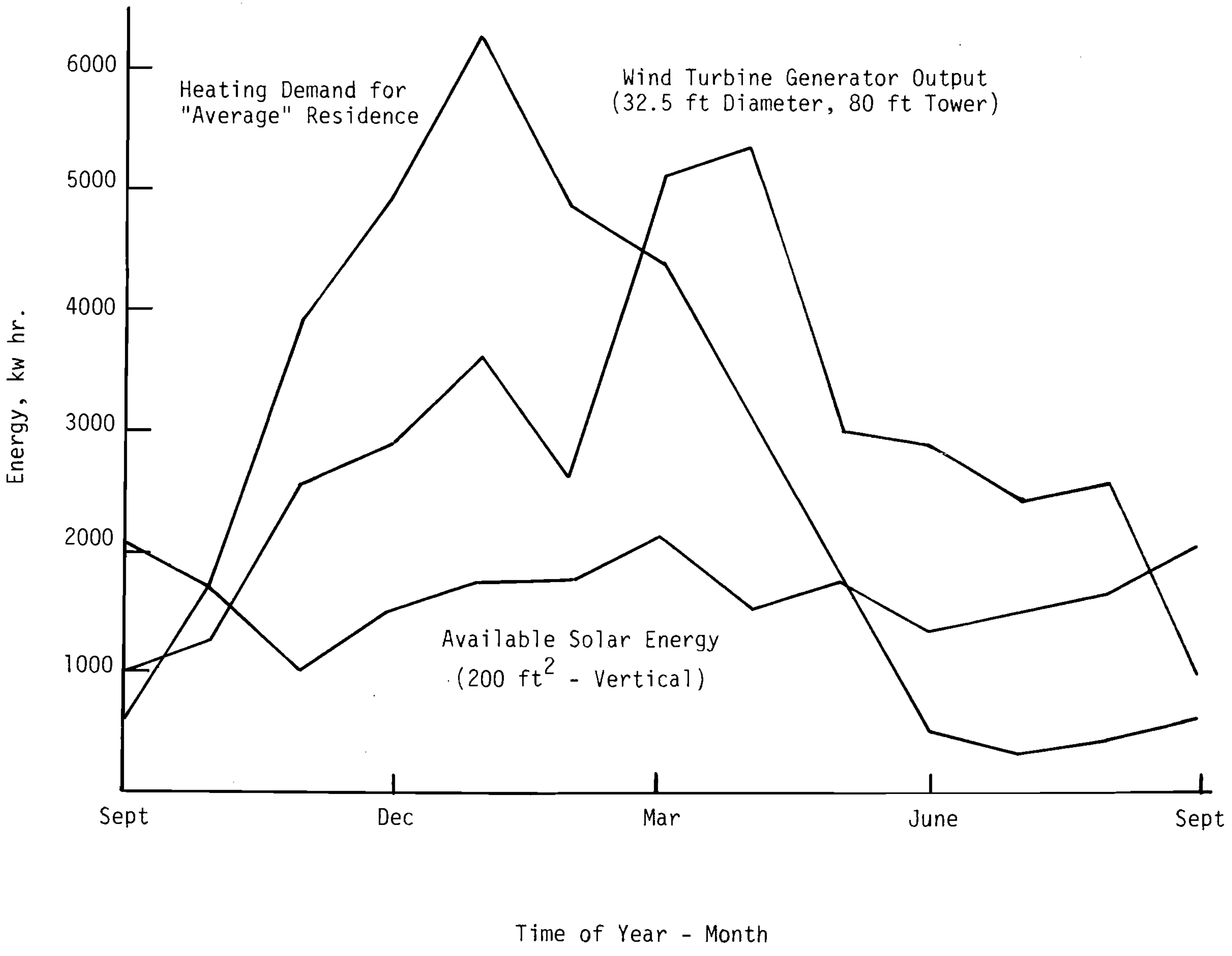


Figure 2. Energy Inputs and Heating Load

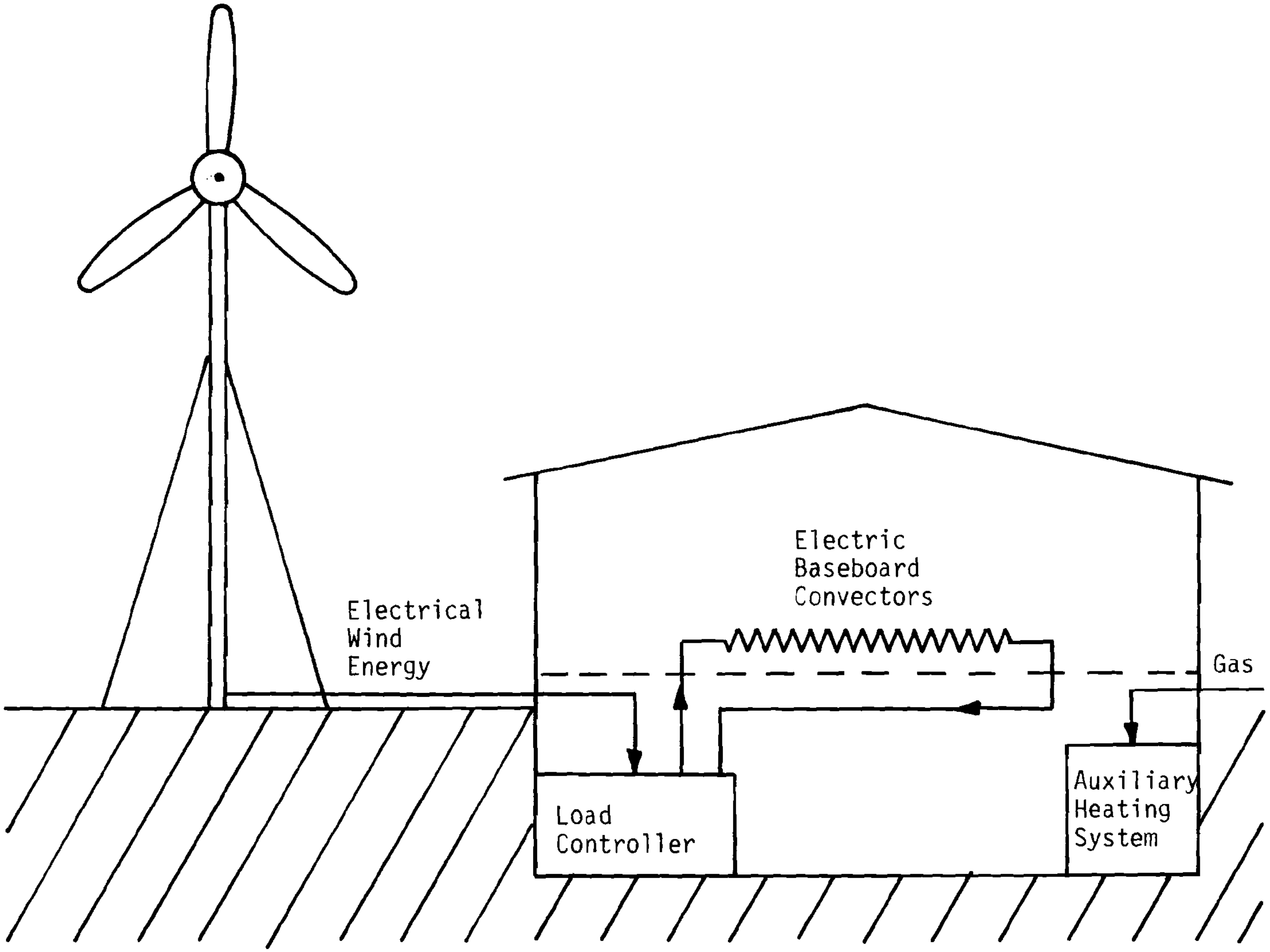


Figure 3. Model 1A - Wind Turbine Generator, and Electric Baseboards (No Storage)

Solar Habitat I. When there is a demand for heating and wind energy is available, the elctricity from the WTG is dissipated through electric baseboard convectors located in the basement and main floor of Solar Habitat I. In a situation where there is a demand for heating but no wind energy available, the auxiliary hot air furnace is used to supply the heating needs. If there is no heating demand, the wind energy is lost as the central logic system feathers the wind turbine's blades. From analytical studies, the "Average" New England home (17,000 BTU/°F day) which incorporates Model 1A for heating and has a wind regime similar to Bradley Field wind data will be supplied with approximately 33% of its heating (1). From experimental and analytical work (to be discussed later) it was estimated that the heating load of Solar Habitat I is 8,000 BTU/°F day. With this heating load, analytical modeling predicts that 54% of the load would be supplied by Model 1A.

2.1.2 Model 2. This model (Figure 4) incorporates a storage medium into the wind system. In this model, the electricity produced from the wind is dissipated through immersion heaters which are in large water storage tanks. The size of the storage tanks can vary from 500-3500 gallons. If there is a demand for heating and thermal energy is available in the storage tanks, water is pumped from the storage tanks through baseboard convectors. If the energy in the storage tanks is not great enough to supply the heating demand, the auxiliary hot air furnace is used to supply the demand. The analytical studies predict that with this system, 70% of the heating load will be supplied for the "Average" New England home (17,000 BTU/°F day) and 100% will be supplied for Solar Habitat I (8,000 BTU/°F day).

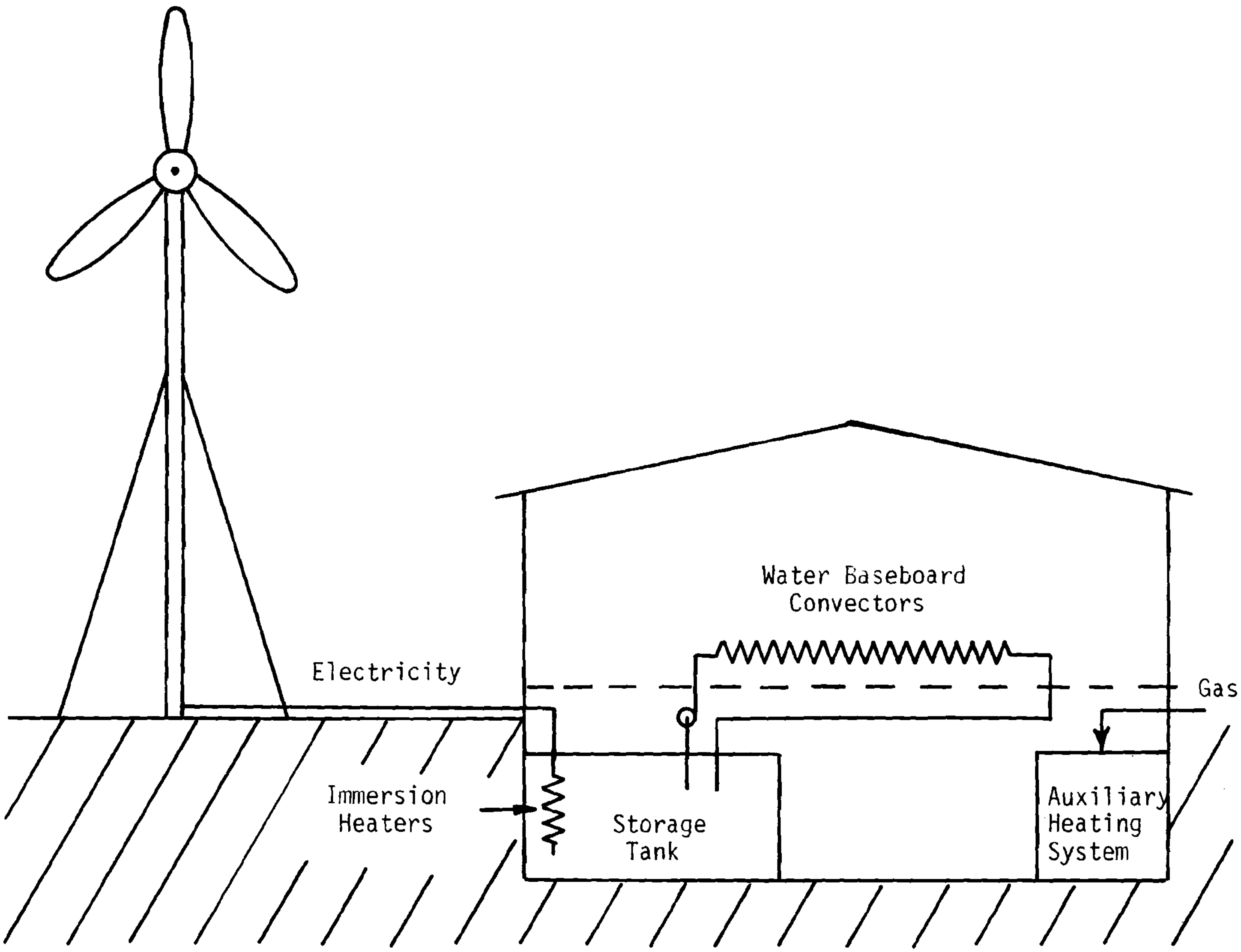


Figure 4. Model 2 - Wind Turbine Generator, Water Storage and Water Baseboards

2.1.3 Model 3A. This model (Figure 5) utilized both wind and solar energy. The energy from the solar collectors is transferred to a large thermal system via a heat exchanger. In the same tank the energy from the WTG is dissipated through immersion heaters. When there is a heating demand, the energy in the storage tanks is then distributed to Solar Habitat I. If there is not sufficient energy in the storage tank to meet the heating demand, the auxiliary hot air furnace is utilized. The analytical studies predict that with this model, 80% of the heating demand will be supplied for the "Average" New England home (17,000 BTU/°F day) and 100% for Solar Habitat I (8,000 BTU/°F day).

2.1.4 Model 3B. In Model 3B (Figure 6) the energy from the flat plate solar collectors is stored in water storage tank I, and the wind energy is dissipated into water storage tank II. When there is a heating demand, the energy from storage tank I is then distributed to Solar Habitat I by baseboard convectors. If the temperature of storage tank I falls below a fixed level, storage tank II will then be used for heating. If both tank I and tank II together do not supply sufficient energy to meet the demand, the auxiliary hot air furnace will be used to supply the needed energy. Analytical results predict that approximately 80% of the total heating load will be supplied to an "Average" size residential home (17,000 BTU/°F day) and 100% will be supplied to Solar Habitat I (8,000 BTU/°F day).

2.2 Subsystem Description and Analytical Modeling

In order to better evaluate the performance of the previously discussed models, it is essential to first determine the performance of each subsystem involved. These subsystems include the piping system,

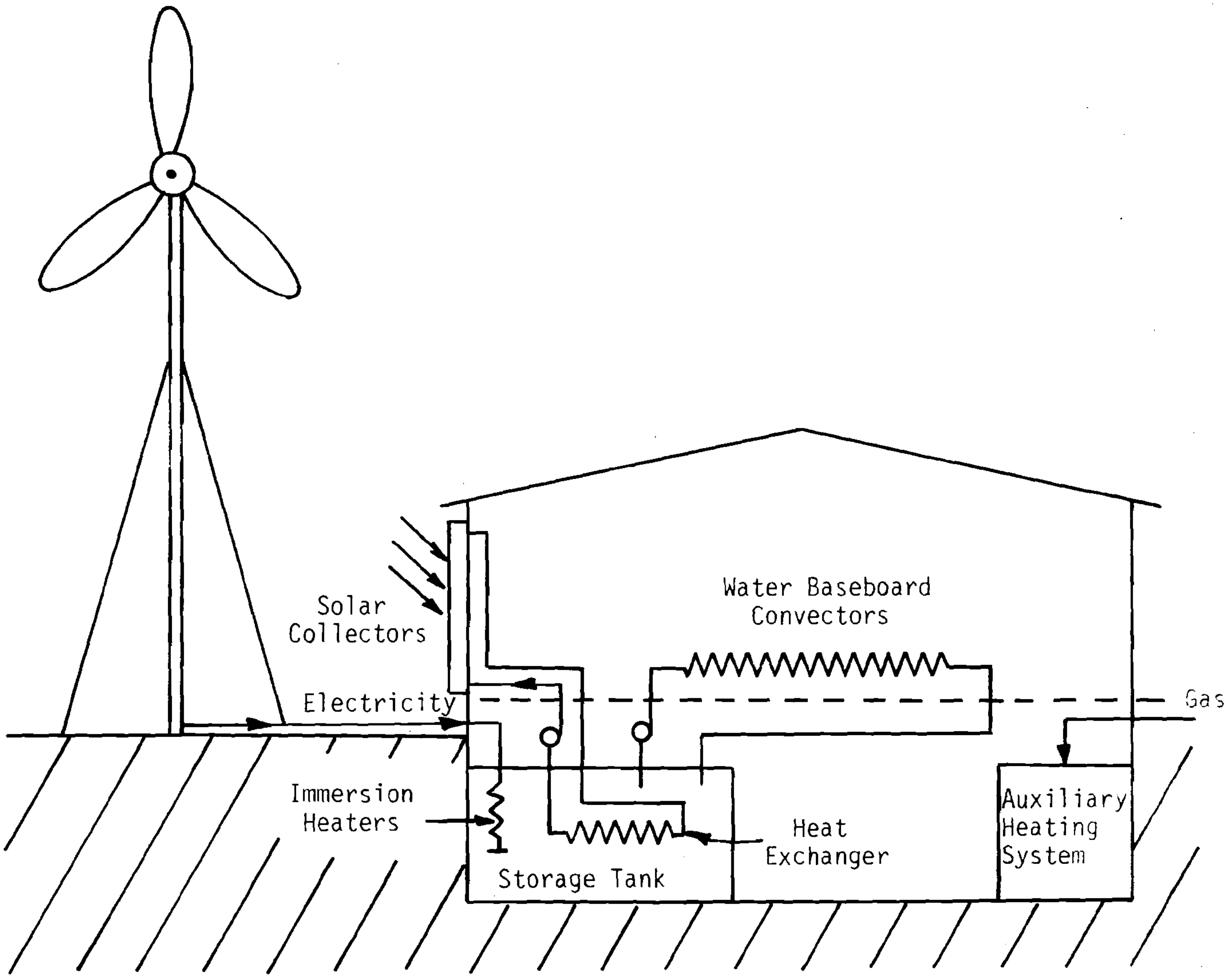


Figure 5. Model 3A - Wind Turbine Generator and Solar Collectors with Water Storage and Baseboard Convectors

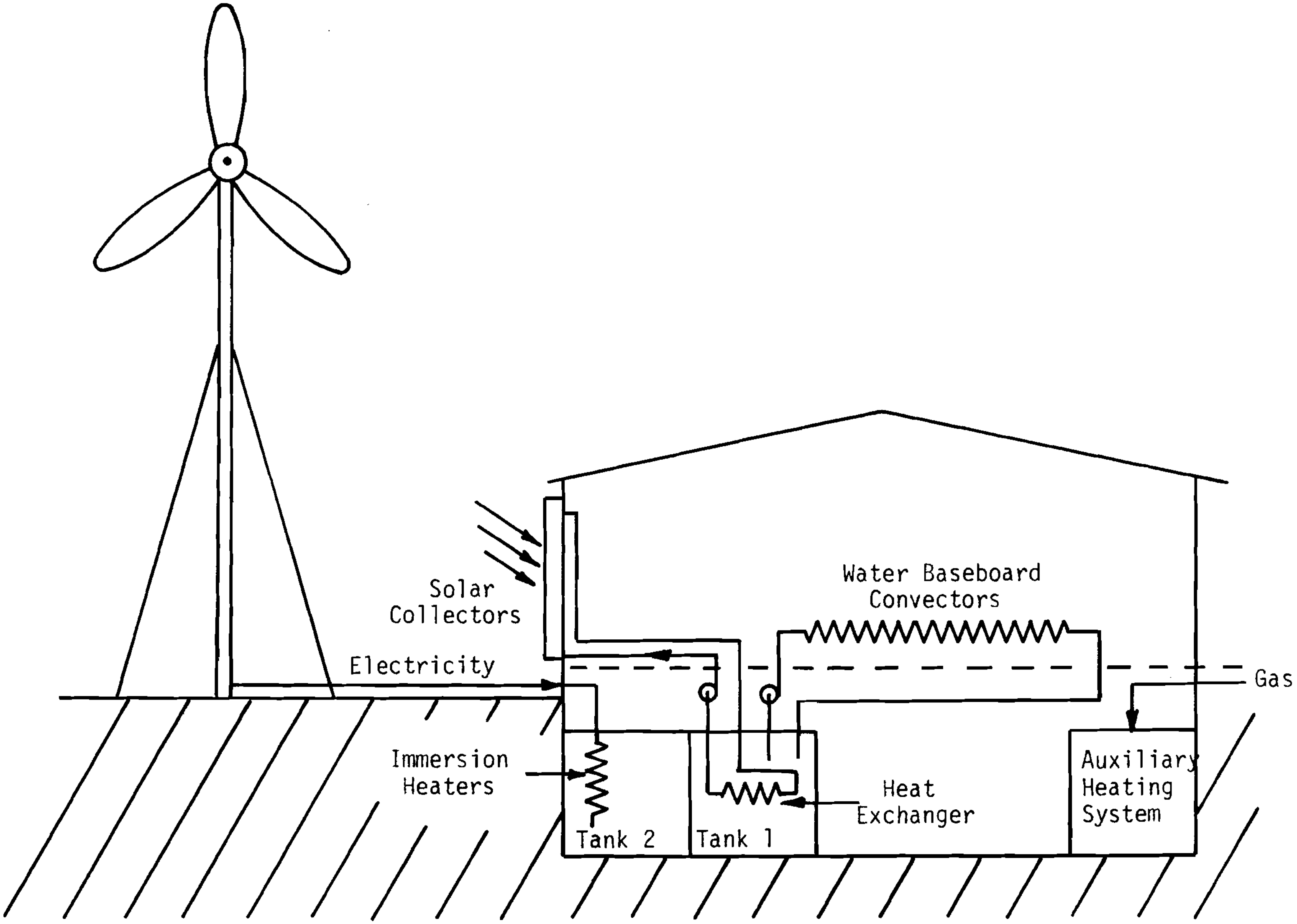


Figure 6. Model 3B - Wind Turbine Generator and Solar Collectors with Separate Storage and Baseboard Convectors

the storage tanks, the solar collectors, the heat exchanger, the baseboard convectors, the wind turbine generator (WTG), the hot air heater, and the residence itself, Solar Habitat I. A description of each of the subsystems and the analytical work previously conducted to predict their operation is provided below.

2.2.1 Piping. The piping subsystem includes all of the pumps, flow meters, and pressure gauges necessary for the solar collector loop and the baseboard convectors. (Note: The solar collector loop is defined as the combination of the solar collectors, the heat exchanger, and the storage tank.) Five pumps are utilized in this subsystem: three are used for the baseboard convector loops, one is used to pump a propylene-glycol water mixture through the collectors, and one is used to pump water from the storage tank through the heat exchanger in the solar collector loop. Five flow meters are utilized: three in the baseboard convector loops, one to measure the flow rate through the collectors, and one to measure the flow rate through the tank side of the heat exchanger. Six pressure gauges are located at various positions in the solar collector loop. These are essentially installed to monitor information from the collector loop and to help evaluate any problems in the system. More details on the piping subsystem can be found in Reference 3.

2.2.2 Storage Tank. There are five concrete storage tanks in the basement of Solar Habitat I. They include a 500 gallon storage tank, two 1000 gallon storage tanks, a 2000 gallon storage tank, and a 3500 gallon storage tank. For more details on the construction specifications of the storage tanks, see Reference 3. To date, only one of the 1000 gallon storage tanks has been fully insulated and calibrated. Details of the insulation used for this storage tank are shown in Figure 7. The

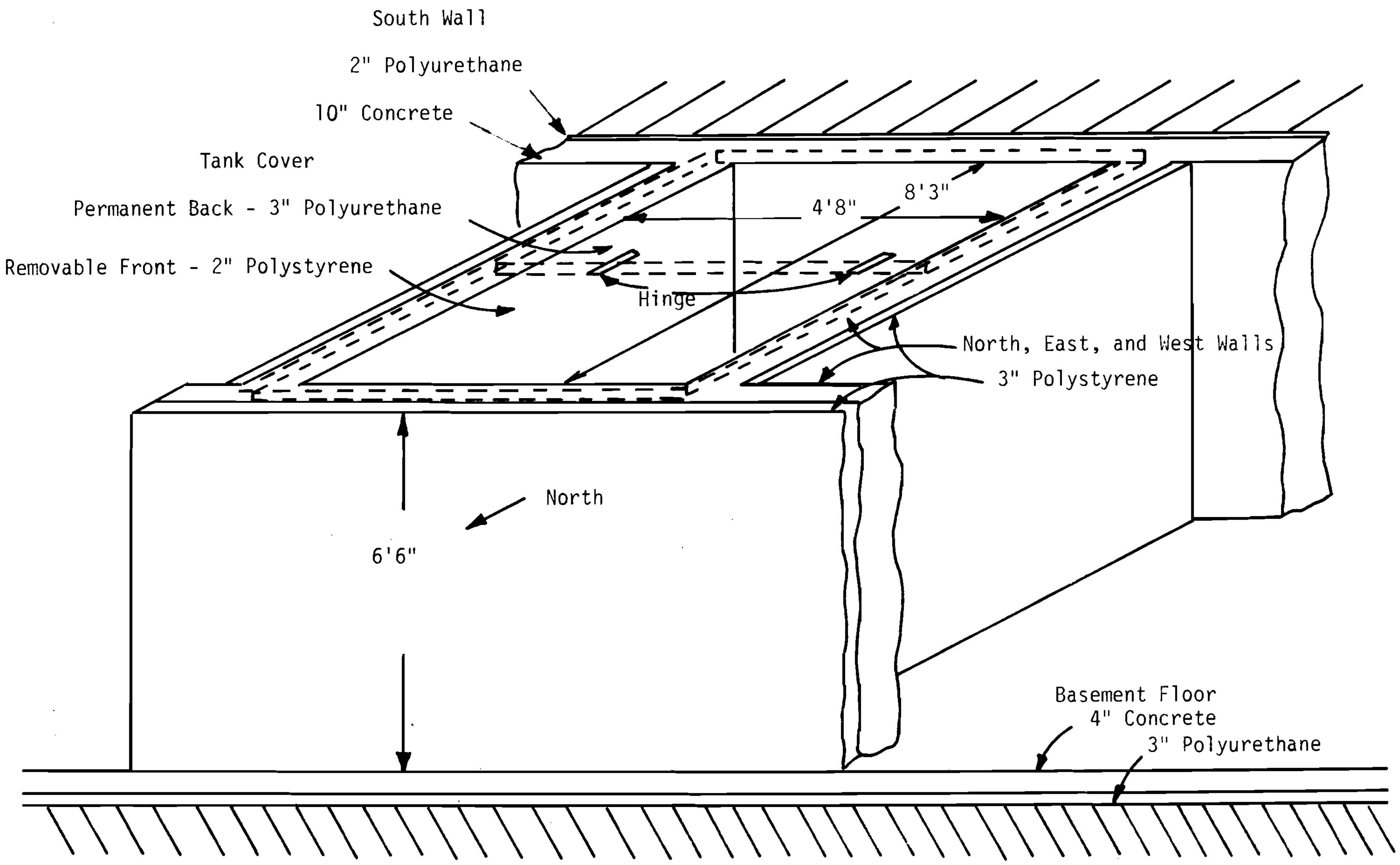


Figure 7. One Thousand Gallon Storage Tank Design

amount of water this tank can hold if filled to the top exceeds 1000 gallons of water, and to minimize the tank's heat loss per gallon of water, the tank was filled to the top. This increased the capacity of the tank to approximately 1700 gallons and decreased the heat loss per gallon of water by an estimated 32%.

The initial analytical modeling of the tank was obtained from using a simple one dimensional heat transfer model. In the computer simulation of the solar house (4), the tank losses were calculated according to the following equation

$$\dot{Q}_t = A_s U_t (T_s - T_a) \qquad (1)$$

where

$\dot{Q}_t$ = Rate of heat transfer from the tank

A_s = Surface area of tank

U_t = Overall heat transfer coefficient of the tank

T_s = Temperature of the water in the storage tank

T_a = Ambient basement temperature (65°F)

See Appendix A for calculation of A_s and U_t. After numerical substitution Equation (1) can be written as

$$\dot{Q}_t \text{ (BTU/hr)} = -774.87 + 11.92\, T_s(°\text{F}) \qquad (2)$$

It should be noted that this initial analysis assumed the ambient temperature around the storage tank is 65°F, the tank temperature is uniform, the heat transfer is one-dimensional, the insulation around the tank has the same resistance value, and the surface area of the tank is equal to the surface area needed to fill a cubic tank to 1000 gallons.

In order to improve the accuracy of the analytical model for the storage tanks, the following more detailed model was formulated. Applying one dimensional heat transfer approximations for separate parts of the tank, the total heat loss from the tank can be expressed by:

$$\dot{Q}_t = U_E A_E\,(T_s - T_a) + U_W A_W (T_s - T_a) + U_N A_N (T_s - T_a) + U_T A_T (T_s - T_a) + U_B A_B (T_s - T_b) + U_S A_S (T_s - T_g) \qquad (3)$$

where the subscripts W, E, S, N, T, B = west, east, south, north, top, and bottom sides respectively,

and

U = Overall heat transfer coefficient for the respective sides

A = Area of the respective sides

T_b = Temperature of the ground below the tank (assumed at 55°F)

T_g = Average temperature of the ground on south wall which is assumed to be $\frac{\text{avg ambient temp} + 55°\text{F}}{2}$

Appendix A includes details of the numerical calculations for this model. After substitution, the governing analytical equation reduces to:

$$\dot{Q}_t\ (\text{BTU/hr}) = -873.04 + 14.43\ T_s (°\text{F}) \qquad (4)$$

A plot of the rate of heat transfer for both analytical models as a function of temperature within the storage tank is shown in Figure 8.

As can be seen from Figure 8, the improved model predicts a higher rate of heat transfer than previous analytical work. This is due to the inclusion in the analysis of the actual dimension of the tank, the actual overall heat transfer coefficients, and an estimation of the ground temperatures surrounding the tank.

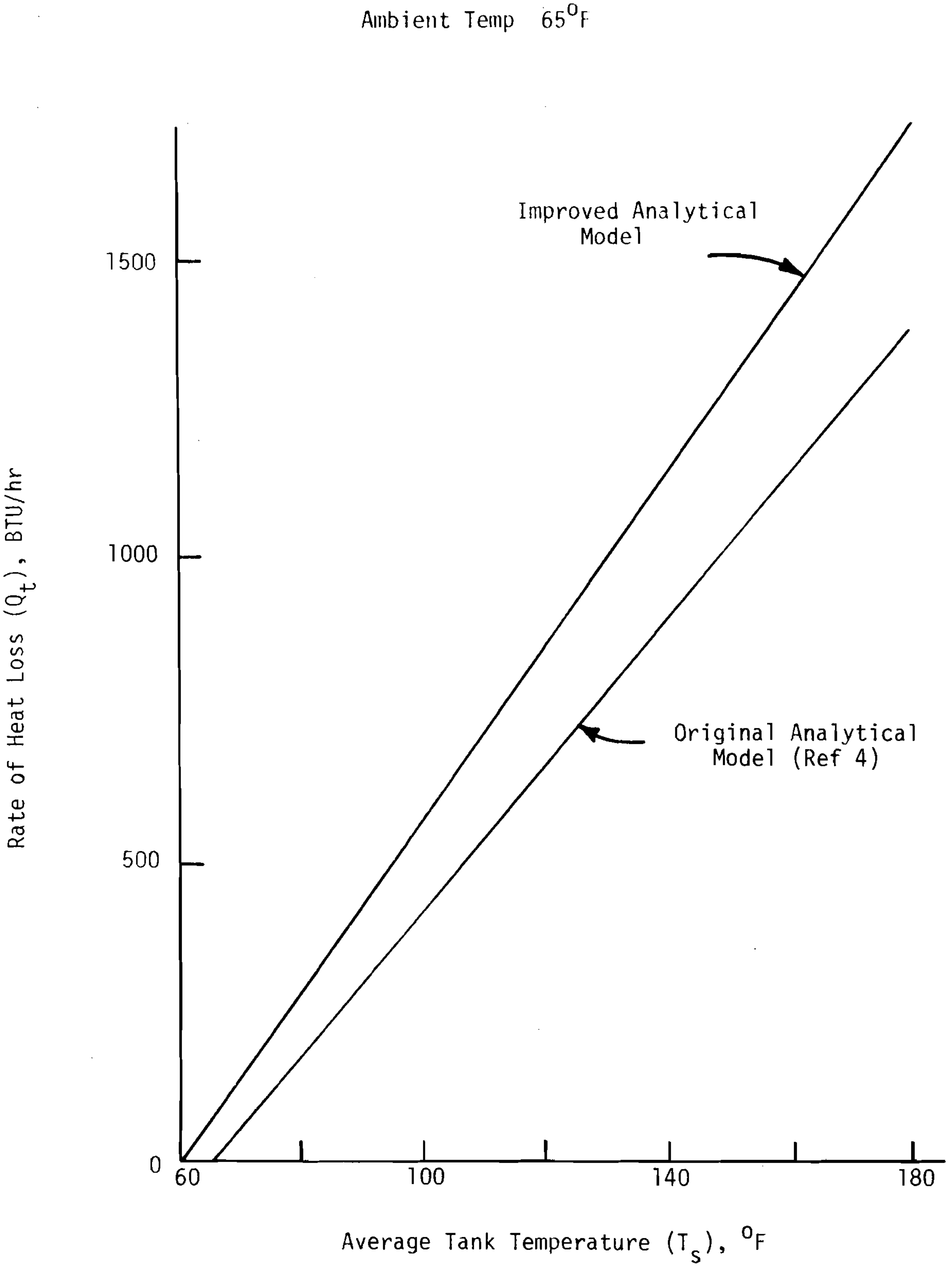


Figure 8. Predicted Heat Loss Rate from the Storage Tank

To better evaluate the storage tank subsystem an estimate of the portion of thermal energy lost from the storage tank to the ground was desired. This value was estimated to be the sum of the overall heat transfer coefficients of the walls exposed to the earth, $U_S + U_B$, divided by the overall heat transfer coefficient for the entire tank. From the more detailed model the overall heat transfer coefficient for the entire tank is the slope of the curve in Figure 8 or 14.43 BTU/hr °F. Using this approach, the results obtained predict that 29% of the heat transferred from the tank is lost to the ground.

2.2.3 Solar Collectors. A schematic of the solar collector loop is shown in Figure 9. The solar collector system for Solar Habitat I consists of 200 ft^2 of vertical flat plate collectors. These collectors have a black copper absorber plate with a double glazing system (1/8 in water white tempered glass and one layer of Tedlar). The collector system is a closed loop with the heat transfer fluid being a 60/40 mixture of propylene-glycol and water. The energy obtained from the sun is then transferred to the storage medium via a heat exchanger.

The analytical modeling of the collectors is essentially based on the method presented in Duffie and Beckman (6). The overall heat transfer coefficient throughout the cover system, U_{cc}, was calculated by the method of Whillier (7) for a glass and Tedlar cover system. A listing of the computer model called "Dixon 1" is in Appendix B. Three different plots of efficiencies generated by the model with varying ambient temperatures are shown in Figure 10. The slope of these curves is $F'U_1$, where F' is the collector efficiency factor and U_1 is the overall heat transfer coefficient from the absorber plate to the ambient air. As can be seen, the slope of these curves is slightly dependent on the ambient temperature. The other

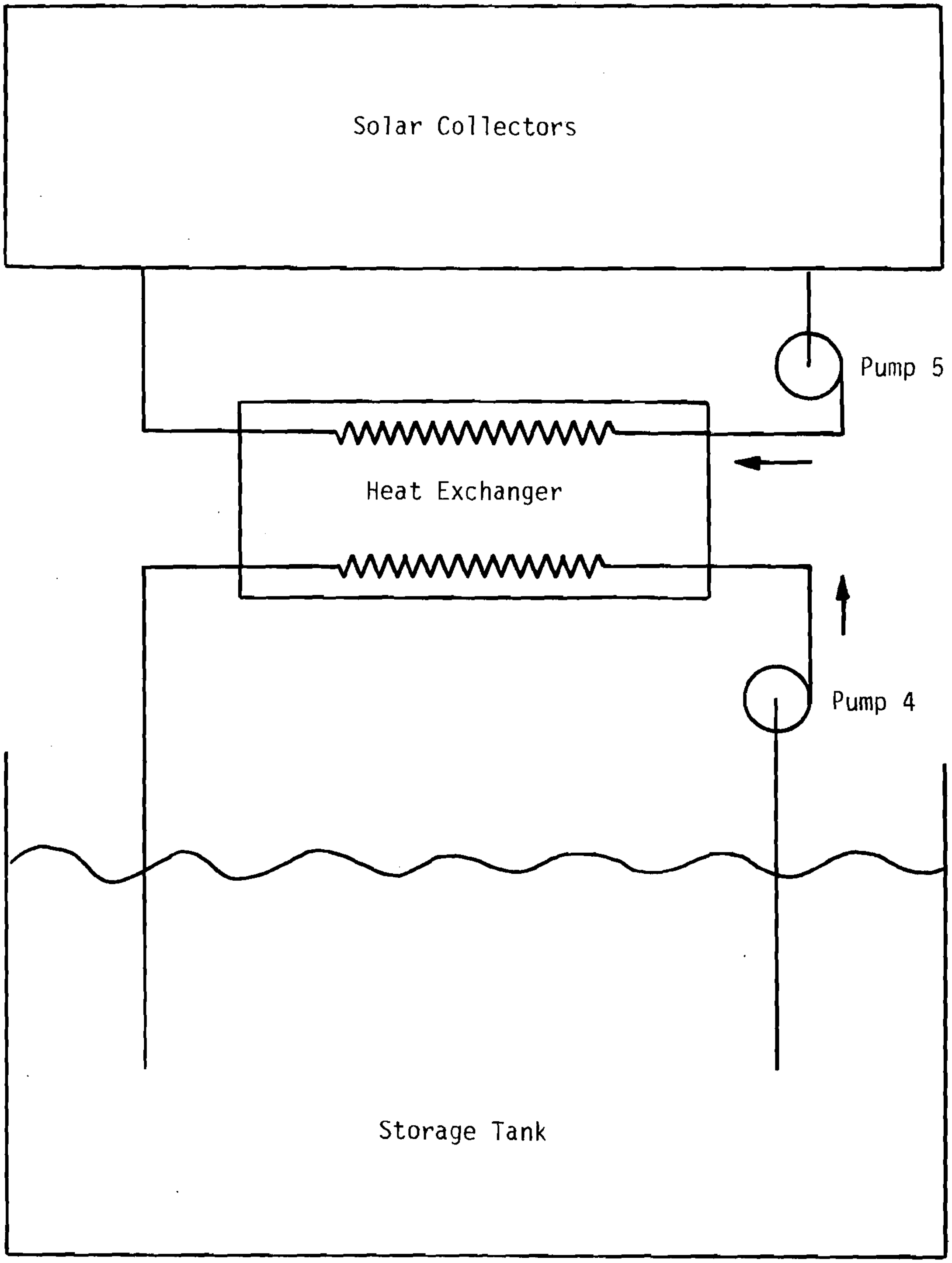


Figure 9. Solar Collector Loop

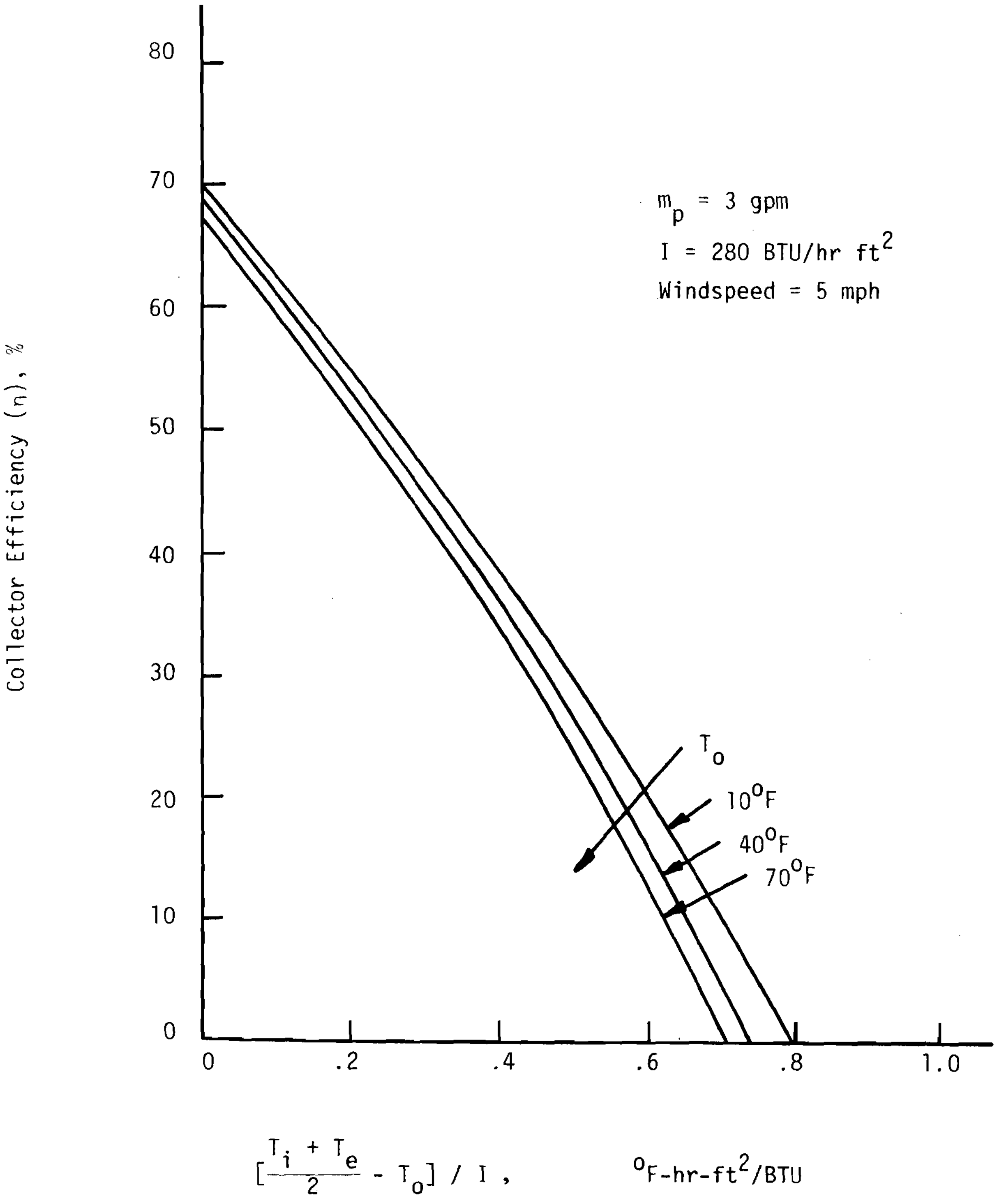


Figure 10. Analytical Performance of Solar Habitat I's Collectors

collector variables, which are flow rate and insulation rate, do not appreciably affect the slope of these curves. More details on the modeling and description of the solar system can be found in References (4) and (8).

2.2.4 Heat Exchanger. The heat exchanger used in the solar collector loop in Figure 9 is a shell and tube, two pass heat exchanger. The heat exchanger is rated for flow rates (water) of 2.4 gpm-19 gpm on the shell side (collector side) and 4.5 gpm-31 gpm on the tube side (tank side). The design flow rates for the heat exchanger were 2 gpm-4.5 gpm on the shell side and 16 gpm-25 gpm on the tube side.

The analytical model for this heat exchanger was done using the general effectiveness relationship (for a 2-pass heat exchanger) of Kraus and Kern (9). Based on an overall heat transfer coefficient, U_o = 300 BTU/hrft^2°F (10,11), the effectiveness as a function of the shell side flow rate can be determined for specified tube side flow rates. Figure 11 illustrates the predicted heat exchanger effectiveness as a function of shell side flow rate for a tube side flow rate of 18 gpm (8).

2.2.5 Baseboard Convectors. A total of fifty linear feet of baseboard convectors is installed in three loops (each with separate circulator pumps) in Solar Habitat I. Each linear foot of convector is comprised of two parallel flow elements. Hot water from the storage tank enters one element and returns to the storage tank through the other element. Two of the convector loops are on the main floor: one placed in the living area, which has a length of 16 linear feet, and the other placed in the kitchen, bedroom, and bathroom areas, with a total length of 18 linear feet. The third loop is located in the basement and has a length of 16 linear feet. Reference 3 contains more details of the

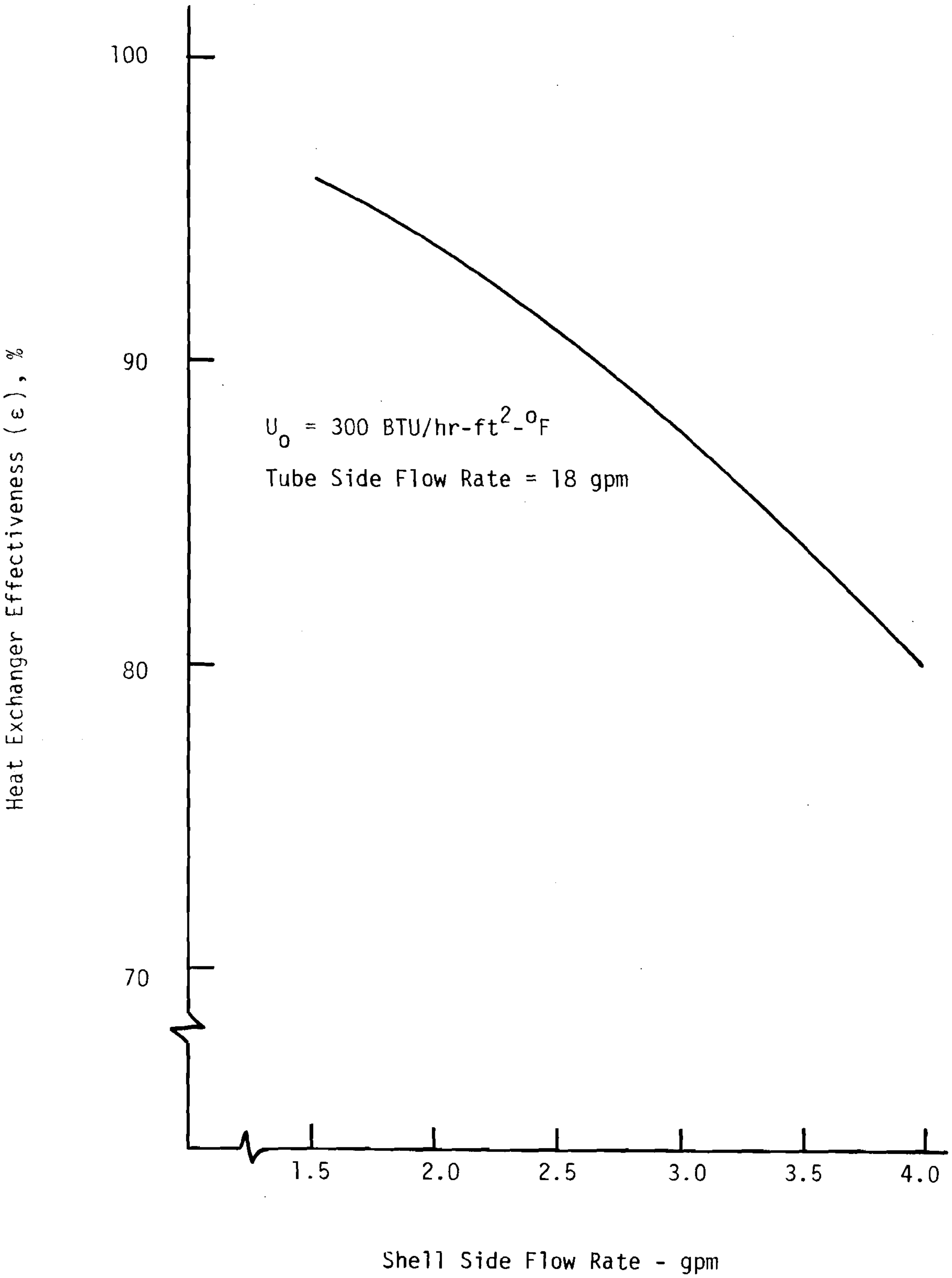


Figure 11. Predicted Effectiveness of Heat Exchanger

baseboard convector system.

Specifications from the manufacturer indicated that the normal operating range of an average water temperature to the convectors is between 160 - 220°F with a flow rate of 1 gpm. For Solar Habitat I, the operating range of the average water temperature to the baseboard convectors is expected to be between 80 - 190°F. Thus, the estimated performance of the convectors in Solar Habitat I had to be extrapolated from the dealer specifications. An overall thermal conductance of 1.43 $BTU/hrft^2{}^\circ F$ for the convector was estimated from the manufacturer's specification (12). Assuming that the outside heat transfer coefficient dominates the value for the coefficient of heat transfer, the following approximation applies (13)

$$U_c \alpha \ \Delta T_c^{\ 1.25} \tag{5}$$

where

U_c = Overall heat transfer coefficient of the baseboard convectors

ΔT_c = temperature difference between the fluid temperature and the ambient temperature (65°F)

From Equation 5 the performance curve of a one element convector can be calculated. Also, for the double element configuration, the manufacturer specified that the rate of heat transfer per foot of convector is only 1.3 times as great as that of the single element configuration (14). A summary of the predicted performance of the double element baseboard convectors, (the rates of heat transfer per linear foot of convector as a function of the average water temperature) is shown in Figure 12.

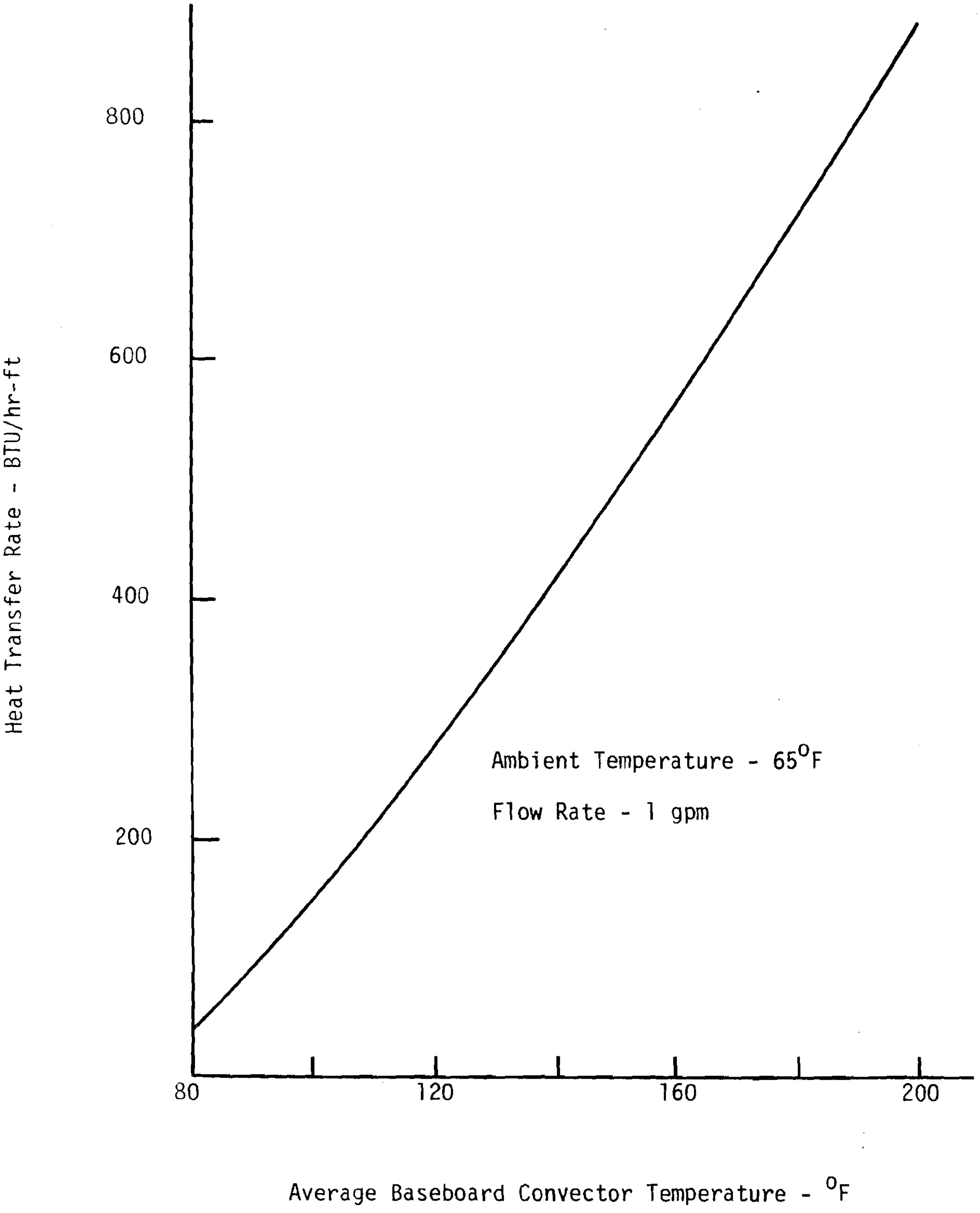


Figure 12. Predicted Performance of Baseboard Convectors

2.2.6 Wind Turbine Generator. The wind turbine generator is the main component of the New England Wind Furnace concept. It has a diameter of 32.5 ft with three near optimum shaped blades for maximum performance. The machine is of the downwind type and, at Solar Habitat 1 is placed atop a 60 ft guyed steel tower. This particular WTG is rated at 25 kW in a 26.1 mph windspeed and has variable pitch and variable generator excitation to optimize the power output for a given windspeed. The analytically predicted power output of the WTG is summarized in Figure 13 which illustrates the theoretical maximum power output from a WTG and the predicted power output as a function of windspeed. (For more details on the description of this WTG and the analytical modeling, see Reference 2.)

2.2.7 Auxiliary Hot Air Heater. The auxiliary heating system consists of a 60,000 BTU/hr forced hot air propane furnace. This furnace is utilized when there is neither sufficient solar nor wind energy available to supply the heating demand. When there is an energy demand, the auxiliary system forces hot air into the basement. The hot air then rises to the main floor through a one inch opening around the perimeter of Solar Habitat I. In the analytical modeling the efficiency of the hot air furnace was assumed to be 70% (4).

2.2.8 Solar Habitat I. Solar Habitat I is a 32 ft by 48 ft, well insulated, prefabricated structure. As calculated in Reference 4, the roof, walls, windows, doors and the basement of Solar Habitat I have overall heat transfer coefficients of .0192, .034, .062, .040 and .060 BTU/hrft^2°F, respectively. Figure 14 gives details on the types of insulation used in the house construction (15). In addition to extensive

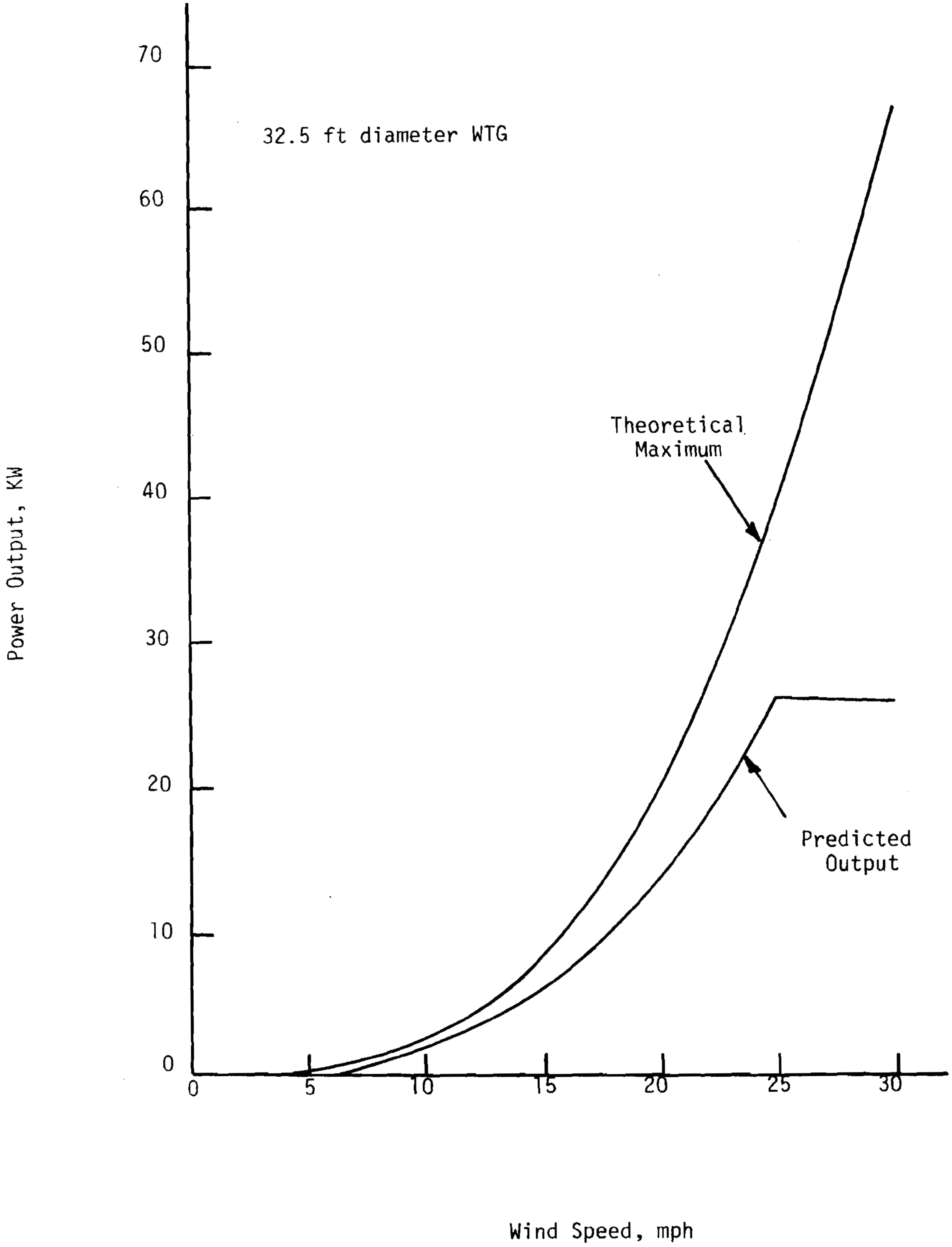


Figure 13. Comparison of the Theoretical Maximum and Predicted Power Output of the Wind Turbine Generator

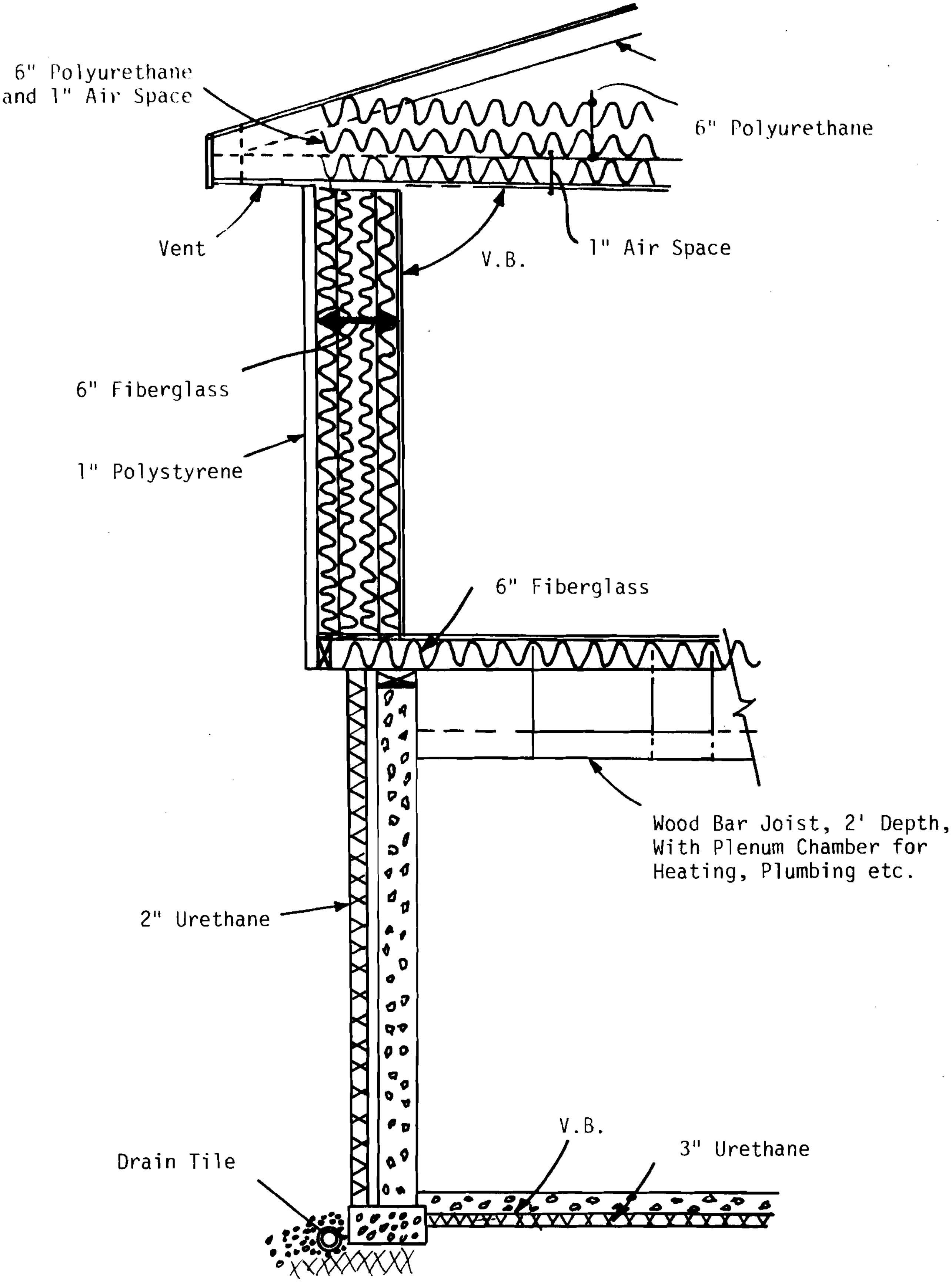


Figure 14. Construction Design of Solar Habitat I

use of insulation, the window construction used in Solar Habitat I is unique. The windows are permanent fixture designed with four panes of glass. These windows are designed to provide ventilation for Solar Habitat I and to minimize the heat loss through the windows. Figure 15 gives a description and illustration of the window construction and ventilation system. The design of Solar Habitat I constitutes a very tight house with most of the infiltration controlled by a forced exhaust ventilation system, which blows air out of the basement, causing air to be drawn in through the windows as shown in Figure 15.

All analytical models of Solar Habitat I were done according to ASHRAE standards (15). (Reference 4 gives the details of the exact modeling of Solar Habitat I.) Included as model inputs were the insulating properties of the materials used in construction, the amount of solar energy gained through the windows, and the air infiltration rate. Detailed calculations showed that the heating load of Solar Habitat I was a strong function of the infiltration rate. Other researchers (17, 18) have also recently shown the importance of infiltration rates on residential heating loads. If an infiltration rate of 1 air change/hour is assumed, the predicted heating load of Solar Habitat I is 17,000 BTU's/°F day. By varying the infiltration rate in the analytical modeling, the heating load of Solar Habitat I for various infiltration rates can be determined as is shown in Figure 16.

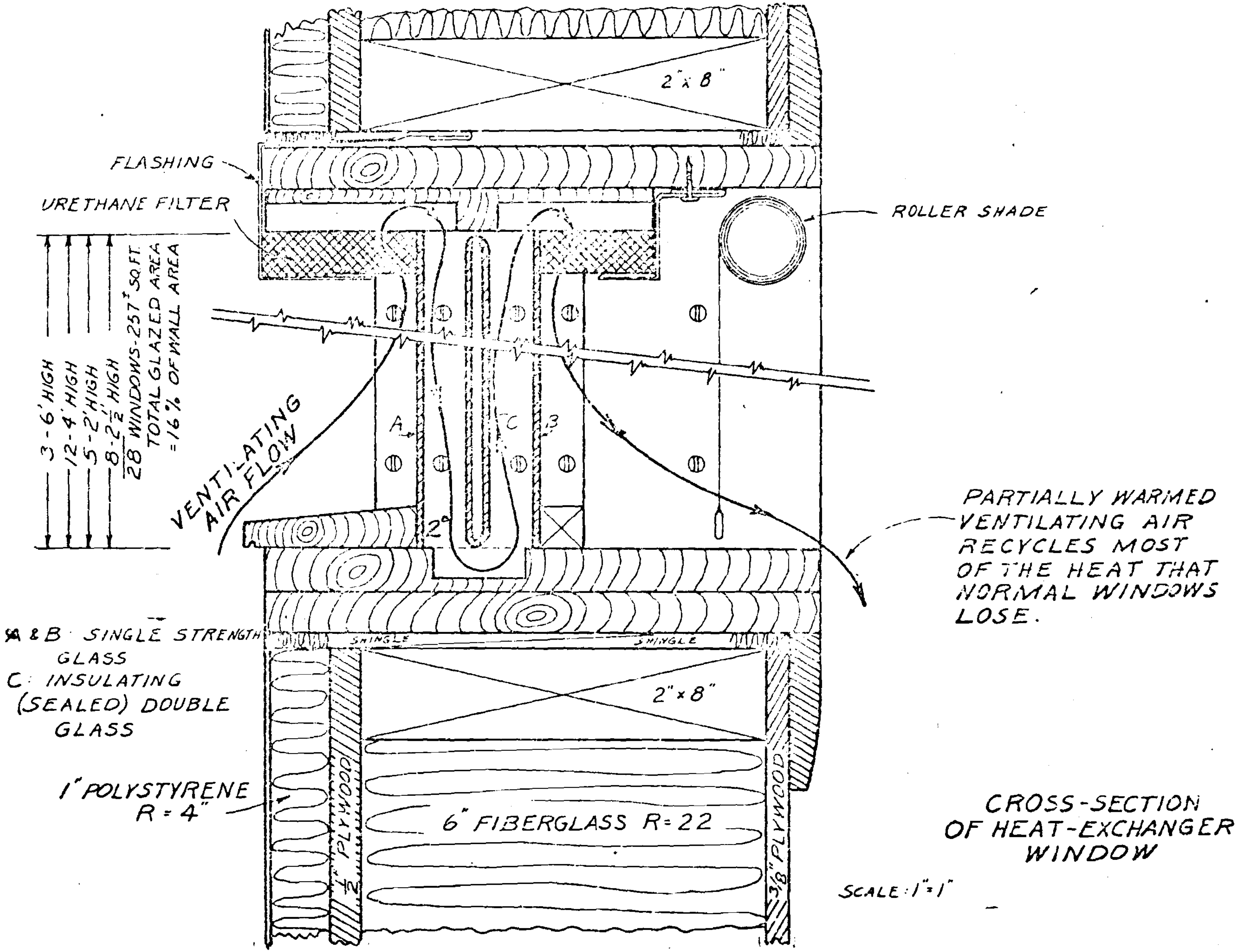


Figure 15. Window Design of Solar Habitat I

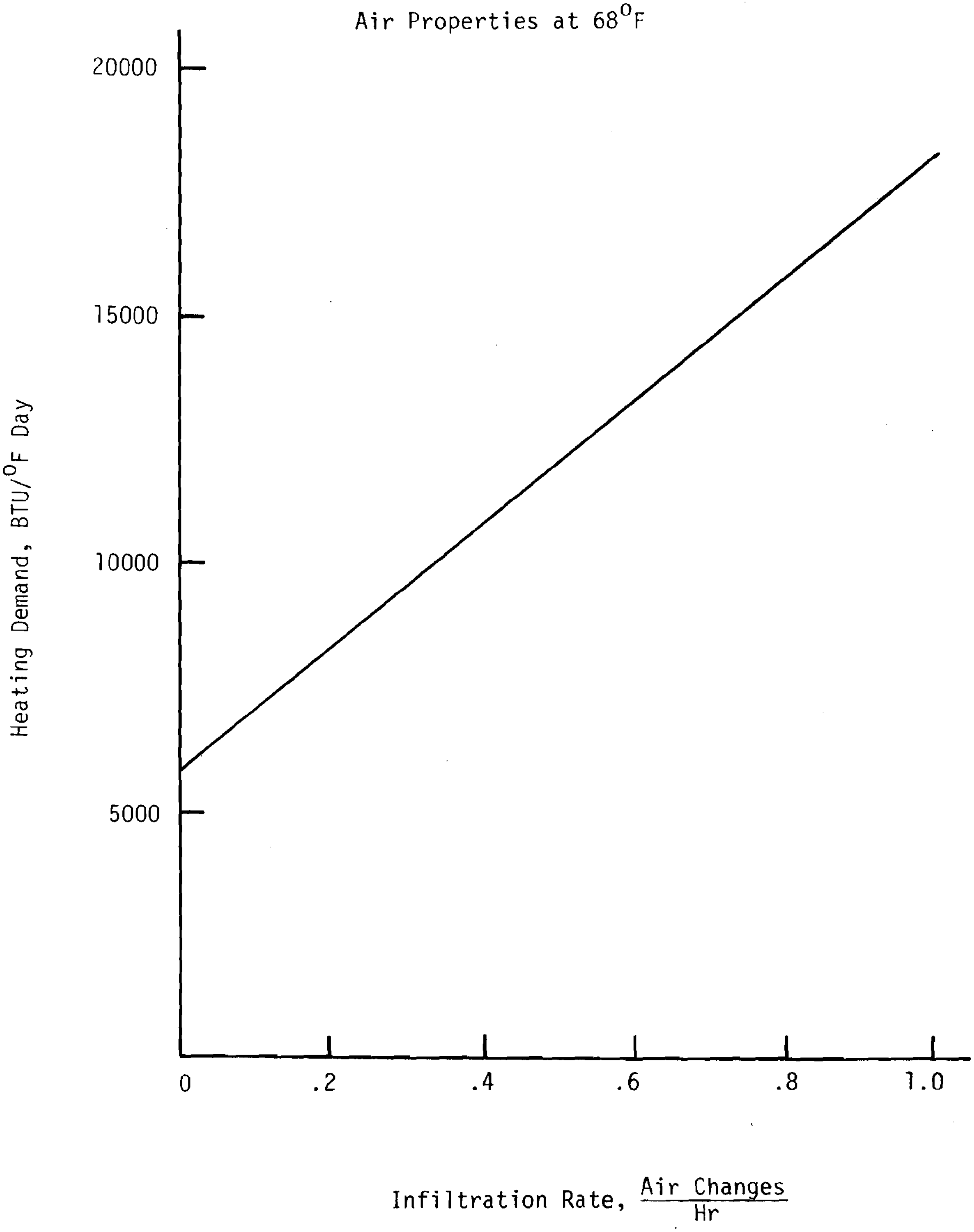


Figure 16. Heating Demand of Solar Habitat I as a Function of the Infiltration Rate

CHAPTER III

EXPERIMENTAL TEST PROCEDURES

In order to determine how effectively Solar Habitat I utilized solar and wind energy, an energy balance between the heating load of Solar Habitat I and the amount of solar and auxiliary heat supplied to Solar Habitat I was determined experimentally. Before this was possible, the performance of the subsystems of Solar Habitat I had to be experimentally measured. As previously discussed, these subsystems included the piping system, storage tanks, flat plate solar collectors, heat exchanger, baseboard convectors, wind turbine generator, auxiliary hot air furnace, and Solar Habitat I. Once all subsystems were experimentally calibrated by monitoring such variables as solar insolation, wind speed, and ambient temperature, the heating load of Solar Habitat I and the amount of solar and wind energy collected and used as a function of time could be determined. Also, from the knowledge of individual subcomponent performance, the thermal performance of various overall system arrangements could be evaluated.

In order to obtain the most conclusive and useful results, the tests of the subsystems and models were conducted in the sequence shown below. All test sheets, data collected, and other important information for each subsystem and model is discussed in detail in the specified Appendice(s). Appendix C summarizes the necessary instrumentation for each of the tests.

1) Piping
2) Storage tank

3) Solar collectors
4) Heat exchanger
5) Baseboard convectors
6) Wind turbine generator
7) Hot air furnace
8) Solar Habitat I
9) Models

3.1 Piping

The important information determined for the piping subsystem was: the calibration of all flow meters in the system, the calibration of all pressure gauges, determination of all pump capacities, and the determination of no flow (deadhead) pressures in each loop. Since the piping in all loops was insulated, the heat loss from the piping was assumed to be negligible.

A deadweight gauge was used as a standard for the calibration of the six pressure gauges to be used in the solar collector piping system. Each pressure gauge was tested from 0-50 psig, in increments of 5 psig. The test was repeated three times. The accuracy, sensitivity, and calibration of each pressure gauge was recorded. After the pressure gauges were calibrated, they were placed in the solar collector loop as described in Appendix C and illustrated in Figure 17. After their installation, the deadhead pressure in the flow loop was measured and recorded.

The method used to calibrate the flow meters in the piping system was to first accurately calibrate a flow meter in the laboratory, and then use that secondary standard flow meter in series with the flow

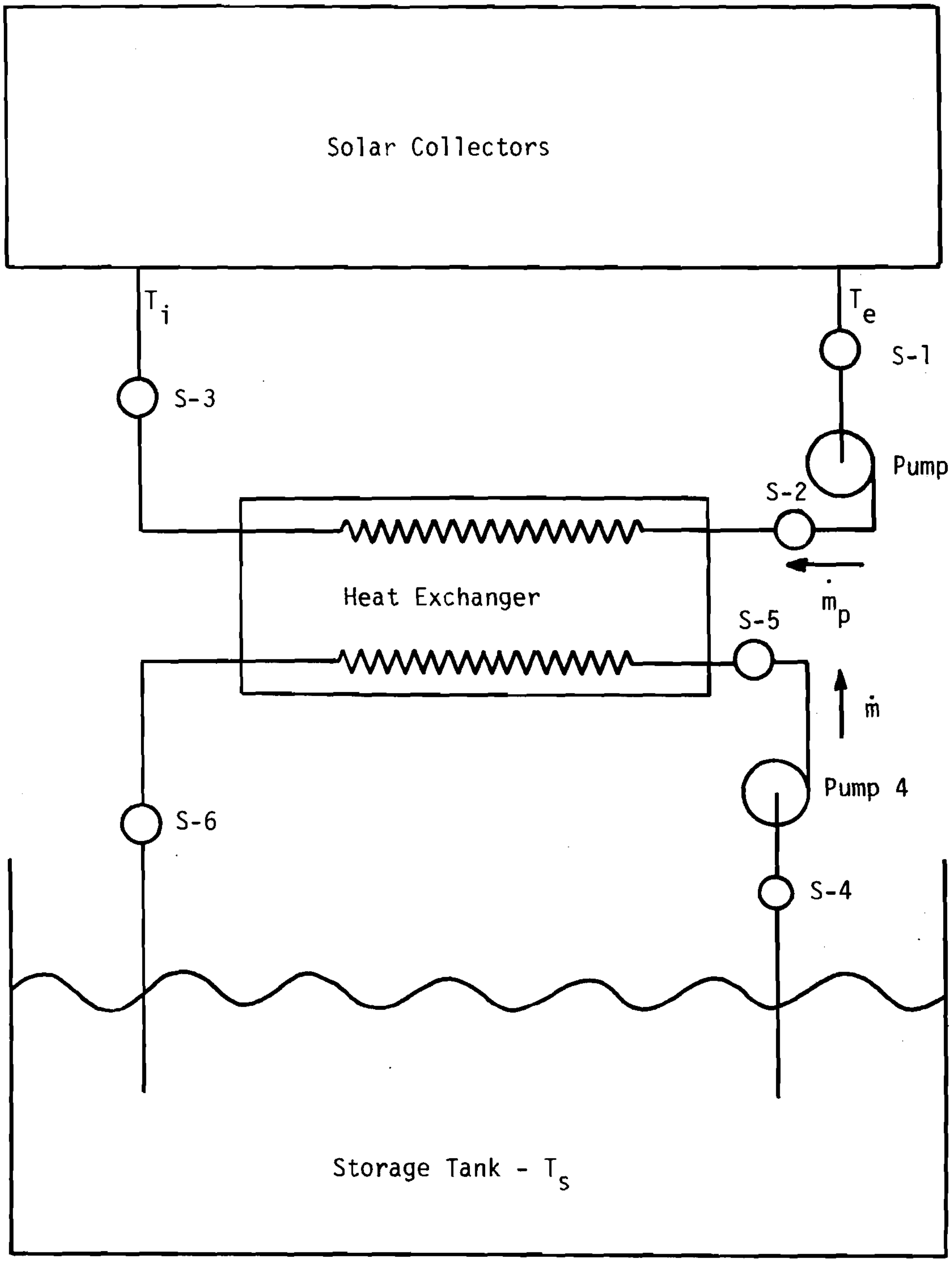


Figure 17. Solar Collector Loop

meters in the piping system to calibrate each of them. The secondary standard flow meter was calibrated by establishing a steady flow through the flow meter and then measuring the volume and/or the mass of the flowing fluid that passed through in an accurately timed interval. Before this test was conducted, the flow meter was mounted in a vertical position, and in such a manner that the flow rate was not influenced by the flow distribution upstream. The secondary standard flow meter was calibrated from 1 to 6.6 gpm. Once the flow in the meter became steady, the water was diverted to a calibrated container, and at that moment an electric timer began. When the water level reached 30 gallons, the timer was stopped, and the calibrated flow rate in this test was compared with the flow meter's reading.

After the secondary standard flow meter was calibrated, it was installed in Solar Habitat I and used to calibrate each of the flow meters in the piping system. To calibrate the flow meters in the piping system, the secondary standard flow meter was placed in series with the particular flow meter to be tested. Then the flow rate through the secondary standard flow meter was increased from 1 to 6.6 gpm in various increments. The accuracy, sensitivity and the best fit calibration of the particular flow meter being tested was calculated from the data obtained. This same procedure was conducted three times for each flow meter tested. After all flow meters were calibrated, the maximum capacity of each pump was measured and recorded. Test sheets, data, calculations and other important information are found in Appendix D.

3.2 Storage Tanks

An important parameter in evaluating each storage tank is the rate of heat transfer from the tank as a function of its temperature. The heat loss rate from the tank was experimentally determined by heating the tank to an arbitrary temperature and then monitoring the temperature decay of the tank as a function of time. The energy balance equation for the tank is given by:

$$\dot{Q}_t = U_E A_E (T_s - T_a) + U_W A_W (T_s - T_a) + U_N A_N (T_s - T_a) + U_T A_T (T_s - T_a)$$
$$+ U_B A_B (T_s - T_b) + U_S A_S (T_s - T_g) \qquad (3)$$

or

$$\dot{Q}_t = \underbrace{(U_E A_E + U_W A_W + U_N A_N + U_T A_T + U_B A_B + U_S A_S)}_{C_1} T_s$$
$$\underbrace{- [(U_E A_E + U_W A_W + U_N A_N + U_T A_T) T_a + U_B A_B T_b + U_S A_S T_g]}_{C_2} \qquad (6)$$

Since

$$Q_t = C \rho V \frac{dT_s}{dt} \qquad (7)$$

where

C = Specific heat of water

ρ = Density of water

V = Volume of water in tank

t = Time

and the values of C_1 and C_2 remain essentially constant in a one dimensional analysis. Equation 6 can be rewritten as

$$\dot{Q}_t = C\rho V \frac{dT_s}{dt} = C_1 T_s + C_2 \qquad (8)$$

The form of Equation 8 is identical to the equation of a straight line with C_1 as the slope and C_2 as the y intercept. In order to obtain an empirical equation that describes the rate of heat transfer from the tank for a corresponding tank temperature, the values of C_1 and C_2 had to be determined experimentally. This was accomplished by obtaining numerous experimental values for $\dot{Q}_t$ and the corresponding T_s, and then using a regression analysis technique to find the best fit values for C_1 and C_2.

The test procedure used to obtain the data points, $\dot{Q}_t$ and T_s, is described next. Since the values of C, ρ, and V in Equation 7 are known or easily measured, the value of $\dot{Q}_t$ can be determined by evaluating $\frac{dT_s}{dt}$ for a corresponding T_s. This was done by raising the temperature in the storage tank to an arbitrary temperature by means of an immersion heater connected to Solar Habitat I's utility supplied electrical system and then monitoring the temperature and the change in temperature in the tank per unit of time. In order to assure a uniform tank temperature, pump 4 of Figure 17 was used to mix the water in the storage tank (pump 5 was turned off). The heat lost by passing the tank water through the pump and heat exchanger was minimized by insulating the exposed surfaces. The tank temperature was monitored as a function of time during this test. Since the majority of the data obtained for the storage tank test was taken simultaneously with the testing of Solar Habitat I, a scan period of every three minutes was used. For tests conducted independent of the Solar Habitat I test, a scan period of thirty minutes was chosen.

Instrumentation, test data, calculations, and other important information used in the storage tank test are summarized in Appendices C and E.

3.3 Solar Collector

The test method for determining the thermal performance of the flat plate collectors was similar to the National Bureau of Standard's method for rating solar collectors (8, 19). A schematic of the solar collector loop is shown in Figure 17. Based on Reference 19, the efficiency of a flat plate collector is given by:

$$\eta = F'(\tau\alpha)_e - F'U_1 \frac{\left[\frac{(T_i+T_e)}{2} - T_o\right]}{I} \qquad (9)$$

where

η = Efficiency of the collector

F' = Collector efficiency factor

$(\tau\alpha)_e$ = Effective transmittance - absorptance product

T_i = Temperature of the fluid at the inlet to the collector

T_e = Temperature of the fluid at the exit of the collector

T_o = Outside ambient temperature

I = Solar insolation rate per unit area

The desired experimental information required was a plot of the collector's efficiency as a function of the parameter

$$\frac{\left[\frac{T_i+T_e}{2} - T_o\right]}{I}$$

A straight line should result where the slope is equal to $F'U_1$ and the y intercept given by $F'(\tau\alpha)_e$. It should be noted that U_1 may not be constant since it is a function of the plate temperature and the ambient temperature. Also, $(\tau\alpha)_e$ may not be constant since it can vary with incident angle to the collector.

The test intervals were of twenty minutes duration. Each test point was calculated using averaged test data from the last ten minutes of each test interval. The first ten minutes of test data in each interval was discarded to allow for possible transient effects. With the test sessions conducted on site, the only test parameters under experimental control were the flow rate through the collectors and, to a lesser extent, the fluid inlet temperature T_i, to the collectors. The collector loop flow rates used for these tests were: 2,3, and 4 gpm. Observations of wind speed, wind direction and cloud cover were taken at regular intervals during the test sessions. Instrumentation used is summarized in Appendix C. Data was taken at one minute intervals during the test sessions. The data was recorded on cassetts tape and then read into the UMass computer and reduced using the computer programs "STES12A" and "STES10A". (A listing of program STES12A appears in Appendix F.)

Collector efficiency was based on an overall energy balance around the collector calculated from the equation

$$\eta = \frac{\dot{m}_p\, C_p\, (T_e - T_i)/A_c}{I} \tag{10}$$

where

$\dot{m}_p$ = Flow rate of the heat transfer fluid

C_p = Specific heat of the heat transfer fluid

A_c = Aperture area of the collector

The values of (T_e-T_i) and I used were the average of the last ten minutes of data at each test interval. The value of $\dot{m}_p$ was read from sensor 9 (see Appendix C) at the beginning and end of each test interval. The collector fluid was a 60/40 solution of propylene glycol/water. The specific heat of the solution was obtained from ASHRAE data (6). Tests sheets, calculations, and other important information are given in Appendix F.

3.4 Heat Exchanger

To measure the performance of the heat exchanger, (see schematic of Figure 17), the effectiveness was experimentally determined. Heat exchanger effectiveness, ε, is defined as the ratio of the actual rate of heat transferred to the maximum possible rate of heat transferred (8). From this definition of heat exchanger effectiveness,

$$\varepsilon = \frac{\dot{m}_p C_p \, (T_e-T_i)}{C_{min} \, (T_e-T_s)} \tag{11}$$

where

C_{min} = Smaller of the $(\dot{m}_p \, C_p)$ and $(\dot{m} \, C)$ magnitudes

To determine the overall performance of the heat exchanger, a plot of effectiveness as a function of the flow rate on the tank side of the heat exchanger (tube side) for various solar collector side flow rates (shell side) was obtained.

The heat exchanger tests were carried out concurrently with the solar collector tests. Thus, the same test intervals and sampling rates were used. The test method for the heat exchanger was to determine the effectiveness as a function of the flow rate in the tank side of the heat exchanger (tube side). This was experimentally carried out for varying flow rates (2, 3, and 4 gpm) on the collector side (shell side) of the heat exchanger. (All instrumentation used for this test is summarized in Appendix C.) The effectiveness was calculated by computer program STES10A and STES12A using data recorded during the test sessions. Program STES12A plus test sheets, data, calculations, and general information sheets is shown in Appendices F and G.

3.5 Baseboard Convectors

The simplified schematic shown in Figure 18 illustrates the three convector loops in Solar Habitat I. Their performance was measured by determining the rate of heat transferred per linear ft of convector as a function of the average temperature of the water that passes through the convector. For example, based on an energy balance equation for the bedroom convector loop, the rate at which energy is added to the house from this convector loop, $\dot{Q}_1$, is equal to the rate at which energy is given up by the convector loop or

$$\dot{Q}_1 = \frac{m_c C (T_{i_1} - T_{e_1})}{\ell_1} \qquad (12)$$

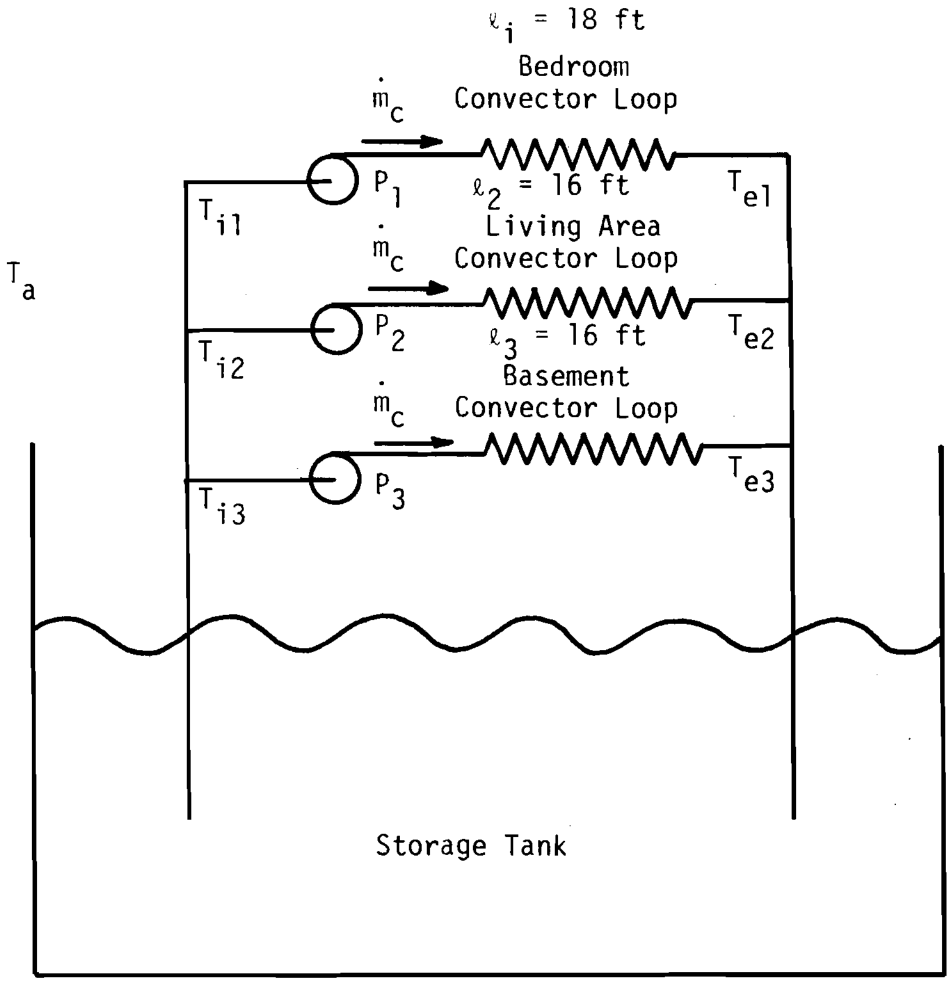
with the average temperature T_{avg} defined by

$$T_{avg} = 65°F + \overline{\Delta T} \qquad (13)$$

where

$\overline{\Delta T}$ = Logarithmic mean overall temperature difference between the convector fluid and the ambient air temperature

From this information the rate of heat transfer per linear ft of convector as a function of the estimated average temperature of the fluid inside the convector can be determined and compared to its predicted performance.



s = Subscript for loops 1, 2, and 3

ℓ_s = Linear length of convectors

T_{es} = Exit temperature of convectors

T_{is} = Inlet temperature of convectors

P_s = Pump used for each convector

$\dot{m}_c$ = Flow rate through each convector

Figure 18. Baseboard Convector Loops

To obtain $\dot{Q}_1$ and T_{avg} in Equation 12 and 13 respectively, the values of $\dot{m}_c$, C, ℓ_1, T_{i_1}, T_{e_1}, and $\overline{\Delta T}$ as a function of time must be determined. The values of C and ℓ_1 are constants and can be readily obtained. Since the flow rate through the baseboard convectors is a constant (.89 gpm when there is a heating demand), the monitoring of $\dot{m}_c$ is accomplished by an on-off voltage signal from a central logic unit which controls the heating of Solar Habitat I. The value of $\overline{\Delta T}$ is a function of T_{i_1}, T_{e_1}. Thus, by monitoring, $\dot{m}_c$, T_{i_1}, and T_{e_1} as a function of time, $\dot{Q}_1$ and T_{avg} can be calcualted. (Details of the instrumentation used in this test are discussed in Appendix C.)

For convenience, the testing of Solar Habitat I and the baseboard convectors was done simultaneously. A scan period of three minutes was chosen so as to optimize the cassette's capacity without sacrificing error in the convector and house test. Testing of the convectors was conducted at arbitrary tank temperatures ranging from 105°F to 178°F. The data, computer programs, calculations and other important information are summarized in Appendix H.

3.6 Wind Turbine Generator

The power output of the WTG is defined as the power delivered to the immersion heaters or the electric baseboards. To evaluate the overall performance of the wind turbine generator (WTG), tests were planned to determine the electrical power output of the wind furnace as a function of wind speed and the efficiency of the WTG, η (power output/theoretical maximum power output), as a function of wind speed. By monitoring both the power output of the WTG and the wind speed simultaneously, a check of the predicted WTG performance would be carried out.

Full testing of the WTG at Solar Habitat I has not been totally completed at this time due to experimental delays. However, preliminary details of the experimental performance of the WTG can be found in Reference 2.

3.7 Auxiliary Hot Air Furnace

The two important parameters that needed to be determined from the hot air furnace were the amount of and the time when energy was supplied to Solar Habitat I. They were experimentally determined by recording the propane used daily (via a positive displacement flow meter) in a log book. The specifications on this positive displacement flow meter used are given in Appendix C. By knowing the daily amount of propane used (at 2522 BTU/ft^3) and assuming a furnace efficiency of 70% (4), the amount of energy added to Solar Habitat I could be determined.

3.8 Solar Habitat I

The primary information needed to evaluate Solar Habitat I was the rate at which it transfers thermal energy under varying weather conditions. Assuming steady state, and applying basic heat transfer principles, the following equation summarizes the energy balance used for Solar Habitat I:

$$\dot{Q}_S = \dot{Q}_L \tag{14}$$

where

$\dot{Q}_S$ = Rate at which thermal energy is supplied to Solar Habitat I

$\dot{Q}_L$ = Heating load of Solar Habitat I

For the testing of Solar Habitat I, the main source of thermal energy supplying the heating demand was a heated water storage tank (with the auxiliary hot air heater turned off). As was discussed previously, a portion of this thermal energy ($\dot{Q}_T$) was continuously transferred through the storage tank walls to Solar Habitat I, while the remainder of the thermal energy ($\dot{Q}_C$) was distributed to Solar Habitat I by means of baseboard convectors when there was a heating demand. Since Solar Habitat I was continuously occupied, sources of thermal energy other than the baseboard convectors-storage tank system must be considered. These sources include the thermal energy gained from dissipating electricity through household appliances and laboratory equipment which were operated throughout the day ($\dot{Q}_E$), the thermal energy lost from the domestic hot water heater to Solar Habitat I ($\dot{Q}_{HW}$), the thermal energy gained due to human habitation ($\dot{Q}_H$), and the thermal energy gained from the use of the gas stove ($\dot{Q}_{ST}$). For calculational purposes, the values of $\dot{Q}_T$, $\dot{Q}_c$, $\dot{Q}_E$, $\dot{Q}_{Hw}$, $\dot{Q}_H$, and $\dot{Q}_{ST}$ were based on the total daily energy these sources supplied to Solar Habitat I. As each energy source discussed supplied a portion of the daily heating load; the following energy balance was developed:

$$\dot{Q}_S = \dot{Q}_T + \dot{Q}_E + \dot{Q}_c + \dot{Q}_{Hw} + \dot{Q}_H + \dot{Q}_{ST} \qquad (15)$$

As discussed previously in the storage tank and baseboard convector sections:

$$\dot{Q}_t = C_1 T_s + C_2 \qquad (8)$$

and

$$\dot{Q}_{ch} = \dot{Q}_1 + \dot{Q}_2 + \dot{Q}_3 \qquad (16)$$

The values $\dot{Q}_t$ and $\dot{Q}_{ch}$ were evaluated on an hourly basis; therefore, the appropriate adjustments must be made for the daily energy usage. Thus

$$\dot{Q}_T = \dot{Q}_t \times \text{(desired time interval)} \qquad (8')$$

and

$$\dot{Q}_C = \dot{Q}_{ch} \times \text{(desired time interval)} \qquad (16')$$

The electrical energy dissipated into thermal energy was estimated from the daily readings of the utility company's kilowatt-hour meter. From this reading and knowledge of appliances used, the portion of electricity that was used as shaft energy and the portion that was dissipated as thermal energy could be estimated (16). Since $\dot{Q}_{HW}$, $\dot{Q}_H$, and $\dot{Q}_{ST}$ comprises a small portion of the energy supplied for the heating, experimental tests were not conducted and estimations of the respective values were made (16, 20).

By conducting experiments to obtain the values of $\dot{Q}_C$ and $\dot{Q}_T$ and by estimating the values of $\dot{Q}_E$, $\dot{Q}_{HW}$, $\dot{Q}_H$ and $\dot{Q}_{ST}$, the amount of thermal energy which is supplied to Solar Habitat I on a daily basis can be obtained. Detailed calculations of $\dot{Q}_{HW}$, $\dot{Q}_H$, $\dot{Q}_{ST}$, $\dot{Q}_E$, $\dot{Q}_C$ and $\dot{Q}_T$ are shown in Appendix I. The amount of energy supplied to Solar Habitat I was divided into two categories, one being the total energy supplied to Solar Habitat I, $\dot{Q}_S$ and the other being the amount of energy supplied to Solar Habitat I from the storage tank, $\dot{Q}_{SS}$, (simply the sum of $\dot{Q}_T$ and $\dot{Q}_C$). This distinction was made to differentiate between the sources of energy which added thermal energy to Solar Habitat I as a by-product of some other essential operations ($\dot{Q}_E$, $\dot{Q}_{HW}$, $\dot{Q}_H$, and $\dot{Q}_{ST}$) and the sources of energy which were necessary to maintain Solar Habitat I at a comfortable temperature level ($\dot{Q}_T$ and $\dot{Q}_C$). Essentially, $\dot{Q}_{SS}$ represents the amount of energy which the solar (wind plus flat plate collectors) energy sources or the auxiliary heating system must supply to meet the heating demand.

In order to equate $\dot{Q}_S$ (and $\dot{Q}_{SS}$) to $\dot{Q}_L$ via Equation 14, a brief discussion of the independent variables which govern the value of $\dot{Q}_L$ is necessary. The heating load of Solar Habitat I can be summarized by the following equation:

$$\dot{Q}_L = \dot{Q}_i + \dot{Q}_{h\ell} - \dot{Q}_w \tag{17}$$

where

$\dot{Q}_i$ = Rate of energy loss due to infiltration

$\dot{Q}_{h\ell}$ = Rate of energy loss through walls,windows, doors, roof and floor

$\dot{Q}_w$ = Rate of energy gain to Solar Habitat I from solar insolation through the windows

Details on the analytical estimations of the values $\dot{Q}_i$, $\dot{Q}_{h\ell}$, and $\dot{Q}_w$ are discussed in Reference 4.

From Equation 17, it can be deduced that the heating load of Solar Habitat I is a strong function of both the weather conditions and infiltration rate. That is, $\dot{Q}_{h\ell}$ is a function of the temperature difference between the inside and outside ambient air temperatures, $\dot{Q}_w$ is a function of the solar insolation and $\dot{Q}_i$ is a function of the infiltration rate and the temperature difference between the inside and outside ambient air temperatures.

The test conducted and the method of analyzing the data were carried out to correlate $\dot{Q}_S$ and $\dot{Q}_{SS}$ with $\dot{Q}_i$, $\dot{Q}_{h\ell}$, $\dot{Q}_w$, and $\dot{Q}_L$. In order to correlate $\dot{Q}_S$ with $\dot{Q}_L$, experimental data was taken to obtain $\dot{Q}_S$ as a function of the average ambient temperature. Specifically, through the experimental graphs of $\dot{Q}_S$ vs $T_{ambient}$ a best fit line with an x-y intercept of 68°F (traditional heat load reference temperature) and 0 BTU/day, was generated. From the slope of this best fit line, an experimental estimation of the total heating load of Solar Habitat I (BTU/°F day) with an experimental average daily solar insolation could be obtained.

From this result, the total amount of heat loss from Solar Habitat I due to infiltration, $\dot{Q}_i$, could be estimated. This was obtained by finding the difference between the experimental heating load of Solar Habitat I and an analytically predicted heating load of Solar Habitat I with a zero infiltration rate. From these results, the total infiltration rate can be estimated. As discussed earlier, the total infiltration rate can be divided into two components, the portion which is caused by natural convection and the portion which is caused by the forced ventilation system. The infiltration caused by natural convection was difficult to measure. However, the infiltration due to the forced ventilation fan was easily measured by obtaining an air flow profile at its exhaust duct. An electronic manometer was used to obtain the air wind speed at twenty five locations in the 9 inch by 4 1/2 inch exhaust duct. Details on this test procedure, data, and calculations are given in Appendix J.

From the tests just discussed, the total heating load of Solar Habitat I with an average daily solar insolation rate and an estimation of the total infiltration rate can be determined. To obtain a better understanding of the heating load of Solar Habitat I, the following analysis of the test data was used to determine (1) the portion of the heating load supplied by the baseboard convector - storage tank system, and (2) what effect solar insolation had on the heating load. This analysis was based on the amount of thermal energy supplied to Solar Habitat I from the storage tank ($\dot{Q}_{SS}$).

To determine what portion of the heating load was supplied by the storage tank, the experimental values of $\dot{Q}_{SS}$ as a function of the average daily temperature were plotted and the best fit line through the data was determined. The slope of the best fit line represents the heating load of Solar Habitat I with an average daily solar insolation rate, C_S, and the x- intercept represents the average daily temperature at which the demand for thermal energy from the storage tank begins, T_x. A value of T_x lower than the traditional heating load reference temperature of 68°F implies that sources of energy other than the thermal energy supplied from the tank, ($\dot{Q}_H$, $\dot{Q}_{HW}$, $\dot{Q}_{ST}$, and $\dot{Q}_E$) supply the heating load.

The effect of solar insolation on the heating load was determined by plotting the experimental values of the heating load (BTU/°F day) as a function of the total daily solar insolation and then finding the best fit line through this data. It should be noted that the data points for this graph are based on the temperature at which there is a demand for energy from the storage tank, T_x, the average daily ambient air temperature, and the corresponding values of $\dot{Q}_{SS}$. From these results, a correlation between $\dot{Q}_L$ and $\dot{Q}_i$, $\dot{Q}_{h\ell}$, and $\dot{Q}_w$ can be determined. Equation (17) can be rewritten as

$$\dot{Q}_{SS} = \dot{Q}_i + \dot{Q}_{h\ell} - \dot{Q}_w \tag{18}$$

$\dot{Q}_{SS}$ can be based on a reference temperature, T_x, instead of 68°F, and based on previous work discussed in this section, the value of $\dot{Q}_{SS}$, $\dot{Q}_i$, and $\dot{Q}_{h\ell}$ can be determined on an average ambient temperature and the experimental average daily total solar insolation rate. From this information, the following empirical equation was assumed

$$\dot{Q}_{SS} = C_S\,(T_x - T_{oa}) = C_i\,(T_x - T_{oa}) + C_{h\ell}\,(T_x - T_{oa}) \tag{19}$$

where

C_i = Constant which describes the heat loss due to infiltration - BTU/°F day

$C_{h\ell}$ = Constant which describes the heat loss through doors, windows, walls, etc. - BTU/°F day

T_{oa} = Average daily ambient air temperature (°F)

With the inclusion of the solar insolation effect, the following generalized empirical equation was developed:

$$\dot{Q}_{SS} = C_i\ (T_x - T_{oa}) + C_{h\ell}\ (T_x - T_{oa}) + [C_w\ (DI-AI)]\ (T_x - T_{oa}) \tag{20}$$

where

C_w = Constant which describes the heat gain through windows - BTU/°F day/(BTU/ft^2 day)

DI = Total daily insolation on a south facing vertical surface

AI = Average total daily solar insolation on a south facing vertical surface for the test period

It should be noted that the value of C_w is equal to the slope of the best fit line through the data of the heating load as a function of solar insolation.

Based on Equation 20, an estimation of the effect of the solar insolation rate, the infiltration rate, and the properties of the insulating materials used in the construction of Solar Habitat I can be made.

The following test procedure was used to obtain the necessary data to evaluate Solar Habitat I. This test used a time period of 20 days duration with the necessary channels scanned every three minutes. (Details on the instrumentation used for this test are discussed in Appendix C.) To minimize the error in measuring the thermal energy which was added to Solar Habitat I, the hot air furnace and the solar collectors were turned off during the test period. Energy was added to the storage tank by means of an immersion heater connected to Solar Habitat's utility supplied electrical system. This was done for a period of ten days, at which time the energy within the tank was sufficient to last for the remainder of the test. Since an accurate average tank temperature was needed to evaluate the value of $\dot{Q}_T$, the water in the storage tank was continuously mixed by means of pump 4 in Figure 17. Additional details of the specific test conducted, calculations, and other important information are shown in Appendix I.

3.9 Overall System Models

To evaluate the overall system models, a plot of $\dot{Q}_{AH}/(\dot{Q}_{SS} + \dot{Q}_{AH})$ as a function of time of year will be experimentally determined, where $\dot{Q}_{AH}$ = amount of auxiliary heat needed to maintain Solar Habitat I at 65°F. From the calibration of all subsystems and previous weather data, a computer simulation can be carried out to estimate the value of $\dot{Q}_{AH}/(\dot{Q}_{SS} + \dot{Q}_{AH})$ as a function of time. This estimation can then be compared to the results of the experimental testing.

A potential method of testing the various overall system models might be as follows. Since the testing of various models will be conducted over a long period of time, the suggested process of data handling is to integrate all the necessary signals which vary frequently with time to obtain the desired experimental data. By doing this, the basic data will be in a more compact form, making the data acquisition and analysis more simplier and efficient. (For example, a suggested integration and scan period might be a period of 15 minutes.)

After the data is obtained, a digital computer program can be used to reduce the data. After sufficient experimental information is obtained, the results can be compared to previous analytical work.

CHAPTER IV

EXPERIMENTAL RESULTS

This chapter discusses the experimental results obtained from the tests conducted to date. These results, sometimes reduced to empirical equations, will be compared to the analytical work which was discussed earlier. As previously mentioned, Appendices D through J include all test information, computer programs, calculations, and data which was needed to evaluate all subsystems.

4.1 Piping

The important information to be determined for the piping system was the calibration of all flow meters, the pump capacity of the solar collector loop, the calibration of all pressure gauges, and the dead-head pressures in the solar collector loop (Appendix D). The calibration of a standard flow meter was necessary in order to calibrate the remaining flow meters in the piping system. This standard flow meter was calibrated in the laboratory and was then used in series with each flow meter in the piping system for individual calibration. The results obtained are shown in Table 1. The flow meter on the tank side of the heat exchanger was not calibrated as its flow capacity was 86 gpm which was considerably higher than the standard flow meter's capacity of 6.6 gpm.

The pump capacity in the solar collector loop was determined next. The capacity of the pump on the tank side of the heat exchanger (tube side) ranged from 0 - 24 gpm, and the capacity on the collector side of the heat exchanger (shell side) ranged from 0 - 4.5

Table 1

Flow Meter Calibration

Sensor Description and Corresponding Sensor Number in Appendix C	Accuracy - gpm	Sensitivity	Best Fit Line Calibration y = flow rate in gpm x = flow meter reading(%)
S-7, Secondary standard rotameter (6.6 gpm maximum flow)	± .0198	$.066 \frac{\text{gpm}}{\text{div.}}$	y = .06583 x -.00709
S-8, Rotameter on the tank side of the heat exchanger (-86 gpm maximum flow)		$1 \frac{\text{gpm}}{\text{div.}}$	
S-9, Rotameter on the collector side of the heat exchanger (11 gpm maximum flow)	± .1265	$.2 \frac{\text{gpm}}{\text{div.}}$	y = .9885 x - .00623
S-10, Three identical rotameters in the baseboard convector system (3.55 gpm maximum flow)	± .0302	$.071 \frac{\text{gpm}}{\text{div.}}$	y = 3.532 x

gpm. These pump capacities agreed favorably with the manufacturer's specifications. It was not possible to measure the pump capacity of the convector pumps since the maximum flow capacity exceeded the maximum flow rate in the line flow meter. (Manufacturer;s specifications suggested that the maximum flow for the basement, living area, and bedroom pumps was 4 gpm.)

Finally, the calibration of the pressure gauges was determined for the piping system. The calibration of the pressure gauges was carried out using a dead weight gauge test are shown in Table 2. A regression analysis was used to obtain a best fit line for the data and is also summarized in the same table. After the installation and checkout of the heating system was complete, the deadhead pressure in the collector loop was measured. The deadhead pressure on the tank side of the heat exchanger was 23.5 psig. The collector side of the heat exchanger, a closed system, was charged (via an external charging pump) to a pressure of 42 psig with the pump off. With the collector loop on and a valve in the loop closed, the deadhead pressure was 44 psig.

4.2 Storage Tank

The information used to evaluate the performance of the storage tanks was the rate of heat transferred from the tank as a function of the average tank temperature (Appendix E). As discussed earlier, the rate of heat transferred from the tank is given by Equation 8,

$$\dot{Q}_t = C_1 T_s + C_2 \tag{8}$$

Based on a one dimensional analysis, the values of C_1 and C_2 are a function of the properties of the materials used in the tank design,

Table 2

Pressure Gauge Calibration

Sensor Description and Corresponding Sensor Number in Appendix C	Accuracy - psig	Sensitivity psig/div.	Best Fit Line Calibration y = pressure in psig x = reading on pressure gauge calibrated
S-1, Pressure gauge: (30 inches vacuum to 15 psi)	± .14	.5	y = 1.0092 x - .0019
S-2, Pressure gauge: (0 to 30 psi)	± .30	.5	y = .9899 x - .0230
S-3, Pressure gauge: (30 inches vacuum to 15 psi)	± 1.21	.5	y = 1.0804 x - .4949
S-4, Pressure gauge: (0 to 60 psi)	± .32	1	y = .9947 x - .3545
S-5, Pressure gauge: (0 to 60 psi)	± .30	1	y = 1.005 x - .0704
S-6, Pressure gauge: (0 to 100 psi)	± .19	1	y = .9962 x - .0163

the inside ambient air temperature, and the ground temperature surrounding the tank. All of these were expected to be constant during the test period. For the storage tank test (which was conducted from February 28 to March 9 and March 11 to March 14, 1977), 106 data points were obtained. However, in trying to fit the experimental data to one straight line, indications were that the values of C_1 and C_2 were not constants. In order to obtain a more realistic empirical fit, the experimental data was divided into three sections. Each section included the heat loss data obtained when the average tank temperature was between 60 - 105^{O}F, 105 - 150^{O}F, and 150 - 180^{O}F. From this data, the best fit line for each section was calculated. Figure 19 compares the empirical equation obtained with previous analytical work. As can be seen from the experimental analysis, the heat loss from the storage tank (measured by the thermal leakage rate) is far greater than analytic studies. The discrepancy between the empirical and analytical results can be attributed to the lack of consideration for three dimensional heat transfer in the analytical modeling. For the present tank design, it is believed that much of the energy lost from the storage tank, especially at higher temperatures, is conducted along the concrete tank walls to the adjoining concrete walls, which are exposed to the ambient air. To improve the storage tank performance, a minimization of losses of this type is essential.

4.3 Solar Collectors

The solar collector tests were conducted on three different test periods (January 31, February 8, and February 11, 1977). For these tests, three different collector flow rates were used and a total of 19 data points were obtained. A summary of the results showing

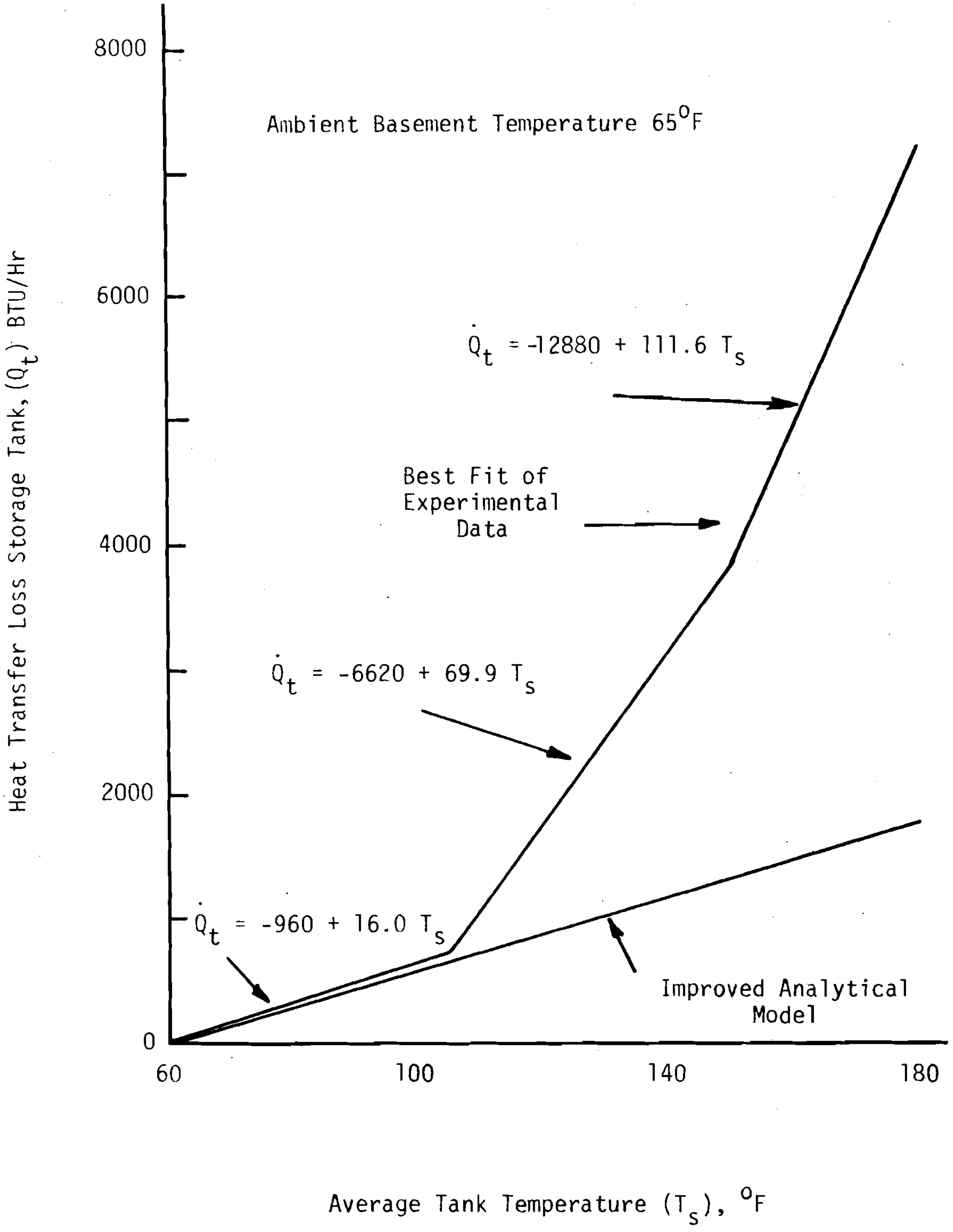


Figure 19. Comparison of Analytical and Experimental Results for Storage Tank

collector efficiency as a function of $\frac{\frac{T_i + T_e}{2} - T_o}{I}$ (refer to Equation 9) is given in Figure 20. This figure also gives the collector efficiency as analytically predicted for three ambient temperatures. Although there is a large amount of data scatter, the experimental results follow closely the efficiency predictions for the ten panel array. From this data, it can be concluded that the solar collectors are performing about as expected. However, future tests may be carried out to reduce the data scatter and increase the test parameter range.

4.4 Heat Exchanger

The heat exchanger tests were conducted simultaneously with the solar collector tests and are summarized in Appendix G. As mentioned earlier, the required information needed to evaluate the heat exchanger performance was effectiveness as a function of the flow rate in the tube side (tank side) for various shell side (collector side) flow rates. The experimental data obtained is shown in Figure 21 and a comparison of these results to previous analytical work (at a tube side flow rate of 18 gpm) is shown in Figure 22. From the tests conducted, it can be seen that there is an excellent correlation between the theoretical predictions and the experimental results.

4.5 Baseboard Convectors

The test for the baseboard convectors was conducted simultaneously with the testing of Solar Habitat I from February 17 to March 9, 1977. 183 test points were obtained from average convector temperatures of 173 to 105^{o}F and a flow rate of .89 gpm. 140 of the data points obtained were for the bedroom, bathroom, kitchen area loop, 43 points were for the living area loop, however, no points were obtained for the

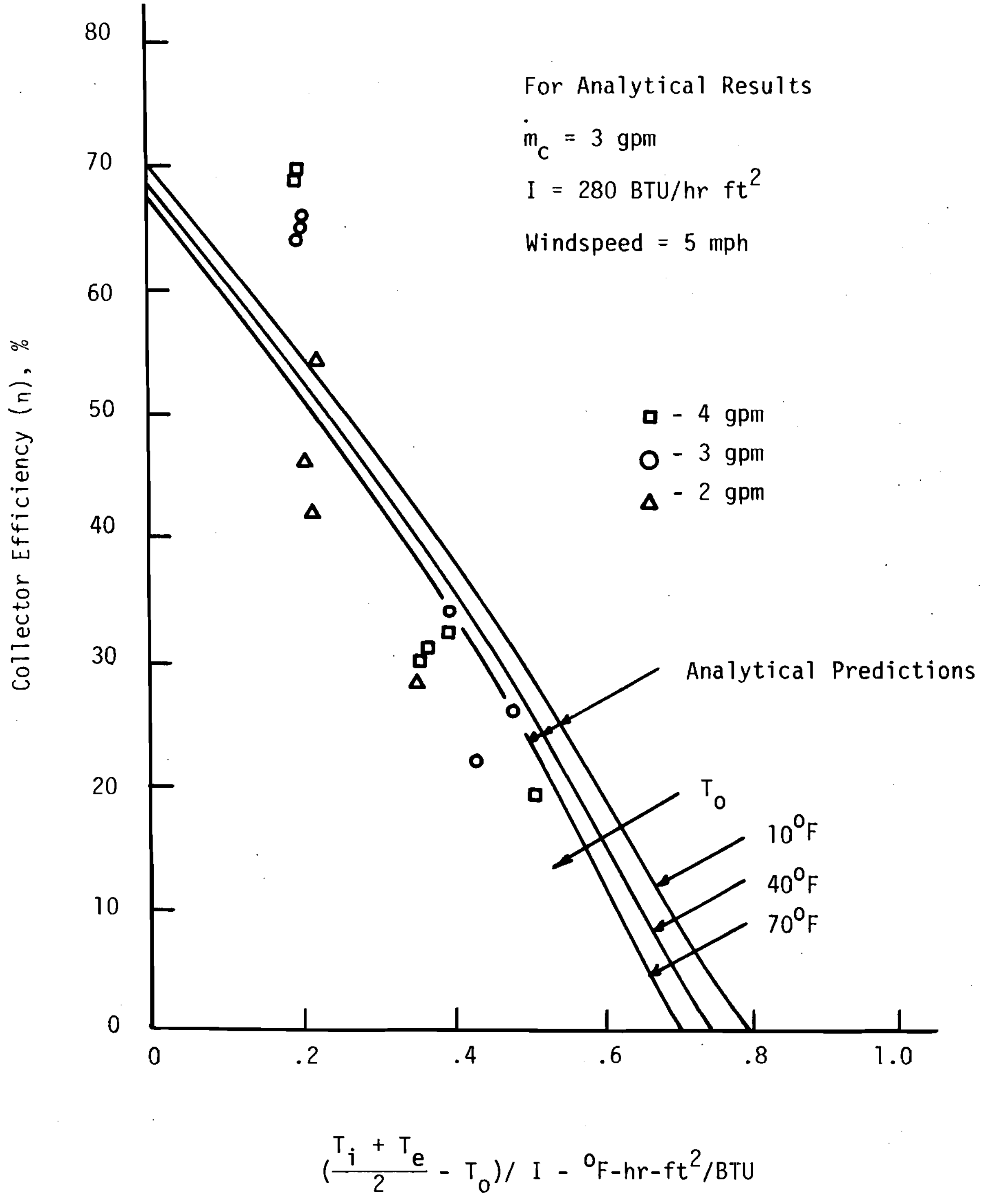


Figure 20. Performance of the Solar Habitat I's Collectors - Experimental Points and Predicted Efficiency Curves

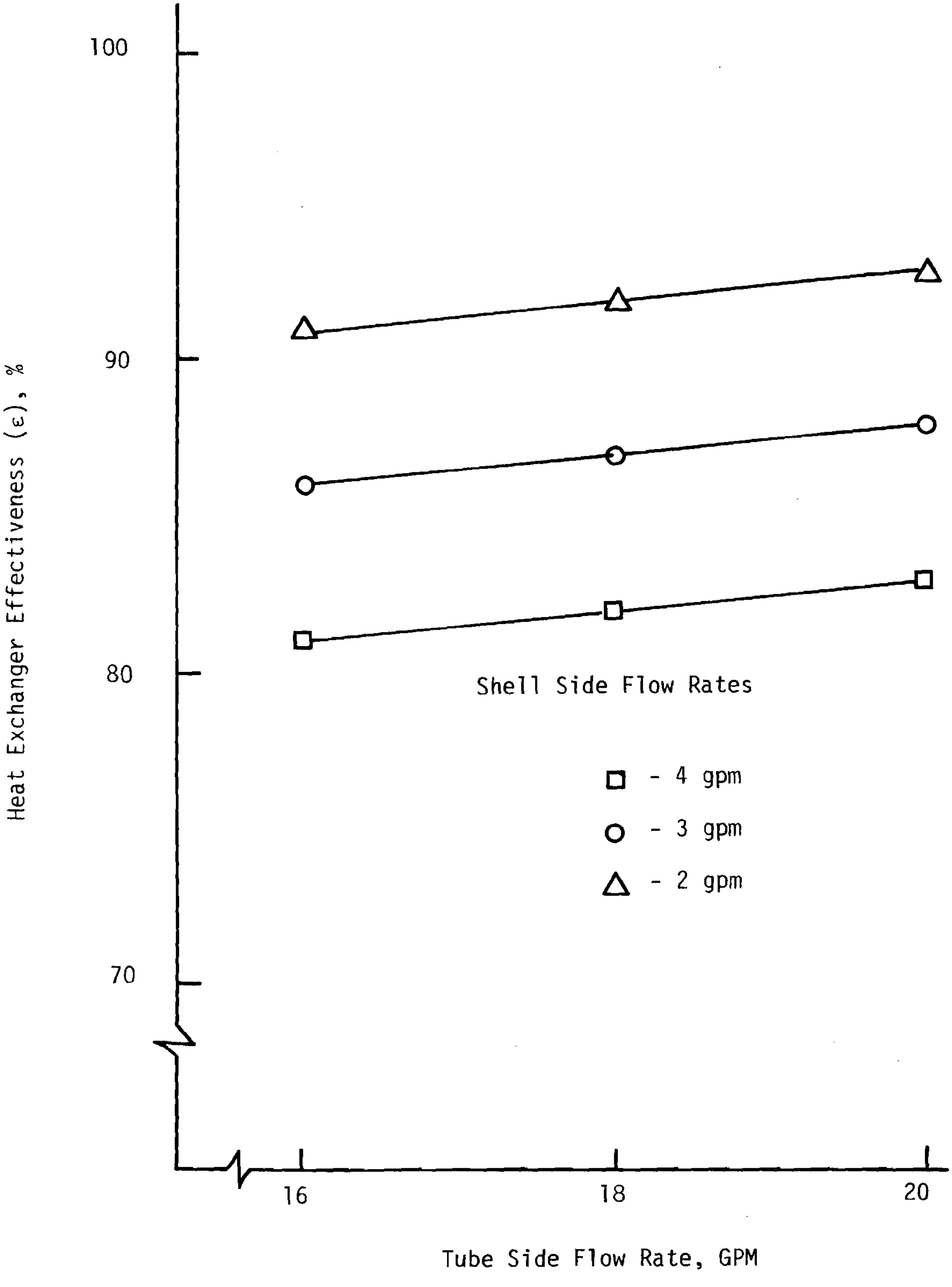


Figure 21. Results of Heat Exchanger Effectiveness Tests

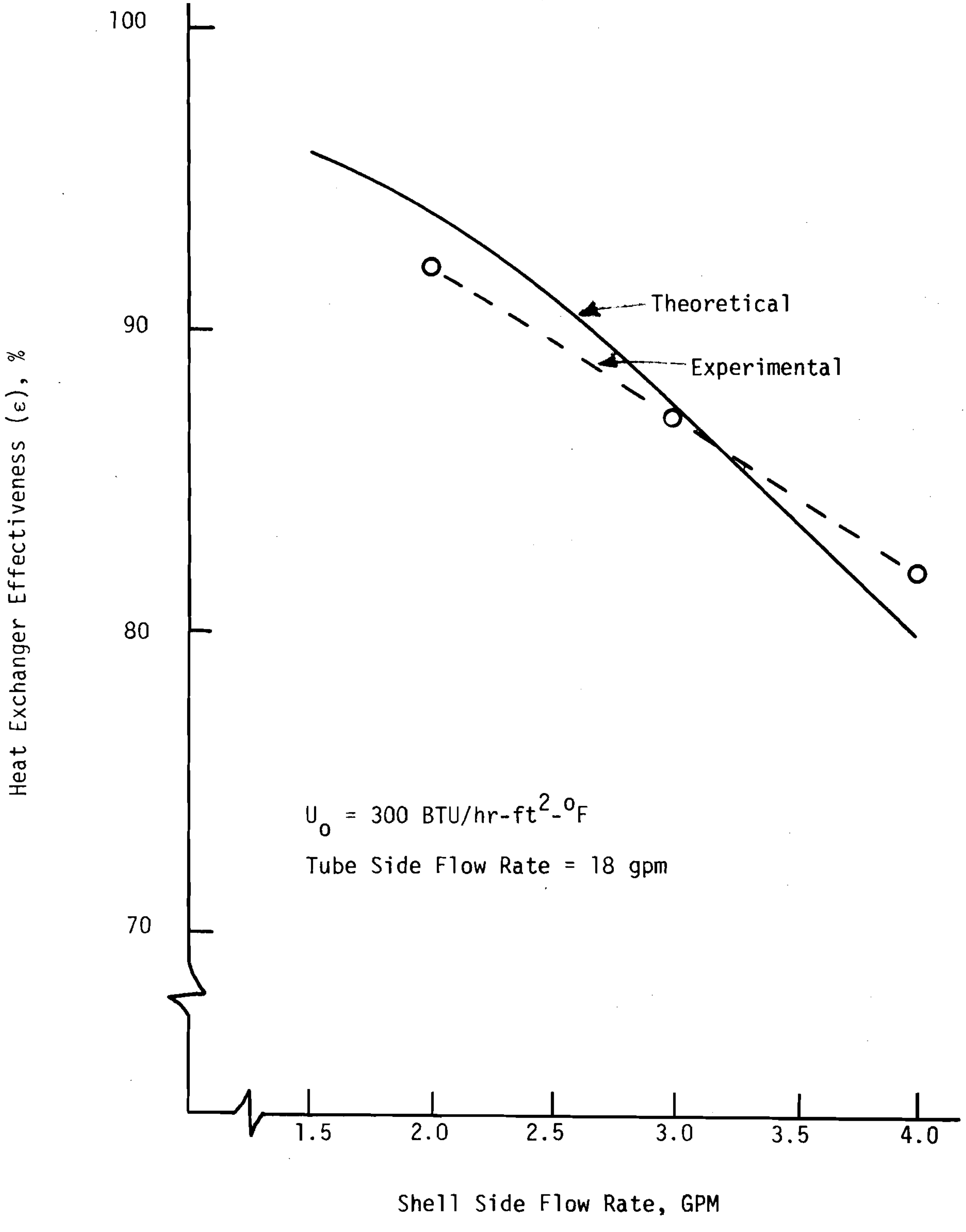


Figure 22. Comparison of the Theoretical and Experimental Results for the Heat Exchanger

basement loop. The fact that the basement loop did not turn on during the entire test period implies that the energy supplied from the storage tank plus the energy added to Solar Habitat I from the laboratory equipment was sufficient to meet the heating demand of the basement alone. A comparison of representative experimental data for both the living area and bedroom convectors to the predicted analytical results is shown in Figure 23. As can be seen from the results, the experimental performance of the convectors falls short of the analytical expectations. One possible explanation for these results is that the experimental test of the convectors used a flow rate through the convectors of .89 gpm while the analytical predictions were based on a flow rate of 1 gpm. Original baseboard convector calculations (3) predicted that the present system would supply twice as much energy to Solar Habitat I for a given average convector temperature. Thus, based on the revised calculations, a question arises as to whether or not the baseboard convectors will provide sufficient thermal energy to Solar Habitat I when both the tank temperature and the outside ambient air temperature are low. This problem will be discussed in more detail later.

4.6 Wind Turbine Generator

The experimental performance of this subcomponent was summarized previously in Chapter III.

4.7 Auxiliary Hot Air Furnace

No additional experimental tests were carried out on this component, thus the previous assumptions used to predict its performance (see Chapter III) were used directly.

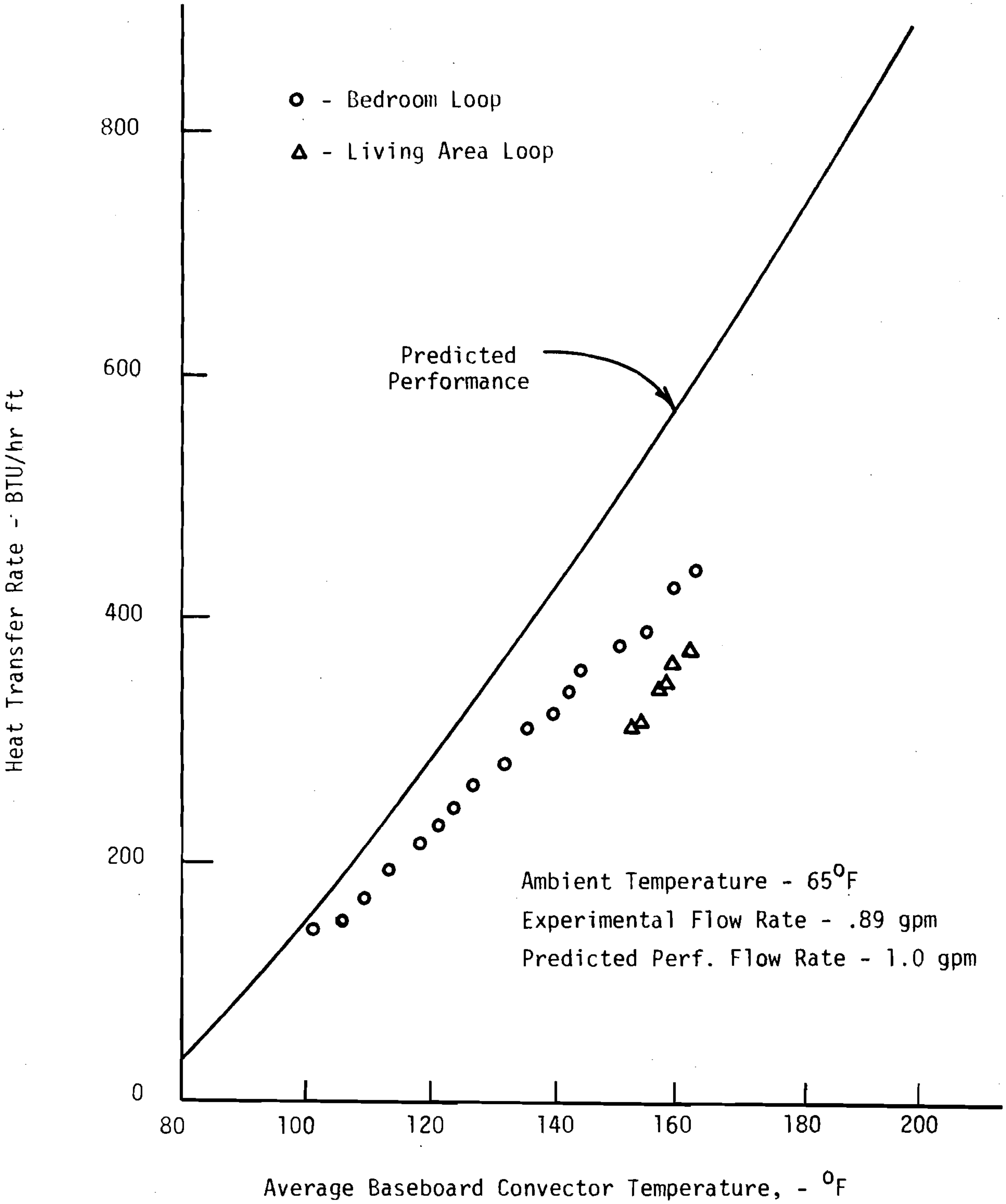


Figure 23. Comparison of the Predicted and Experimental Results for the Baseboard Convectors

4.8 Solar Habitat I

The tests for Solar Habitat I were conducted from February 17 to March 9, 1977. Seventeen complete days of data were obtained and analyzed, while three days of data were lost due to equipment malfunction. The information obtained for each day was: the total energy necessary to heat Solar Habitat I, $\dot{Q}_S$, the amount of thermal energy supplied to Solar Habitat I from the storage tanks, $\dot{Q}_{SS}$, the average daily outside ambient temperature, T_{oa}, and the total daily solar insolation available on a south facing vertical surface, DI.

To determine the total heating load of Solar Habitat I (BTU/°F day), the total energy supplied per day was plotted as a function of the average ambient daily temperature. From this data a best fit line through the conventional reference temperature of 68°F was calculated. The slope of this line represents the number of BTU's required to heat Solar Habitat I per °F day (with an average daily solar insolation rate). Figure 24 shows this experimental data and the resulting best fit line. From the experimental data, the heating load based on a 68°F reference point and an average daily solar insolation rate of 790 BTU/ft^2 day was 7857 BTU/°F day.

The resulting experimental heating load was over 9000 BTU/°F day less than the originally predicted (1) design heating load of 17,000 BTU/°F day. This decrease in heating load can be directly related to a low infiltration rate for Solar Habitat I. That is, the design model assumed an infiltration rate of one air change per hour (representing 65% of the heating load of Solar Habitat I). As discussed previously, the infiltration rate is a combination of the flow induced by the ventilation system and infiltration due to natural convection, which

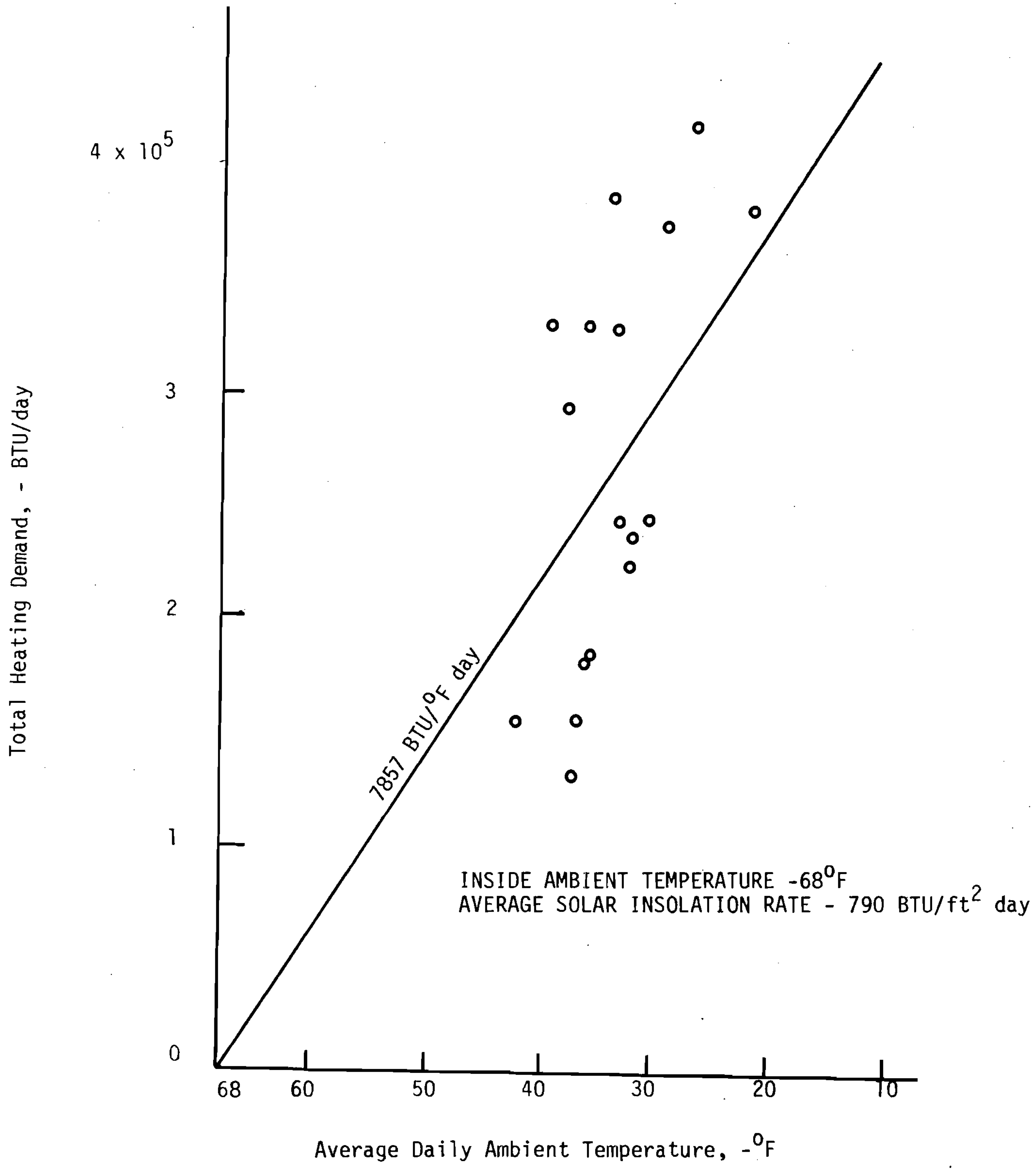


Figure 24. Heating Demand of Solar Habitat I Based on Total Energy Used

was difficult to measure experimentally. Tests conducted showed that the ventilation fan produces an infiltration rate of 0.11 air changes/ hour or 1225 BTU/°F day. In order to estimate the energy lost from Solar Habitat I due to the total infiltration rate the difference between the actual experimental heating load (7857 BTU/°F day) and the analytical heating load for zero infiltration (5850 BTU/°F day) was calculated, and from this value the total infiltration rate was estimated to be 0.18 air changes per hour (2007 BTU/°F day) which is about 25% of the total heating load for Solar Habitat I.

In the previous paragraphs the experimental heating load of Solar Habitat I was calculated based on the total amount of energy used. Another important parameter which must be considered in evaluating Solar Habitat I is the amount of thermal energy supplied to Solar Haibtat I from the storage tank. This parameter is important as it is an indication of the amount of energy which must be supplied by the wind turbine generator and the solar collectors to heat Solar Habitat I. To evaluate this parameter, the experimental values for the amount of energy supplied from the storage tank to Solar Habitat I as a function of the average daily temperature were plotted. Figure 25 shows these points and a best fit line through them. As discussed earlier, the slope of this line represents the heating load of Solar Habitat I for an experimental daily solar insolation rate (7870 BTU/°F day with an insolation rate of 790 BTU/ft^2 day) and the x intercept is the reference temperature (T_x) at which the heating load begins (49.8°F). The results obtained indicate that other sources of energy, which are essential for human

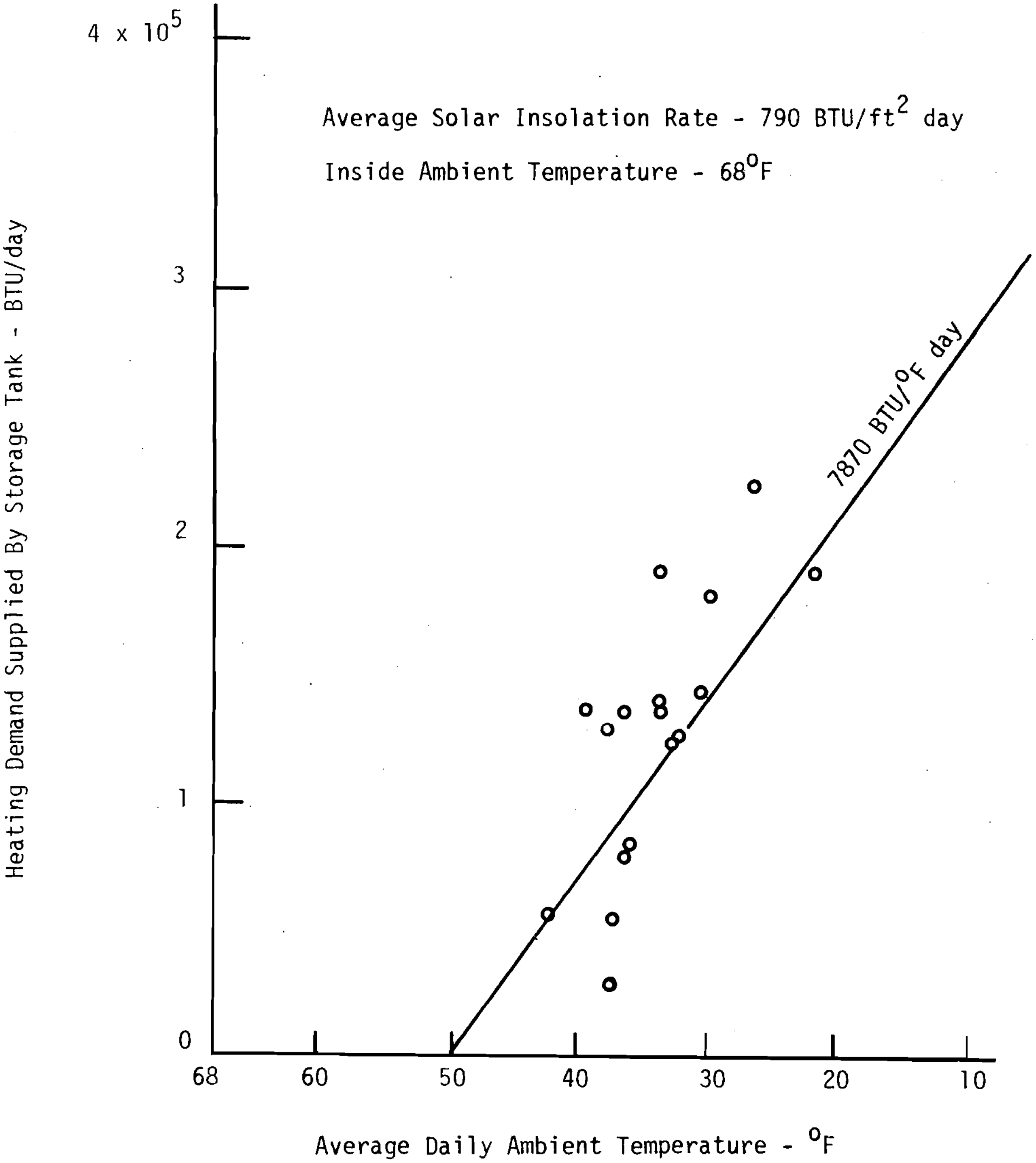


Figure 25. Heating Demand of Solar Habitat I Based On Energy Supplied from Storage Tank

habitation, (Q_E, Q_{ST}, Q_{Hw}, and Q_H - estimation of the values are discussed in Appendix I) supply the necessary thermal energy to heat Solar Habitat I on a 49.8°F average temperature day with a total solar insolation rate of 790 BTU/ft^2 day.

Thus far, the effects of the infiltration rate and the average daily temperature on the heating load have been discussed. To complete the experimental evaluation of Solar Habitat I a more detailed discussion of the effect of solar insolation on the heating load will be considered. As mentioned earlier in section 3.8 an empirical equation of the form

$$\dot{Q}_{SS} = C_i\ (T_x - T_{oa}) + C_{h\ell}\ (T_x - T_{oa}) + [C_w(DI - AI)](T_x - T_{oa}) \tag{20}$$

was proposed. Thus far the values of C_i, $C_{h\ell}$, AI, and T_x have been estimated to be 2007 BTU/°F day, 5850 BTU/°F day, 790 BTU/ft^2 day and 49.8°F, respectively, and the value of $\dot{Q}_{SS}$, T_{oa}, DI are variables which are experimentally measured. The remaining constant, C_w, which is unknown, is estimated by plotting (see Figure 26) the experimental daily supplied heating load (BTU/°F day) based on the 49.8°F reference point, as a function of the total daily solar insolation rate, DI. Through this data, a best fit line was obtained with the slope equal to C_w.

Thus, substituting the experimental constant into Equation 20, the following relationship for $\dot{Q}_{SS}$ can be obtained,

$$\dot{Q}_{SS} = 2007\ (49.8 - T_{oa}) + 5850\ (49.8 - T_{oa})$$

$$+ [-2.462\ (DI - 790.)]\ (49.8 - T_{oa}) \tag{21}$$

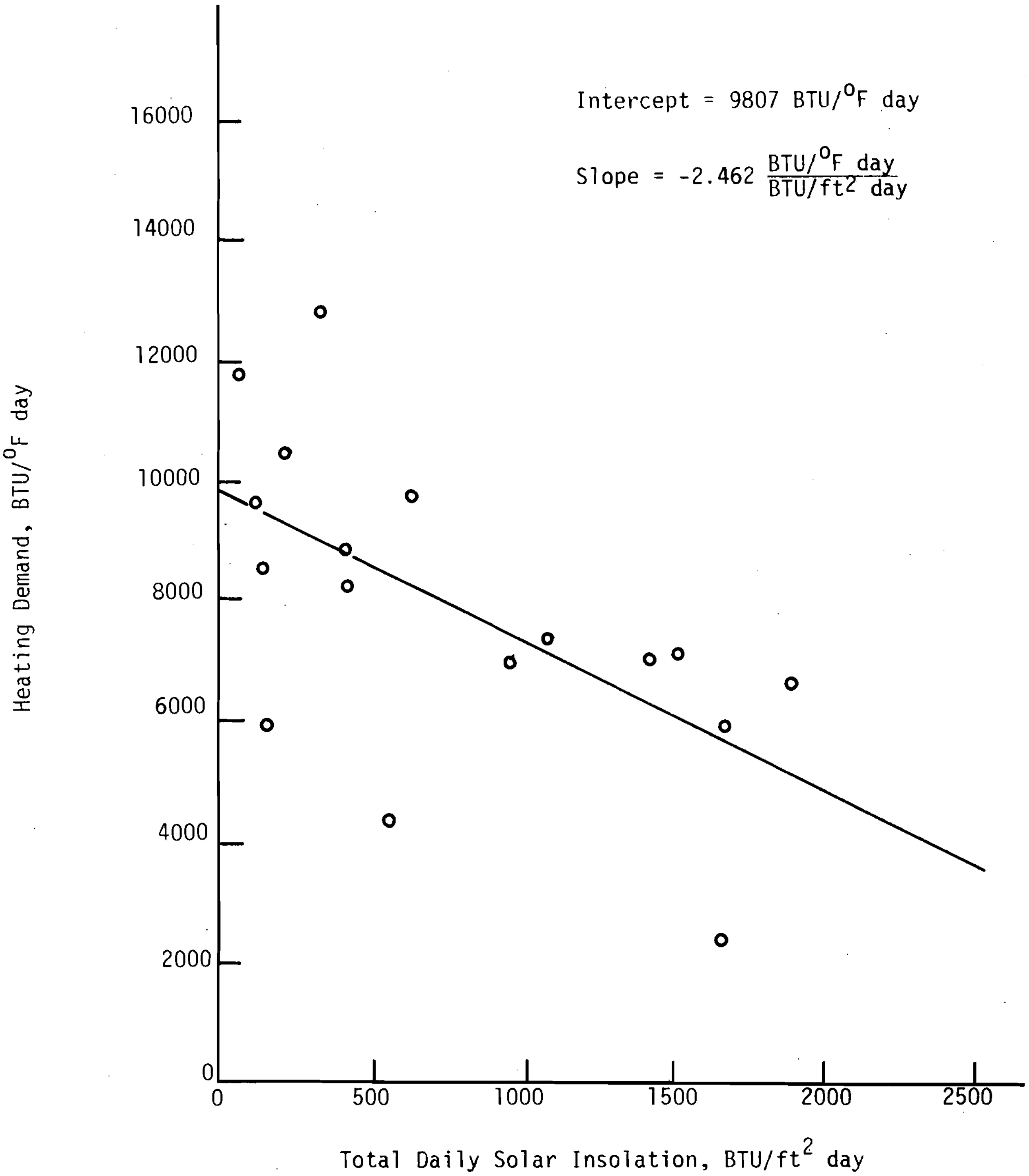


Figure 26. Effect of the Solar Insolation Rate On the Heating Load of Solar Habitat I

This represents an important relationship, since given average daily temperature and the total daily solar insolation available on vertical surface facing south, an estimation of the amount of thermal energy required from the wind turbine generator and the solar collectors can be made. Equation (21) is also important as it differentiates between the three rates of heat transfer ($\dot{Q}_i$, $\dot{Q}_{h\ell}$, and $\dot{Q}_w$), which comprise the total heating load of Solar Habitat I, $\dot{Q}_L$. From the results obtained to date, it appears that the analytical work compares favorably with experimental data. However, due to the many variables involved in doing the experimental testing, it is difficult to come to any concrete conclusions as to the specific values of the overall heat transfer coefficients through the walls, floors, ceilings, doors, and windows; the exact infiltration rate into Solar Habitat I and the amount of solar energy transmitted into and absorbed by Solar Habitat I.

CHAPTER V

RECOMMENDATIONS AND CONCLUSIONS

From the experimental results and analytical work conducted to date, a number of recommended changes to Solar Habitat I can be made. The first of these recommendations concerns the redesign of the storage tank insulation. As can be seen from Figure 19, the heat loss from the storage tanks far exceeds the heat loss rate desired. Due to the insulating of the outer walls of the storage tank, three-dimensional heat conduction becomes an important factor in the heat loss from the tank at high tank temperatures. The suggested design to solve this problem consists of insulating the inner portion of the concrete tank with 3 inches of polyurethane insulation then covering the urethane with a swimming pool liner. Due to mechanical deterioration and heat loss through the top covers, it is also strongly suggested that the tank covers be redesigned. A suggested design for the cover system is illustrated in Figure 27. Applying a one dimensional heat transfer model to this tank design, the estimated rate of heat transfer from the storage tank as a function of tank temperature is compared to the actual experimental results in Figure 28. It is estimated that 18% is lost to the ground compared to 29% with the previous storage tank design. It is believed that a concrete tank design similar to the one just discussed would be the best design for the wind furnace concept installed in a newly constructed home. If the wind furnace installation is a retrofit system, an insulated steel tank design may be more advantageous.

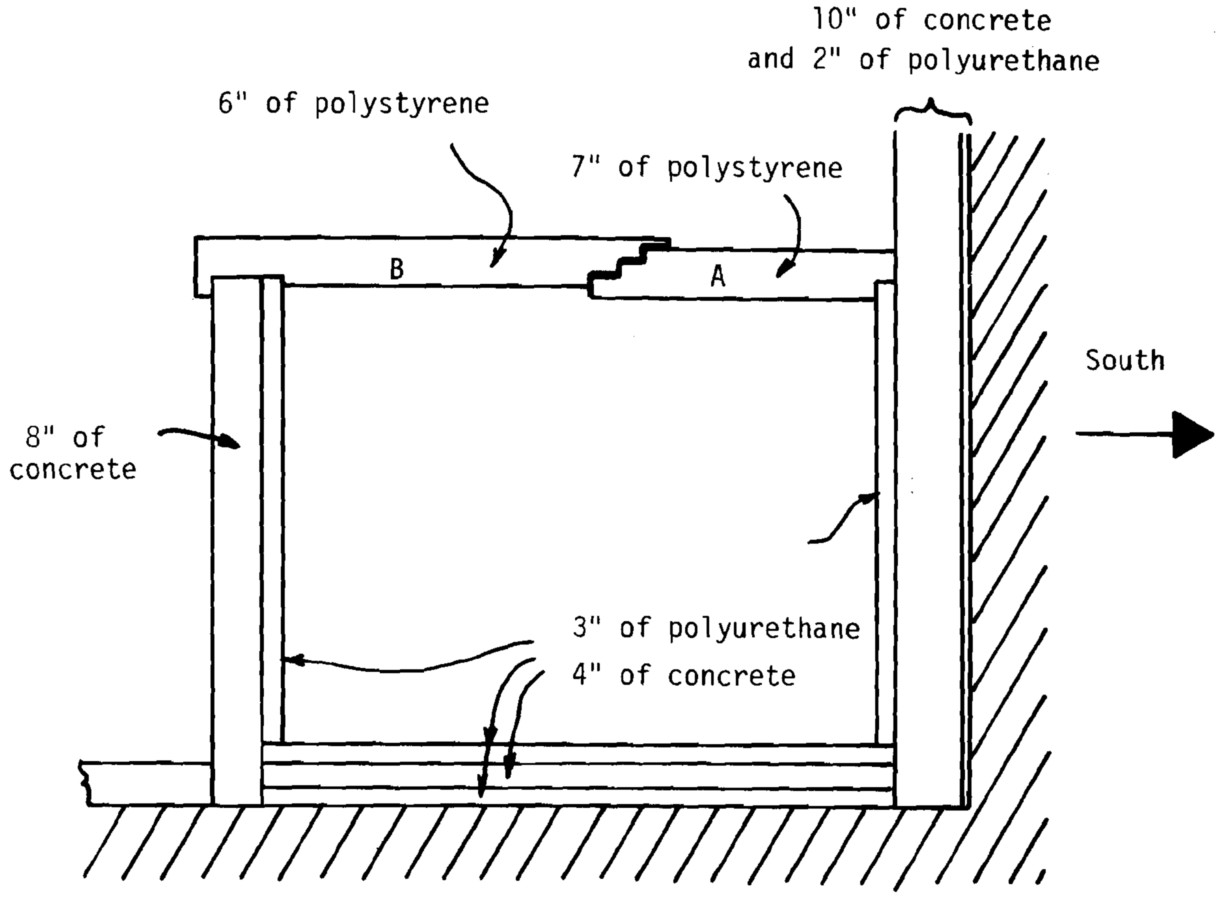


Figure 27. Redesign of Storage Tank and Cover

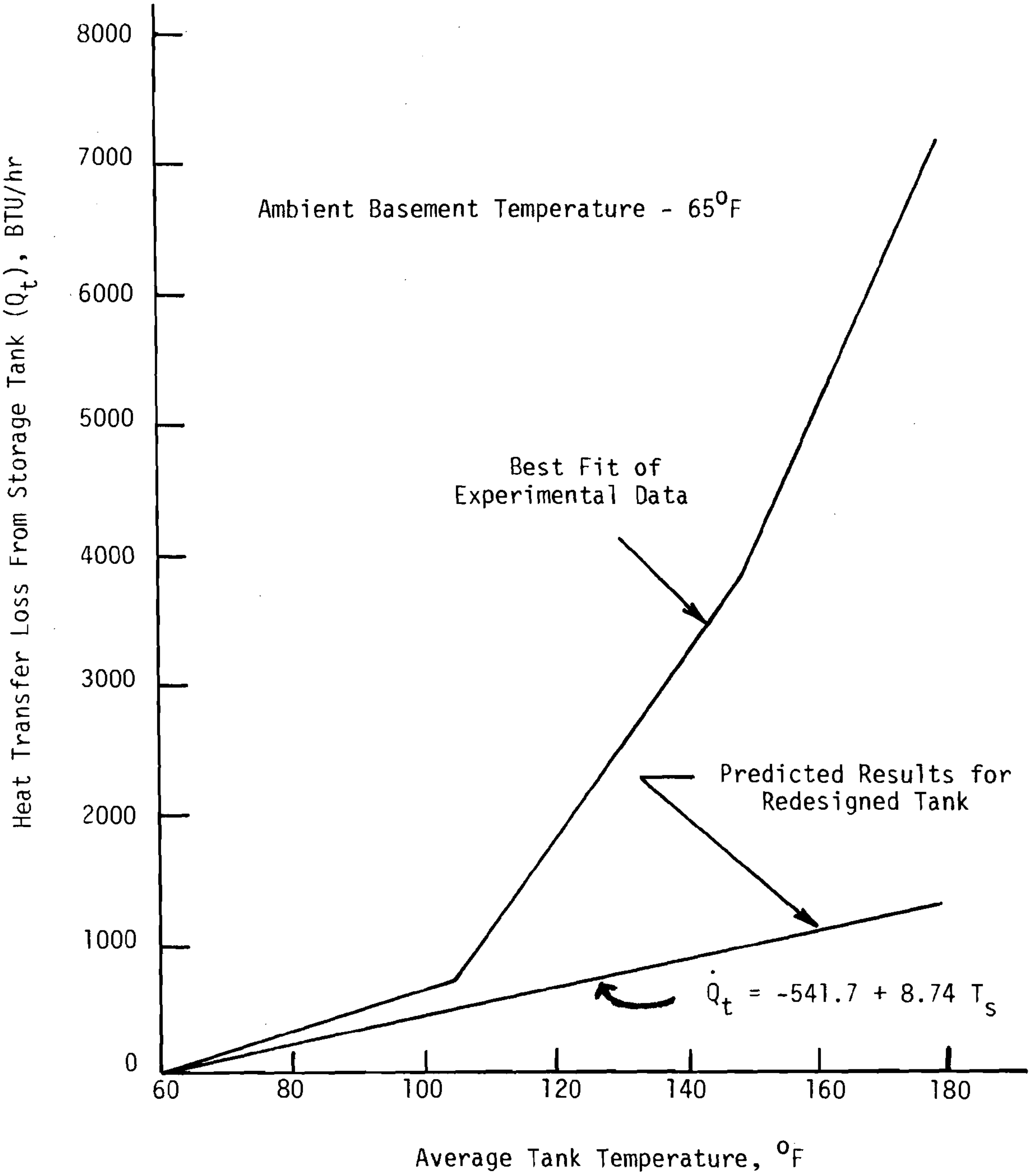


Figure 28. Comparison of the Experimental Results to the Predicted Performance of the Redesigned Storage Tank

Another problem which deserves consideration is the fact that the baseboard convectors may not be able to supply the needed thermal energy when the storage tank temperature is low. Figure 29 shows the heating load of Solar Habitat I as a function of the storage tank temperatures. This graph demonstrates the maximum amount of energy which can be supplied by the baseboard convectors for a given tank temperature and the total thermal energy, Q_S, which is supplied to Solar Habitat I for a given tank temperature. As can be seen from the graph, a tank temperature of 112^oF is needed to supply the heating demand for an average January temperature in the Amherst area of 24^oF. To determine the best solution to this problem, it is suggested that testing be conducted throughout an entire heating season to determine what effect the baseboard convectors have on the overall performance of the Wind Furnace concept. This data may then indicate if it is necessary to add more convectors or to let the auxiliary heating system provide the needed thermal energy.

As discussed in section 3.9, the method of obtaining data for overall system models must be evaluated to make optimum use of the data acquisition system. Essentially a key problem is that certain sensor signals need to be scanned frequently to obtain accurate data and other sensor signals need to be scanned less frequently. Presently, the only solution to this problem is to scan all the sensors at a frequent scan interval, thus the cassette tape becomes full of data in a very short time period. Figure 30 shows a plot of the number of days on line as a function of the scan period for varying numbers of channels

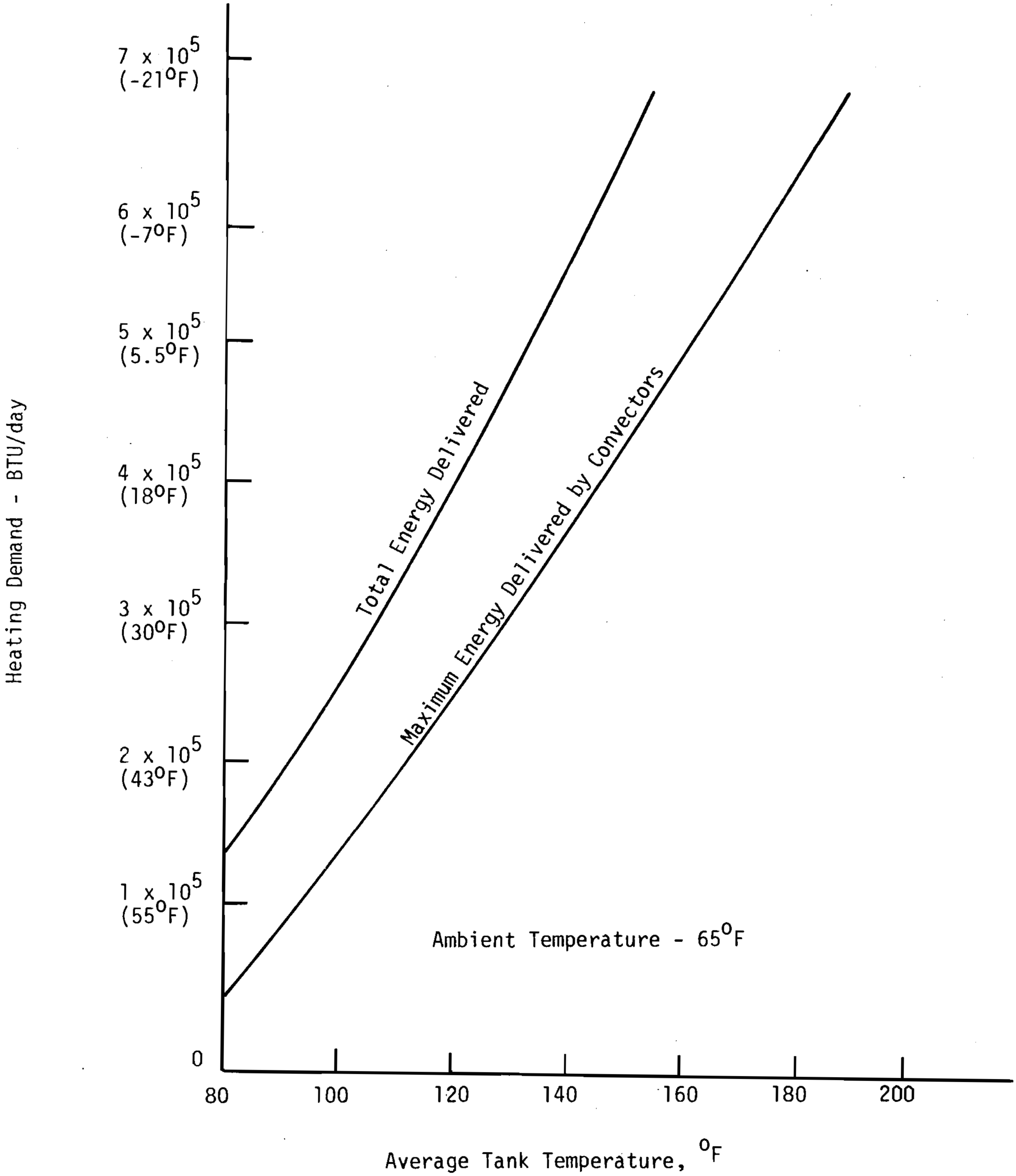


Figure 29. Maximum Thermal Energy Supplied to Solar Habitat I as a Function of the Tank Temperature

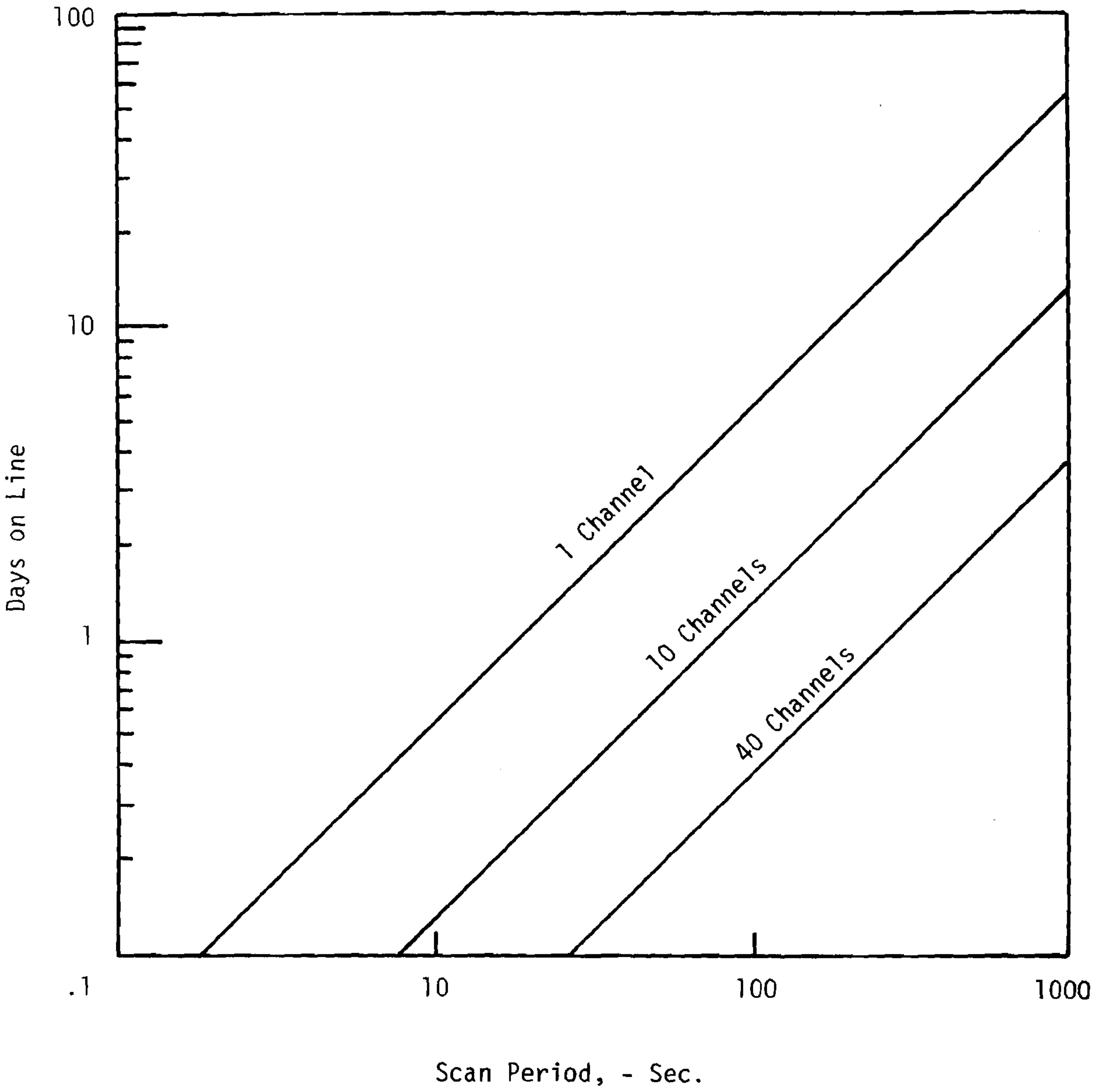


Figure 30. Capacity of the Cassette Tape as a Function of the Scan Period

scanned. From this figure, it can be seen that the length of time the data logger is on line decreases significantly as the scan period is decreased. The suggested solution to this problem is to integrate all sensor outputs which vary frequently with time. The suggested integration period would be a duration of fifteen minutes. Just prior to the finish of the integration period, scan all necessary channels by means of the remote scan control switch on the data logger. Integrating the necessary information affects several factors: increases the length of time the data logger is on line, it makes the analysis of data a much simpler and efficient process by decreasing the time needed by personnel to obtain and analyze the data and it decreases the storage and computer time needed to analyze the data.

One other problem which needs further consideration is temperature stratification within the storage tanks. At a tank temperature of 160°F, the tank can be stratified as much as 25°F. Since the storage tanks are such an integral part of the wind furnace concept it is felt that more effort in analytical work as well as experimental work should be devoted to obtain a better understanding of the storage tanks. If it is found that the stratification is significant under certain operating conditions, this information may be used to improve the overall performance of the subsystems, by using water from the warmest area of the tank for the baseboard convectors or using water from the coldest area of the tank for the solar collector loop. Also, since the performance of some of the subsystems is based on an average tank temperature, it is important to have a good understanding of the stratification in the tank to determine the true average tank temperature so that an accurate estimation of the subsystem performance can be obtained.

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APPENDIX A

ANALYTICAL MODELING OF STORAGE TANK

In the original computer modeling of the storage tank the following equation describes the rate of heat transfer from the tank.

$$\dot{Q}_t = A_s U_t (T_s - T_a) \qquad (1)$$

For this model the shape of the tank was assumed to be a cube. Thus the volume of the tank can be calculated by the following equation

$$T_v = G/7.4805(\text{gal./ft}^3) = 133.68\ (\text{ft}^3) \qquad (\text{A1})$$

where

T_v = Volume of the tank -ft^3

G = Number of gallons of water in the tank (1000 gallons)

Since the tank being considered was a cube the length of one side can be calculated by the following equation

$$\text{side} = T_v^{1/3} = 5.11\ \text{ft} \qquad (\text{A2})$$

where

side = Length of one side of the tank - ft

Thus the surface area of the entire tank, A_s, can be calculated by the following equation

$$A_s = (6)\ (\text{side})^2 = 156.62\ \text{ft}^2 \qquad (\text{A3})$$

To calculate the overall heat transfer coefficient of the tank, U_t, the following equation was used

$$U_t = \frac{1}{(\text{RIN} + \text{RINS} + T_n/k_t)} = .0761\ \text{BTU/hr ft}^2\ {}^o\text{F} \qquad (\text{A4})$$

where

RIN = inside film thermal resistance of the tank

$$= .68 \frac{\text{hr ft}^2\ {}^{o}\text{F}}{\text{BTU}}$$

RINS = thermal resistance of storage tank insulation

$$= 12 \frac{\text{hr ft}^2\ {}^{o}\text{F}}{\text{BTU}}$$

k_t = thermal conductivity of concrete = .54 BTU/hr ft ^{o}F

T_h = thickness of storage concrete wall = .25 ft

Thus substituting these results into equation (1) and assuming

$T_a = 65^{o}\text{F}$

$$\dot{Q}_t = A_s U_t (T_s - T_a) \qquad (1)$$

or

$$\dot{Q}_t \ (\text{BTU/hr}) = -\ 774.87 + 11.92\ T_s\ ({}^{o}\text{F}) \qquad (\text{A5})$$

The actual construction of the storage tank was different from the original tank design therefore an improved analytical model was developed. This improved analytical model solves for the variables in Equation 3.

From Figure 7 it can be seen that

$$A_E = A_W = (8.25\text{ ft}) \times (6.5\text{ ft}) = 53.625\text{ ft}^2 \qquad (\text{A6})$$

$$A_N = A_S = (6.5\text{ ft}) \times (4.67\text{ ft}) = 30.333\text{ ft}^2 \qquad (\text{A7})$$

$$A_B = A_T = (8.25\text{ ft}) \times (4.67\text{ ft}) = 38.05\text{ ft}^2 \qquad (\text{A8})$$

To calculate the overall heat transfer coefficients in Equation 3 the following thermal conductivities of the materials used in the construction of the storage tanks are: polyurethane, k_u = .0133 BTU/hr ft ^{o}F, polystyrene, k_s = .0233 BTU/hr ft ^{o}F, and concrete, k_c = .54 BTU/hr ft ^{o}F. Since the film coefficients are a negligible part of the overall heat transfer coefficients they will be neglected in this analysis. The overall heat transfer coefficients for the north, east, west, south, and bottom of the storage tanks are calculated by the following equations,

$$U_{N,E,W} = \frac{1}{T_{ni}/k_s + T_n/k_c} = .0499 \text{ BTU/hrft}^2{}^\circ\text{F} \tag{A9}$$

$$U_S = \frac{1}{T_{si}/k_u + T_s/k_c} = .0712 \text{ BTU/hrft}^2{}^\circ\text{F} \tag{A10}$$

and

$$U_B = \frac{1}{T_{bi}/k_u + T_b/k_c} = .0515 \text{ BTU/hrft}^2{}^\circ\text{F} \tag{A11}$$

where

T_{ni} = Thickness of insulation on the north, east, and west walls = .25 ft.

T_n = Thickness of concrete for the north, east, and west walls = .67 ft.

T_{si} = Thickness of insulation used on the south wall = .167 ft.

T_s = Thickness of concrete for the south wall = .83 ft.

T_{bi} = Thickness of insulation underneath the floor = .25 ft.

T_b = Thickness of the basement floor = .33 ft.

Since the front portion of the tank cover is constructed from different materials than the rear section (Figure 7), the analysis of the cover was divided into two sections. The area of the front, A_{TF}, is

$$A_{TF} = (4.33 \text{ ft}) \times (5.33 \text{ ft}) = 23.1 \text{ ft}^2 \tag{A12}$$

and the area of the rear, A_{TR}, is

$$A_{TR} = (4.25\ \text{ft}) \times (4.67\ \text{ft}) = 19.8\ \text{ft}^2 \tag{A13}$$

To calculate the overall heat transfer coefficients for the front and rear sections, U_{TF} and U_{TR} respectively, the following equations are used

$$U_{TF} = \frac{1}{T_{tf}/k_s} = .0796\ \text{BTU/hrft}^2{}^\circ\text{F} \tag{A14}$$

$$U_{TR} = \frac{1}{T_{tr}/k_u} = .0533\ \text{BTU/hrft}^2{}^\circ\text{F} \tag{A15}$$

where

T_{tf} = Thickness of the insulation used for front portion of the cover = .167 ft.

T_{tr} = Thickness of the insulation used for the rear portion of the cover = .25 ft.

Also in this analysis it should be noted that the ambient temperature in the basement was assumed to be 65°F, the ground temperature below the basement, T_b, was assumed to be 55°F and the temperature on the south wall, T_g, assumed to be the

$$T_g = \frac{T_b + T_{aa}}{2} \tag{A16}$$

where T_{aa} = Average temperature of the ambient air temperature for the period under consideration (for test completed T_g = 44°F).

Thus substituting these results into Equation 3

$$Q_t = U_E A_E (T_s - T_a) + U_W A_W (T_s - T_a) + U_N A_N (T_s - T_a) + U_{TF} A_{TF} (T_s - T_a)$$
$$+ U_{TR} A_{TR} (T_s - T_a) + U_B A_B (T_s - T_b) + U_s A_s (T_s - T_g) \qquad \text{(A17)}$$

or

$$\dot{Q}_t(\text{BTU/hr}) = -873.04 + 14.43\, T_s(^{o}\text{F}) \qquad \text{(A18)}$$

APPENDIX B

THEORETICAL COLLECTOR PERFORMANCE

1. Computer Program: DIXONI
2. Results of DIXONI Computer Runs

```
00100 PROGRAM DIXON1(INPUT,OUTPUT)
00105C
00110C       PROGRAM CALCULATES COLLECTOR EFFICIENCY ACCORDING TO
00120C       DUFFIE AND BECKMAN-"SOLAR ENERGY THERMAL PROCESSES"
00130C       FOR COPPER ABSORBER WITH TWO GLAZINGS,INNER TEDLAR
00140C       OUTER GLASS
00150C
00160 PRINT 100
00170 100 FORMAT(1X,*TA=?*,2X,*FLOW=?*,2X,*HR=?*,2X,*WNSP=?*)
00180 READ,TA,FLOW,HR,WNSP
00190 TA1=(TA-32.)/1.8+273.
00200 TA2=TA+460.
00210 FLOW0=(FLOW/10.)*491.
00220 FLOW1=FLOW0*.454
00230 CP=.85
00240 CP1=CP*.293*1.8/.454
00250 HR1=HR*3.155
00260 H1=301.84
00270 DI1=.008255
00280 TN=6.
00290 TL1=2.1336
00300 AC1=1.59831
00310 SIGMA=1.714E-09
00320 EP=.98
00330 ET=.63
00340 EG=.88
00350 UT0=0.
00360 TFI=TA
00370 TAU=0.3
00380 HW=1.+0.3*WNSP
00390 DEL1=3.429E-04
00400 EK1=385.
00410 W1=.127
00420 D1=.009525
00430 S=HR*.79
00440 S1=S*.293/.093
00450 TSKY1=.0552*TA1**1.5
00460 TSKY=((TSKY1-273.)*1.8)+32.
00470 TSKY2=TSKY+460.
00480 PRINT,TA,FLOW,HR,WNSP
00490 PRINT 200
00500 200 FORMAT(//,6X,3HTFI,7X,3HTFE,7X,3HTPM,8X,2HT2,8X,2HT1,
00510+9X,2HUL,6X,2HQU,8X,1HX,7X,3HEFF,/)
00520 60 CONTINUE
00530 TFI1=(TFI-32.)/1.8+273.
00540 TFI2=TFI+460.
00550 TFE=TFI+10.
00560 TFE1=(TFE-32.)/1.8+273.
00570 TFE2=TFE+460.
00580 20 QU01=FLOW1*CP1*(TFE1-TFI1)
00590 TPM1=(QU01/(H1*3.1416*DI1*TN*TL1))+(TFE1+TFI1)/2.
00600 TPM=(TPM1-273.)*1.8+32.
00610 TPM2=TPM+460.
00620C
00630C        UT CALCULATED ACCORDING TO WHILLIER,
00640C        SOLAR ENERGY 7,43,1963
00650C
00660 T12=.15*(TPM2-TA2)+TA2
00670 T22=.75*(TPM2-TA2)+TA2
00680 30 CONTINUE
00690 HR1S=SIGMA*(T12**4-TSKY2**4)/(T12-TSKY2)
```

```
00700 HRP1=SIGMA*(TPM2**4-T12**4)/(TPM2-T12)
00710 HRP2=SIGMA*(TPM2**4-T22**4)/(TPM2-T22)
00720 HR21=SIGMA*(T22**4-T12**4)/(T22-T12)
00730 HP2=.17*(TPM2-T22)**.25
00740 H21=.17*(T22-T12)**.25
00750 XS1=(T12-TSKY2)/(T12-TA2)
00751 EP1=1./(1./EP+1./EG-1.)
00752 EP2=1./(1./EP+1./E1-1.)
00753 E21=1./(1./E1+1./EG-1.)
00760 ZA=1./(HW+EG*HR1S*XS1)
00770 ZB=TAU*HRP1*EP1
00780 ZC=1./(HP2+HRP2*EP2)
00790 ZD=1./(H21+HR21*E21)
00800 UT=1./(ZA+1./(ZB+1./(ZC+ZD)))
00810 T12=TA2+UT*(TPM2-TA2)/(HW+EG*HR1S*XS1)
00820 T22=TPM2-(UT*(TPM2-TA2)-TAU*HRP1*EP1*(TPM2-T12))/
00830+(HP2+HRP2*EP2)
00840 DUT=UT-UT0
00850 IF(ABS(DUT).LT..001) GO TO 40
00860 UT0=UT
00870 GO TO 30
00880 40 CONTINUE
00890 UT1=UT*5.678
00900 UL3=.6814+.2554
00910 UL1=UT1+UL3
00920 UL=UL1/5.678
00930 EM1=(UL1/(EK1*DEL1))**.5
00940 A1=EM1*(W1-D1)/2.
00950 F11=TANH(A1)/A1
00960 F21=1./(((W1*UL1)/(3.1416*DI1*H1))+(W1/(D1+(W1-D1)*F11)))
00970 B1=FLOW1*CP1/(AC1*UL1)
00980 F31=B1*(1.-1./EXP(F21/B1))
00990 QU1=F31*AC1*(S1-UL1*(TFI1-TA1))
01000 DQ1=QU1-QU01
01010 IF(ABS(DQ1).LE.1.) GO TO 50
01020 IF(DQ1.LT.0.)TFE1=TFE1-.01
01030 IF(DQ1.GT.0.)TFE1=TFE1+.01
01040 GO TO 20
01050 50 EFF=QU1/(HR1*AC1)
01060 X=(((TFE+TFI)/2.)-TA)/HR
01070 T2=T22-460.
01080 T1=T12-460.
01090 QU=QU1/.293
01100 TFE=(TFE1-273.)*1.8+32.
01110 PRINT 120,TFI,TFE,TPM,T2,T1,UL,QU,X,EFF
01120 120 FORMAT(6(4X,F6.2),4X,F6.1,4X,F4.2,4X,F4.2)
01130 IF(EFF.LE..01) GO TO 70
01135 TFI=TFI+10.
01140 GO TO 60
01150 70 STOP
01160 END
READY.
```

```
RUN

 77/03/01. 13.26.43.
   FILE   DIXON1

 TA=?  FLOW=?  HR=?  WNSP=?
? 10.,3.,280.,5.
              10.00              3.00              280.00              5.00


       TFI        TFE        TPM        T2         T1         UL       QU        X        EFF

      10.00      36.16      40.32      25.85      10.07      .77     3278.4     .02     [illegible]
      20.00      45.14      49.13      30.69      10.35      .79     3150.3     .05     [illegible]
      30.00      54.15      57.99      35.98      11.45      .80     3026.5     .09     [illegible]
      40.00      63.18      66.86      41.60      13.14      .80     2904.1     .13     [illegible]
      50.00      72.17      75.69      47.29      14.99      .81     2778.7     .16      .58
      60.00      81.21      84.59      52.60      18.63      .81     2658.5     .20      .55
      70.00      90.12      93.31      58.13      20.32      .82     2520.4     .23      .52
      80.00      99.00     102.02      64.73      21.07      .84     2381.8     .27      .47
      90.00     107.88     110.73      70.62      23.22      .85     2242.2     .30      .47
     100.00     116.75     119.41      76.56      25.45      .86     2099.2     .34      .44
     110.00     125.58     128.06      82.54      27.75      .87     1952.6     .38      .41
     120.00     134.37     136.66      88.55      30.11      .88     1802.6     .41      .37
     130.00     143.15     145.24      94.60      32.54      .89     1649.0     .45      .34
     140.00     151.89     153.78     100.68      35.04      .91     1491.9     .48      .31
     150.00     160.61     162.30     106.80      37.60      .92     1331.1     .52      .28
     160.00     169.33     170.82     112.98      40.24      .93     1166.7     .55      .24
     170.00     178.00     179.27     119.16      42.93      .95      998.7     .57      .21
     180.00     186.62     187.67     125.36      45.67      .96      827.2     .63      .17
     190.00     195.23     196.06     131.60      48.49      .97      651.9     .66      .14
     200.00     203.79     204.39     137.84      51.36      .99      473.1     .70      .10
     210.00     212.33     212.70     144.12      54.30     1.00      290.5     .73      .06
     220.00     220.86     220.99     150.43      57.30     1.02      104.2     .77      .02
     230.00     229.33     229.22     156.73      60.36     1.03      -85.6     .80     -.02
     STOP

SRU      22.336 UNTS.

RUN COMPLETE.
```

```
RNH

 TA=?  FLOW=?  HR=?  WNSP=?
? 40.,3.,280.,5.
         40.00            3.00             280.00            5.00


     TFI       TFE       TPM       T2        T1         UL       QU         X        EFF

    40.00     65.79     69.88     55.67     40.12       .85    3229.9      .02      .67
    50.00     74.69     78.61     60.60     40.67       .87    3094.4      .05      .64
    60.00     83.68     87.44     66.11     42.26       .87    2966.2      .09      .62
    70.00     92.64     96.23     71.75     44.10       .87    2835.7      .13      .59
    80.00    101.57    105.00     77.50     46.13       .88    2702.4      .16      .56
    90.00    110.46    113.71     83.24     48.14       .89    2564.5      .20      .53
   100.00    119.34    122.42     89.07     50.29       .90    2423.4      .23      .50
   110.00    128.17    131.06     94.90     52.46       .91    2278.2      .27      .47
   120.00    136.98    139.68    100.79     54.72       .92    2129.4      .30      .44
   130.00    145.78    148.29    106.72     57.05       .93    1977.0      .34      .41
   140.00    154.52    156.83    112.68     59.43       .94    1821.0      .38      .38
   150.00    163.24    165.34    118.65     61.86       .96    1660.9      .41      .34
   160.00    171.94    173.84    124.68     64.37       .97    1497.5      .45      .31
   170.00    180.61    182.30    130.74     66.95       .98    1330.5      .48      .28
   180.00    189.28    190.76    136.88     69.64      1.00    1160.0      .52      .24
   190.00    197.89    199.15    143.00     72.35      1.01     985.6      .55      .20
   200.00    206.47    207.50    149.14     75.11      1.03     807.5      .59      .17
   210.00    215.01    215.81    155.30     77.93      1.04     625.7      .63      .13
   220.00    223.54    224.10    161.49     80.82      1.05     440.1      .66      .09
   230.00    232.03    232.35    167.70     83.76      1.07     250.9      .70      .05
   240.00    240.48    240.55    173.92     86.76      1.08      57.9      .73      .01
   250.00    248.91    248.74    180.17     89.82      1.10    -138.9      .77     -.03
   STOP

SRU     21.784 UNTS.

RUN COMPLETE.
```

```
RNH

 TA=?  FLOW=?  HR=?  WNSP=?
? 70.,3.,280.,5.
          70.00              3.00              280.00              5.00

     TFI       TFE       TPM        T2         T1          UL      QU        X       EFF

    70.00     95.39     99.43     85.58      70.39        .94    3180.5     .02      .66
    80.00    104.31    108.17     90.98      71.93        .94    3047.0     .05      .63
    90.00    113.25    116.94     96.62      73.87        .94    2912.8     .09      .60
   100.00    122.13    125.65    102.28      75.87        .94    2773.9     .13      .55
   110.00    131.00    134.34    107.95      78.61        .95    2631.9     .16      .53
   120.00    139.83    142.98    113.76      80.09        .96    2483.8     .20      .52
   130.00    148.62    151.58    119.55      82.30        .97    2332.8     .23      .48
   140.00    157.38    160.14    125.37      84.56        .98    2177.9     .27      .45
   150.00    166.10    168.66    131.22      86.89        .99    2019.3     .30      .42
   160.00    174.81    177.16    137.12      89.29       1.01    1857.0     .34      .39
   170.00    183.49    185.64    143.07      91.76       1.02    1690.9     .38      .35
   180.00    192.12    194.05    149.02      94.28       1.03    1521.2     .41      .32
   190.00    200.74    202.44    155.01      96.87       1.05    1347.7     .45      .28
   200.00    209.37    210.86    161.07      99.54       1.06    1170.2     .48      .24
   210.00    217.91    219.17    167.13     102.27       1.08     989.5     .52      .21
   220.00    226.44    227.46    173.19     105.04       1.09     804.6     .55      .17
   230.00    234.94    235.73    179.30     107.86       1.11     615.9     .59      .13
   240.00    243.39    243.93    185.40     110.74       1.12     423.6     .63      .09
   250.00    251.83    252.12    191.53     113.67       1.14     227.4     .66      .05
   260.00    260.24    260.28    197.69     116.67       1.15      27.3     .70      .01
   STOP

SRU      18.467 UNTS.

RUN COMPLETE.
```

APPENDIX C

INSTRUMENTATION

The instrumentation necessary to calibrate the subsystems and the models was installed at appropriate locations in Solar Habitat I. Instrumentation Summary, lists each subsystem, the instrumentation necessary to calibrate that subsystem, the subsystem location, and the method used to record the sensor's output. For many of the tests, the data was received by a data logger and then recorded on cassette tape. At a later time, this data is transferred to the UMass time-sharing computer system, and analyzed using appropriate data reduction programs.

INSTRUMENTATION SUMMARY

Subsystem		Sensor Description	Location of Sensor Within System	Method Used to Record Sensor Output
Piping	1)	Pressure gauge range: 30 inches vacuum to 15psi	before the pump that pumps water from the tank through the heat exchanger in the collector loop	log book
	2)	Pressure gauge range: 0 to 30 psi	after the pump that pumps water from the tank through the heat exchanger in the collector loop	log book
	3)	Pressure gauge range: 30 inches vacuum to 15 psi	after the heat exchanger on the tank side of the collector loop	log book
	4)	Pressure gauge range: 0 to 60 psi	before the pump that pumps propylene-glycol water mixture through the solar collector	log book
	5)	Pressure gauge range: 0 to 60 psi	after the pump that pumps propylene-glycol water mixture through the solar collectors	log book
	6)	Pressure gauge range: 0 to 100 psi	before the heat exchanger on the solar collector side of the collector loop	log book
	7)	Rotameter 6.6 gpm maximum flow	accurately calibrated flow meter used as a secondary standard to calibrate the flow meters in the piping system	log book
	8)	Rotameter 86 gpm maximum flow	rotameter used on the tank side of the collector loop	log book
	9)	Rotameter 11 gpm maximum flow	rotameter used to measure the total flow rate through the solar collectors	log book

INSTRUMENTATION SUMMARY

Subsystem	Sensor Description	Location of Sensor Within System	Method Used to Record Sensor Output
	10) Three identical rotameters 3.55 gpm maximum flow	one rotameter is used in each of three baseboard convector loops	log book
Storage Tanks Also use sensors 39, 43, and 44 for storage tank tests	11) Type T thermocouple	in 1000 gallon tank at an approximate position of 3 ft from south wall, 3 ft from the east wall and 1 inch above the tank floor	Data Acquisition System (D.A.S.) Channel-0
	12) Type T thermocouple	in 1000 gallon tank at an approximate position of 3 ft from south wall, 3 ft from the east wall and 1 inch above the tank floor	D.A.S. Channel-1
	13) Type T thermocouple	in 1000 gallon tank at an approxmate position of 2 1/2 ft from the south wall, 2 ft from the east wall and 1 ft above the tank floor	D.A.S. Channel-2
	14) Type T thermocouple	in 1000 gallon tank at an approximate position of 2 1/2 ft from the south wall, 2 ft from the east wall and 2 ft above the tank floor	D.A.S. Channel-3
	15) Type T thermocouple	in 1000 gallon tank at an approximate position of 2 1/2 ft from the south wall, 2 ft from the east wall and 3 ft above	D.A.S. Channel-4
	16) Type T thermocouple	in 1000 gallon tank at an approximate position of 2 1/2 ft from the south wall, 2 ft from the east wall and 4 1/4 ft above the tank floor	D.A.S. Channel-5

INSTRUMENTATION SUMMARY

Subsystem		Sensor Description	Location of Sensor Within System	Method Used to Record Sensor Output
Storage Tanks Also use sensors 39, 43 and 44 for storage tank tests	17)	Type T thermocouple	in 1000 gallon tank at an approximate position of 2 1/2 ft from the south wall, 2 ft from the east wall and 6 ft above the tank floor	D.A.S. Channel-6
	18)	Type T thermocouple	in 2000 gallon tank at an approximate position of 2 ft from the south wall, 2 ft from the east wall and 1 foot above the tank floor	D.A.S. Channel-25
Solar Collectors Also use sensors 4, 5, 6, 9, 25, 26, 43, and 44 for the solar collector tests	19)	Type T thermocouple	at inlet to the collectors	D.A.S. Channel-14
	20)	Type T thermocouple	at the exit of the collectors	D.A.S. Channel-15
	21)	Type T thermocouple	on plate of the collector	D.A.S. Channel-13
	22)	Black and White Pyranometer	on a vertical surface with an azimuth angle equal to zero	D.A.S. Channel-26
Heat Exchanger Also use sensors 2, 3, 4, 6, 8, 9, 19 and 20 for heat exchanger tests	23)	Type T thermocouple	at inlet to the heat exchanger on the tank side of the collector loop	D.A.S. Channel-17
	24)	Type T thermocouple	at exit of the heat exchanger on the tank side of the collector loop	D.A.S. Channel-18

INSTRUMENTATION SUMMARY

Subsystem		Sensor Description	Location of Sensor Within System	Method Used to Record Sensor Output
Wind Turbine Generator (WTG)	25)	Wind direction sensor	at a height equal to the height of the hub of the WTG, approximately 40 ft from the WTG	D.A.S. Channel-32. Also recorded on a strip chart 2 channel recorder
	26)	Wind speed sensor	at same position as sensor 25	D.A.S. Channel-33. Also recorded on a strip chart 2 channel recorder
	27)	Rectified voltage output of WTG	signal monitored at central logic unit	D.A.S. Channel-34 and strip chart recorder
	28)	Rectified current output of WTG	signal monitored at central logi	D.A.S. Channel-35 and strip chart recorder
Baseboard Convectors Also use sensors 10, 39, 40, 41 and 42 for baseboard convector tests	29)	Type T thermocouple	inlet to the basement loop	D.A.S. Channel-22
	30)	Type T thermocouple	at inlet to the living area loop	D.A.S. Channel-23
	31)	Type T thermocouple	at inlet to the bedroom loop	D.A.S. Channel-24
	32)	Type T thermocouple	at exit of the basement loop	D.A.S. Channel-19
	33)	Type T thermocouple	at exit of the living room area loop	D.A.S. Channel-20
	34)	Type T thermocouple	at exit of the bedroom loop	D.A.S. Channel-21
	35)	On-off signal for basement loop		D.A.S. Channel-30
	36)	On-off signal for living area loop		D.A.S. Channel-28

INSTRUMENTATION SUMMARY

Subsystem	Sensor Description	Location of Sensor Within System	Method Used to Record Sensor Output
Baseboard Convectors Also use sensors 10, 39, 40, 41 and 42 for baseboard convector tests	37) On-off signal for bedroom loop		D.A.S. Channel-29
Hot Air Furnace	38) Positive displacement	in propane line that is connected to the hot air furnace	log book
Solar Habitat I Also uses sensors 10, 14, 18, 22, 25, 26, and 29-38 for Solar Habitat I tests	39) Type T thermocouple	in southeast section of the basement at an approximate height of 5 feet	D.A.S. Channel-7
	40) Type T thermocouple	in northwest section of the basement at an approximate height of one foot	D.A.S. Channel-8
	41) Type T thermocouple	in living area at an approximate height of 3 ft	D.A.S. Channel-9
	42) Type T thermocouple	in bedroom area at an approximate height of 4 ft	D.A.S. Channel-10
	43) Type T thermocouple	at northeast section, of Solar Habitat I at an approximate height of 10 ft above ground	D.A.S. Channel-11
	44) Type T thermocouple	at northwest section outside of Solar Habitat I at an approximate height of 10 ft	D.A.S. Channel-12

INSTRUMENTATION SUMMARY

Subsystem	Sensor Description	Location of Sensor Within System	Method Used to Record Sensor Output
Models 1A, 2, 3A, 3B Also use sensors 8, 9, 10, 14, 19, 20, 22-38, 43, and 44 to test the various models	45) Kilowatt-hour meter	East wall of Solar Habitat I	log book
	46) Pyranometer	fixed at an altitude angle of 60° and an azimuth angle of 0°, used to obtain continuous solar insolation for Amherst, MA	2-channel recorder
	47) Linear thermistor	placed at Solar Habitat I, used to monitor the ambient air temperature continuously	3 channel recorder

APPENDIX D

PIPING SYSTEM INFORMATION

As mentioned earlier the important information to be obtained for the piping system is the calibration of the pressure gauges and the flowmeters. The data obtained for the pressure gauges and the flowmeters calibrations is in Table D1 and Table D2 respectively. From this data a best fit line was obtained using a regression analysis canned program (21).

It should be noted that the three rotameters in the convector loops were calibrated simultaneously. This was done because it was difficult to obtain a flow rate through one of the parallel convector loops alone when domestic water was passed through the standard flow meter (the standard flow meter was connected in series with the three parallel convector loops). Since the three rotameters in the convector loops were identical, these sensors were calibrated by summing the three flow rates through the convector rotameters and comparing these values to the calibrated standard rotameter. Thus, one average calibration for the three convector rotameters was obtained.

TABLE D1

DATA FOR PRESSURE GAUGE CALIBRATIONS

first column - standard pressure - psig
second column - sensor reading - psig
x - reading on pressure gauge calibrated
y - actual pressure (psig)

Sensor - 1
sensitivity - .5 psig/div
accuracy - ±.14 psig
calibration -y=1.0092x-.0019

0.	0.
0.	0.
0.	0.
5.	5.
5.	5.1
5.	4.9
10.	9.9
10.	9.8
10.	9.8
15.	14.8
15.	15.0
15.	14.9

Sensor - 2
sensitivity - .5 psig/div
accuracy - ±.30 psig
calibration -y=.9899x-.0230

0.	0.
0.	0.
0.	0.
5.	5.05
5.	5.2
5.	5.05
10.	10.05
10.	10.0
10.	10.1
15.	15.05
15.	15.05
15.	15.05
20.	20.2
20.	20.
20.	20.05
25.	25.1
25.	25.2
25.	25.1
30.	30.5
30.	30.3
30.	30.5

Sensor - 3
sensitivity - .5 psig/div
accuracy - ±1.2 psig
calibration -y=1.0804x-.4949

0.	0.5
0.	0.5
0.	0.5
5.	5.
5.	4.9
5.	5.1
10.	9.8
10.	9.8
10.	9.7
15.	14.2
15.	14.4
15.	14.4

TABLE D1 (cont.)

Data for Pressure Gauge Calibrations

Sensor - 4
sensitivity - 1 psig/div
accuracy - ±.32 psig
calibration - y=.9947x-.3545

0.	0.
0.	0.
0.	0.
5.	5.1
5.	5.2
5.	5.3
10.	10.
10.	10.
10.	10.
15.	15.
15.	15.2
15.	15.
20.	20.
20.	19.8
20.	20.
25.	25.
25.	25.
25.	25.
30.	30.
30.	30.
30.	29.9
35.	34.8
35.	34.5
35.	34.8
40.	39.7
40.	39.9
40.	39.5
45.	44.8
45.	45.
45.	44.8
50.	49.8
50.	49.5
50.	49.9
55.	54.8
55.	54.9
55.	54.8
60.	59.9
60.	60.
60.	59.9

Sensor - 5
sensitivity - 1 psig/div
accuracy - ±.30 psig
calibration - y=1.005x-.0704

0.	0.
0.	0.
0.	0.
5.	5.2
5.	5.2
5.	5.2
10.	10.5
10.	10.8
10.	10.8
15.	15.3
15.	15.6
15.	15.8
20.	20.2
20.	20.5
20.	20.8
25.	25.2
25.	25.2
25.	25.8
30.	30.8
30.	30.5
30.	30.8
35.	35.6
35.	35.8
35.	36.
40.	40.5
40.	40.8
40.	40.8
45.	45.8
45.	45.8
45.	45.8
50.	50.8
50.	50.1
50.	50.2
55.	55.8
55.	55.1
55.	55.2
60.	60.8
60.	60.8
60.	60.2

Sensor - 6
sensitivity - 1 psig/div
accuracy - ±.19 psig
calibration - y=.9962x-.0163

0.	0.
0.	0.
5.	4.7
5.	4.9
5.	5.
10.	10.
10.	10.
10.	10.5
15.	15.
15.	15.2
15.	14.9
20.	20.
20.	20.2
20.	20.1
25.	25.
25.	25.
25.	25.1
30.	30.5
30.	30.4
30.	30.5
35.	35.2
35.	35.
35.	35.2
40.	40.2
40.	40.5
40.	40.3
45.	45.2
45.	45.
45.	45.
50.	50.
50.	50.
50.	50.1

TABLE D2

DATA FOR ROTAMETER CALIBRATIONS

y - actual flow rate in gpm
x - flow meter reading

Sensor - 7
1st column-reading on secondary standard rotameter - %
2nd column-experimental results of actual flow rate - gpm
sensitivity - .066 gpm/div
accuracy - ±.0198 gpm
calibration - $y=.06583x-.00709$

97.6	6.4428
20.	1.3003
10.0	.6700
35.1	2.2913
64.6	4.2325
49.0	3.2272
80.3	5.2702
81.7	5.3712
97.8	6.4223

Sensor - 9
1st column-actual flow rate through secondary standard rotameter - gpm
2nd column-reading on flow meter being calibrated - gpm
sensitivity - .2 gpm/div
accuracy - ±.1262 gpm
calibration - $y=.9885x-.00623$

3.3173	3.35
4.3377	4.40
4.6339	4.68
2.9882	3.05
.6249	.60
2.2443	2.26
1.5004	1.54
1.7177	1.77
2.1785	2.22
2.5208	2.57
2.7314	2.79
3.5675	3.58
3.9427	4.00
1.0330	1.05

Sensor - 10
1st column-actual flow rate through secondary standard rotameter - gpm
2nd column-summation of the flow rate through the 3 convector flowmeters - %
sensitivity - .071 gpm/div
accuracy - ±.0302 gpm
calibration - $y=3.532x$

4.0085	117.
4.0744	115.5
4.1731	119.
4.1402	120.5
4.2389	118.5
4.1402	116.5
3.0869	85.5
3.8769	109.5
4.0085	117.5
4.0744	116.
4.0744	115.
3.9427	112.
3.7452	103.5
3.0211	83.5
3.1528	89.0
3.9427	113.
4.0085	116.5
3.8111	108.
3.0540	84.
3.3502	93.5
3.9427	111.
4.0085	114.
3.9427	112.
3.8769	110.5
3.7452	106.5
3.4161	95.

APPENDIX E

STORAGE TANK INFORMATION

The storage tank test was conducted simultaneously with the baseboard convectors and Solar Habitat I tests. Specifically the test periods were from February 27 to March 9 and March 11 to March 14, 1977. Previous tests have shown that the water temperature inside the storage would be uniform by agitating the water with pump 4 in Figure 17. Therefore, for the test periods mentioned above the tank was mixed and only sensor 15 of Appendix C was monitored as it represented an average temperature of the storage medium. The data obtained for this test and the testing of the baseboards and Solar Habitat I was recorded by the data acquisition system. A sample of this data is shown in Table I1. From this sample data, the information needed for the storage tank test is the time, the storage tank temperature, and the two outside ambient air temperatures. The remaining sample data is information necessary for the Solar Habitat I and baseboard convector tests. The collected data was transferred to a file and analyzed using the program named HXSH1C (Table I2). One hundred and seven experimental data points were obtained which described the rate of heat transfer from the storage tank for a corresponding tank temperature (Table E1). As mentioned earlier, the data points were divided into three regions (60-105°F, 105-150°F, and 150-180°F) and the best fit line through each region was obtained by using a regression analysis canned program (21).

TABLE E1

HEAT LOSS DATA FOR STORAGE TANK

first column - julian day
second column - hour

third column - average water temperature-°F

fourth column - rate of heat transfer from tank-Btu/hr

```
     **********  PROGRAM TT        **********               PAGE  1
59  1       179.47          7582.6
59  2       178.93          7799.2
59  3       178.41          7293.7
59  4       177.89          7871.4
59  9       173.44          5488.3
59 10       173.05          5777.2
59 11       172.67          5127.3
59 12       172.27          6427.1
59 13       171.79          7510.4
59 14       171.25          8015.9
59 15       170.75          6427.1
59 16       170.30          6499.3
59 18       169.47          5705.0
59 19       169.10          4910.6
59 20       168.77          4694.0
59 21       168.42          5271.7
59 22       168.03          6066.1
59 23       167.62          5705.0
60  0       167.24          5416.1
60  1       166.86          5488.3
60  2       166.46          6138.3
60  3       166.06          5416.1
60 10       160.99          3971.8
60 12       160.40          5055.1
60 13       160.07          4549.5
60 14       159.71          5777.2
60 15       159.34          4982.8
60 16       159.01          4694.0
60 17       158.69          4477.3
60 18       158.37          4694.0
60 19       158.05          4694.0
60 20       157.71          4982.8
60 21       157.37          4766.2
60 22       157.05          4621.8
60 23       156.72          4838.4
61 11       148.92          3033.0
61 12       148.71          3249.7
61 13       148.46          3755.2
61 18       147.20          3755.2
61 19       146.95          3466.3
61 20       146.69          3971.8
61 21       146.42          3755.2
61 22       146.16          3971.8
61 23       145.88          3899.6
62 12       139.39          2744.2
62 13       139.19          2960.8
62 14       138.99          2888.6
62 15       138.78          3105.2
62 16       138.57          3033.0
62 17       138.36          3033.0
62 18       138.16          2672.0
62 19       137.94          3827.4
62 20       137.72          2527.5
62 21       137.52          3105.2
62 22       137.32          2816.4
62 23       137.10          3466.3
63  0       136.87          3033.0
63  1       136.67          2888.6
63  2       136.47          2960.8
63  3       136.28          2455.3
```

```
63   4       136.10            2744.2
63   5       135.88            3466.3
64  12       122.68            1877.6
64   6       121.67            2238.7
64   7       121.54            1299.9
64   8       121.44            1805.4
64   9       121.29            2310.9
64  10       121.15            1877.6
64  11       121.03            1660.9
64  12       120.90            2022.0
64  13       120.75            2310.9
64  14       120.62            1444.3
64  15       120.49            2166.5
64  16       120.35            1949.8
64  17       120.21            2094.2
64  18       120.09            1372.1
65  15       117.64            1227.7
65  16       117.56            1011.0
65  17       117.47            1588.7
65  18       117.35            1733.2
65  19       117.26            1083.2
65  20       117.16            1733.2
65  21       117.05            1372.1
65  22       116.96            1299.9
65  23       116.84            2094.2
66   0       116.71            1660.9
66   1       116.59            1805.4
66   2       116.47            1733.2
67  12       107.48             577.7
67  13       107.44             794.4
67  14       107.38             794.4
67  15       107.33             794.4
67  16       107.26            1155.4
67  17       107.19             794.4
67  18       107.14             722.1
67  19       107.10             361.1
67  20       107.06             794.4
67  21       107.01             794.4
67  22       106.92            1660.9
67  23       106.84             722.1
68   0       106.79             577.7
68   1       106.74             866.6
68   2       106.68             866.6
68   3       106.62             866.6
68   4       106.56            1083.2
70  12        99.00             624.1
71  15        88.01             448.0
```

APPENDIX F

SOLAR COLLECTOR INFORMATION

Testing of the solar collectors was conducted during three different days and a total of 19 test points were obtained (8). Important information concerning the tests is summarized in Table F1. Estimations of the specific heat of the propylene-glycol mixture as a function of the fluid temperature was obtained from ASHREA Handbook of Fundamentals (16). Other information which was essential to the evaluation of the collectors was monitored by the instrumentation discussed in Appendix C and recorded by the data acquisition system installed at Solar Habitat I. A sample of the data obtained is shown in Table F2. The data obtained for all tests was then used as an input to the computer program STES12A (Table F3) which calculated the desired results (Table F4).

TABLE F1

SOLAR COLLECTOR AND HEAT EXCHANGER TEST INFORMATION

Test Number	Julian Day	Test Period	Collector Flow Rate (gpm)	Windspeed (mph) and Direction	Cloud Cover 0 -Cloudy 10-Clear	Snow Cover	Pressure (psig)	Ambient Temperature(°F)	Solar Insolation Rate $(\frac{BTU}{hr\ ft^2})$	Tank Side Flow Rate through Heat Exchanger (gpm)
10	39	10:45-11:05am	4.0	5-NNW	10	yes	33	24.1	300	20
10	39	11:05-11:25	4.0	5-NNW	10	yes	33	26.5	306	18
10	39	11:25-11:45	4.0	5-NNW	10	yes	33	26.6	310	16
10	39	11:45-12:05pm	3.0	7-NNW	10	yes	34	26.4	311	16
10	39	12:05-12:25	3.0	6-N	10	yes	34	27.3	310	18
10	39	12:25-12:45	3.0	6-NNW	10	yes	34	28.1	307	20
10	39	12:45- 1:05	2.0	9-N	10	yes	35	28.7	301	20
10	39	1:05- 1:25	2.0	6-NNW	10	yes	36	28.4	291	18
10	39	1:25- 1:45	2.0	7-NW	10	yes	36	28.7	279	16
12	42	10:30-10:50am	3.0	5-W	8	yes	47	37.1	201	20
12	42	10:50-11:10	3.0	6-W	7	yes	47	37.4	184	18
12	42	11:10-11:30	3.0	7-NW	9	yes	47	39.2	243	16
12	42	11:30-11:50	2.0	6-NW	9	yes	47	40.8	240	16
12	42	11:50-12:10pm	2.0	8-W	9	yes	47	41.3	244	18
12	42	12:10-12:30	2.0	8-W	9	yes	48	42.1	238	20
12	42	12:30-12:50	4.0	7-W	9	yes	48	42.8	235	20
12	42	12:50- 1:10	4.0	9-NW	8	yes	48	43.8	221	18
12	42	1:10- 1:30	4.0	8-W	8	yes	48	43.7	204	16

TABLE F2

SAMPLE DATA

```
  000010
  7 +  66.0 F    11 +  27.6 F    12 +  28.1 F    13 + 143.2 F    14 +  74.8 F
 16 + 107.3 F    17 +  70.4 F    18 +  73.7 F    25 +  69.9 F    26 +11.436MV
039:12:31:00
  000010
  7 +  66.1 F    11 +  27.7 F    12 +  28.0 F    13 + 143.2 F    14 +  74.9 F
 16 + 107.3 F    17 +  70.5 F    18 +  73.6 F    25 +  69.8 F    26 +11.420MV
039:12:32:00
  000010
  7 +  66.1 F    11 +  27.7 F    12 +  28.2 F    13 + 143.1 F    14 +  74.9 F
 16 + 107.2 F    17 +  70.5 F    18 +  73.8 F    25 +  70.0 F    26 +11.396MV
039:12:33:00
  000010
  7 +  66.1 F    11 +  27.7 F    12 +  27.9 F    13 + 143.0 F    14 +  74.8 F
 16 + 107.1 F    17 +  70.4 F    18 +  73.7 F    25 +  70.0 F    26 +11.416MV
039:12:34:00
  000010
  7 +  66.2 F    11 +  27.6 F    12 +  28.1 F    13 + 143.1 F    14 +  74.9 F
 16 + 107.2 F    17 +  70.6 F    18 +  73.8 F    25 +  69.8 F    26 +11.401MV
039:12:35:00
```

TABLE F3

COMPUTER PROGRAM

STES12A

```
[illegible]
 77/06/02. 09.53.45.
   FILE    STEC126

00100 PROGRAM STEC126(INPUT,OUTPUT,TAPE1,TAPE2)
00110 DIMENSION GPM(10),TC(27,27),EPPLY(26),IGPM(10)
112 PRINT 100
114 100 FORMAT(///,25X,*COLLECTOR TESTS*)
120 M=1
151 READ(1,)(GPM(I),IGPM(I),I=1,9)
00165 15 CONTINUE
00170 DO 20 K=1,20
00180 READ(2,1000)NDAY,NHOUR,MIN,NSEC
00190 READ(2,2000)NTEST
00200 READ(2,3000)I,TC(I,K),I,TC(I,K),I,TC(I,K),I,TC(I,K),I,
00205+TC(I,K)
00210 READ(2,4000)I,TC(I,K),I,TC(I,K),I,TC(I,K),I,TC(I,K),
00215+EPPLY(K)
00220 IF(K.EQ.15)30,20
00230 30 IHOUR=NHOUR $ IMIN=MIN $ ISEC=NSEC
00240 20 CONTINUE
00250 DO 40 I=11,20
00260 SUMTC7=TC(7,I)+SUMTC7
00270 SUMTC11=TC(11,I)+SUMTC11
00280 SUMTC12=TC(12,I)+SUMTC12
00290 SUMTC13=TC(13,I)+SUMTC13
00300 SUMTC14=TC(14,I)+SUMTC14
00310 SUMTC16=TC(16,I)+SUMTC16
00320 SUMTC17=TC(17,I)+SUMTC17
00330 SUMTC18=TC(18,I)+SUMTC18
00340 SUMTC1=TC(1,I)+SUMTC1
00350 SUMEPPY=EPPLY(I)+SUMEPPY
00360 40 CONTINUE
00370 HXOUT=SUMTC18/10.
00380 HXIN=SUMTC17/10.
00390 COLIN=SUMTC14/10.
00400 COLOUT=SUMTC16/10.
00410 COLPLT=SUMTC13/10.
00420 AMB=(SUMTC11+SUMTC12)/20.
00430 XINSOL=(SUMEPPY/10.)*1000./36.98
00440 DELTAT=((COLIN+COLOUT)/2.)-AMB
00450 X=DELTAT/XINSOL
00460 COLEFF=GPM(M)*493.*.85*(COLOUT-COLIN)/(XINSOL*196.)
00470 HXEFF=(COLOUT-COLIN)/(COLOUT-HXIN)
480 PRINT 200,NTEST,NDAY
490 200 FORMAT(//,2X,*TEST NUMBER *,I6,8X,
500+*JULIAN DAY *,I3)
501 PRINT 300,GPM(M),IGPM(M)
505 300 FORMAT(/,2X,*TOTAL FLOW RATES, COLL. SIDE  *,
506+F3.1,* GPM*,3X,*TANK SIDE *,F4.1,* GPM*)
510 PRINT 400,IHOUR,IMIN
515 400 FORMAT(/,2X,*MIDPOINT OF TEST INTERVAL, HOUR *,
516+I2,* MIN *,I2)
520 PRINT 500
521 500 FORMAT(/,2X,*COLIN*,5X,*COLOUT*,5X,*COLPLT*,5X,
522+*AM[illegible] F5,9X,
523[illegible]
524+*-----*,4X,*-----*,/,43X,*FT2*,5X,*BTUH*/)
525 PRINT 600,COLIN,COLOUT,COLPLT,AMB,XINSOL,X,COLEFF
526 600 FORMAT(2X,F5.1,6X,F5.1,6X,F5.1,4X,F5.1,4X,F4.0,
527+5X,F3.2,7X,F3.2)
530 PRINT 700
```

```
531 700 FORMAT(//,2X,*HX EFFECTIVENESS*,//,2X,*COLL. SIDE*
532+,10X,*TANK SIDE*,6X,*EFF*,/,2X,*INL.*,3X,*OUT*,10X,
533+*INL.*,2X,*OUT*/)
534 PRINT 800,COLOUT,COLIN,HXIN,HXOUT,HXEFF
535 800 FORMAT(1X,F5.1,2X,F5.1,7X,F5.1,2X,F5.1,5X,F3.2)
536 SUMTC7=SUMTC11=SUMTC12=SUMTC13=SUMTC14=SUMTC16=
537+SUMTC17=SUMTC18=SUMTC1=SUMEFFY=0.0
538 PRINT 900
539 900 FORMAT(/,19X,*----------------------------*,/)
00540 M=M+1
590 IF(M.EQ.10) GO TO 70
00600 GO TO 15
00610 1000 FORMAT(I3,1X,I2,1X,I2,1X,I2)
00620 2000 FORMAT(2X,I6)
00630 3000 FORMAT(1X,5(I2,F8.1,5X))
00640 4000 FORMAT(1X,4(I2,F8.1,5X),3X,F7.3)
00650 70 CONTINUE
00660 END
READY.
```

TABLE F4

SOLAR COLLECTOR AND HEAT EXCHANGER RESULTS

```
READY.
GET,TAPE1=GPMDT10

READY.
GET,TAPE2=TEST10

READY.
RUN

 77/03/08. 09.39.39.
   FILE    STES10A



                                COLLECTOR TESTS

  TEST NUMBER      10         JULIAN DAY  39

  TOTAL FLOW RATES, COLL. SIDE  4.0 GPM   TANK SIDE 20.0 GPM

  MIDPOINT OF TEST INTERVAL, HOUR 10 MIN 59

  COLIN       COLOUT       COLPLT      AMB       INSOL      X      COLEFF
    F            F            F         F         BTUH    F-FT2
                                                  ----    -----
                                                  FT2     BTUH

   72.1        97.3        136.7       24.1       300      .20       .69


  HX EFFECTIVENESS

  COLL. SIDE           TANK SIDE       EFF
  INL.   OUT           INL.   OUT

  97.3   72.1         66.9   70.4      .83
                              ------------------------------
```

```
TEST NUMBER       10          JULIAN DAY   39

TOTAL FLOW RATES, COLL. SIDE  4.0 GPM   TANK SIDE 18.0 GPM

MIDPOINT OF TEST INTERVAL, HOUR 11 MIN 19

COLIN       COLOUT      COLPLT      AMB       INSOL      X      COLEFF
  F           F           F          F        BTUH    F-FT2
                                              ----    -----
                                              FT2     BTUH

 73.5        99.4       139.0       26.5      306      .20        .70


HX EFFECTIVENESS

COLL. SIDE          TANK SIDE       EFF
INL.   OUT          INL.   OUT

99.4   73.5         67.9   71.8     .82

              ---------------------------------------------


TEST NUMBER       10          JULIAN DAY   39

TOTAL FLOW RATES, COLL. SIDE  4.0 GPM   TANK SIDE 16.0 GPM

MIDPOINT OF TEST INTERVAL, HOUR 11 MIN 39

COLIN       COLOUT      COLPLT      AMB       INSOL      X      COLEFF
  F           F           F          F        BTUH    F-FT2
                                              ----    -----
                                              FT2     BTUH

 74.9       101.0       139.9       26.6      310      .20        .69


HX EFFECTIVENESS

COLL. SIDE          TANK SIDE       EFF
INL.   OUT          INL.   OUT

101.0  74.9         68.8   73.1     .81

              ---------------------------------------------
```

```
TEST NUMBER      10          JULIAN DAY  39

TOTAL FLOW RATES, COLL. SIDE  3.0 GPM   TANK SIDE 16.0 GPM

MIDPOINT OF TEST INTERVAL, HOUR 12 MIN  0

COLIN       COLOUT       COLPLT      AMB      INSOL      X      COLEFF
  F            F            F         F        BTUH    F-FT2
                                               ----    -----
                                               FT2      BTUH

 74.7       108.2        143.5      26.4      311      .21        .66

HX EFFECTIVENESS

COLL. SIDE            TANK SIDE       EFF
INL.   OUT            INL.  OUT

108.2   74.7          69.4   73.6      .86

                     -------------------------------


TEST NUMBER      10          JULIAN DAY  39

TOTAL FLOW RATES, COLL. SIDE  3.0 GPM   TANK SIDE 18.0 GPM

MIDPOINT OF TEST INTERVAL, HOUR 12 MIN 20

COLIN       COLOUT       COLPLT      AMB      INSOL      X      COLEFF
  F            F            F         F        BTUH    F-FT2
                                               ----    -----
                                               FT2      BTUH

 74.8       107.4        143.2      27.3      310      .21        .65

HX EFFECTIVENESS

COLL. SIDE            TANK SIDE       EFF
INL.   OUT            INL.  OUT

107.4   74.8          70.1   73.7      .87

                     -------------------------------
```

```
TEST NUMBER       10          JULIAN DAY   39

TOTAL FLOW RATES, COLL. SIDE  3.0 GPM   TANK SIDE 20.0 GPM

MIDPOINT OF TEST INTERVAL, HOUR 12 MIN 40

COLIN       COLOUT       COLPLT      AMB      INSOL     X      COLEFF
  F           F            F          F        BTUH   F-FT2
                                               ----   -----
                                               FT2    BTUH

 75.0       106.8        142.9       28.1     307     .20        .64

HX EFFECTIVENESS

COLL. SIDE            TANK SIDE       EFF
INL.   OUT            INL.   OUT

106.8   75.0          70.7   74.0     .88

               ----------------------------------------


TEST NUMBER       10          JULIAN DAY   39

TOTAL FLOW RATES, COLL. SIDE  2.0 GPM   TANK SIDE 20.0 GPM

MIDPOINT OF TEST INTERVAL, HOUR 13 MIN  0

COLIN       COLOUT       COLPLT      AMB      INSOL     X      COLEFF
  F           F            F          F        BTUH   F-FT2
                                               ----   -----
                                               FT2    BTUH

 74.4       113.6        144.8       28.7     301     .22        .54

HX EFFECTIVENESS

COLL. SIDE            TANK SIDE       EFF
INL.   OUT            INL.   OUT

113.6   74.4          71.3   73.9     .93

               ----------------------------------------
```

```
TEST NUMBER      10          JULIAN DAY  39

TOTAL FLOW RATES, COLL. SIDE  2.0 GPM   TANK SIDE 18.0 GPM

MIDPOINT OF TEST INTERVAL, HOUR 13 MIN 20

COLIN       COLOUT       COLPLT      AMB      INSOL      X     COLEFF
  F           F            F          F        BTUH   F-FT2
                                               ----    ----
                                               FT2     BTUH

 74.6        106.8        139.2      28.4      291     .21       .46

HX EFFECTIVENESS

COLL. SIDE              TANK SIDE      EFF
INL.   OUT              INL.  OUT

106.8   74.6            71.8   74.2     .92

                        ------------------------------


TEST NUMBER      10          JULIAN DAY  39

TOTAL FLOW RATES, COLL. SIDE  2.0 GPM   TANK SIDE 16.0 GPM

MIDPOINT OF TEST INTERVAL, HOUR 13 MIN 40

COLIN       COLOUT       COLPLT      AMB      INSOL      X     COLEFF
  F           F            F          F        BTUH   F-FT2
                                               ----    ----
                                               FT2     BTUH

 74.9        103.1        135.4      28.7      279     .22       .42

HX EFFECTIVENESS

COLL. SIDE              TANK SIDE      EFF
INL.   OUT              INL.  OUT

103.1   74.9            72.3   74.6     .91

                        ------------------------------

END.
```

```
READY.
OLD,STES12A

READY.
GET,TAPE1=GPMDT12

READY.
GET,TAPE2=TEST12

READY.
RUN

 77/03/02. 10.55.40.
   FILE      STES12A


                         COLLECTOR TESTS

  TEST NUMBER      12         JULIAN DAY  42

  TOTAL FLOW RATES, COLL. SIDE  3.0 GPM   TANK SIDE 20.0 GPM

  MIDPOINT OF TEST INTERVAL, HOUR 10 MIN 45

  COLIN     COLOUT     COLPLT     AMB     INSOL      X    COLEFF
    F          F          F        F       BTUH   F-FT2
                                           ----     ----
                                           FT2      BTUH

  121.2      128.1      142.8     37.1     201      .44       .22


  HX EFFECTIVENESS

  COLL. SIDE          TANK SIDE      EFF
  INL.   OUT          INL.  OUT

 128.1  121.2       120.8  121.4     .94

                   ------------------------------
```

```
TEST NUMBER      12          JULIAN DAY  42

TOTAL FLOW RATES, COLL. SIDE  3.0 GPM   TANK SIDE 18.0 GPM

MIDPOINT OF TEST INTERVAL, HOUR 11 MIN  5

COLIN        COLOUT        COLPLT        AMB        INSOL      X       COLEFF
  F             F             F           F         BTUH     F-FT2
                                                    ----     -----
                                                    FT2      BTUH

121.6        129.2         144.4        37.4       184      .48          .26


HX EFFECTIVENESS

COLL. SIDE              TANK SIDE       EFF
INL.   OUT              INL.   OUT

129.2  121.6          120.9  121.8      .92
                    ---------------------------------


TEST NUMBER      12          JULIAN DAY  42

TOTAL FLOW RATES, COLL. SIDE  3.0 GPM   TANK SIDE 16.0 GPM

MIDPOINT OF TEST INTERVAL, HOUR 11 MIN 45

COLIN        COLOUT        COLPLT        AMB        INSOL      X       COLEFF
  F             F             F           F         BTUH     F-FT2
                                                    ----     -----
                                                    FT2      BTUH

121.8        134.8         158.7        39.2       243      .37          .34


HX EFFECTIVENESS

COLL. SIDE              TANK SIDE       EFF
INL.   OUT              INL.   OUT

134.8  121.8          121.1  122.7      .95
                    ---------------------------------
```

```
TEST NUMBER       12          JULIAN DAY   42

TOTAL FLOW RATES, COLL. SIDE  2.0 GPM   TANK SIDE 16.0 GPM

MIDPOINT OF TEST INTERVAL, HOUR 12 MIN  5

COLIN        COLOUT        COLPLT        AMB        INSOL     X        COLEFF
  F            F             F            F         BTUH    F-FT2
                                                    ----    -----
                                                    FT2     BTUH

121.1         138.4        160.5        40.8       240      .37          .31

HX EFFECTIVENESS

COLL. SIDE               TANK SIDE        EFF
INL.    OUT              INL.   OUT

138.4  121.1           121.2  122.5      *01

                    ----------------------------------------

TEST NUMBER       12          JULIAN DAY   42

TOTAL FLOW RATES, COLL. SIDE  2.0 GPM   TANK SIDE 18.0 GPM

MIDPOINT OF TEST INTERVAL, HOUR 12 MIN 25

COLIN        COLOUT        COLPLT        AMB        INSOL     X        COLEFF
  F            F             F            F         BTUH    F-FT2
                                                    ----    -----
                                                    FT2     BTUH

121.0         136.9        158.5        41.3       244      .36          .28

HX EFFECTIVENESS

COLL. SIDE               TANK SIDE        EFF
INL.    OUT              INL.   OUT

136.9  121.0           121.4  122.4      *02

                    ----------------------------------------
```

```
 TEST NUMBER      12         JULIAN DAY  42

 TOTAL FLOW RATES, COLL. SIDE  2.0 GPM   TANK SIDE 20.0 GPM

 MIDPOINT OF TEST INTERVAL, HOUR 12 MIN 45

 COLIN     COLOUT     COLPLT     AMB     INSOL     X     COLEFF
   F          F          F        F      BTUH   F-FT2       .
                                         ----    ----
                                         FT2     BTUH.

 121.1      136.7      158.6     42.1    238     .36        .28


 HX EFFECTIVENESS

 COLL. SIDE          TANK SIDE     EFF
 INL.   OUT          INL.  OUT

136.7  121.1       121.5  122.4     *03

                  -----------------------------


 TEST NUMBER      12         JULIAN DAY  42

 TOTAL FLOW RATES, COLL. SIDE  4.0 GPM   TANK SIDE 20.0 GPM

 MIDPOINT OF TEST INTERVAL, HOUR 13 MIN  5

 COLIN     COLOUT     COLPLT     AMB     INSOL     X     COLEFF
   F          F          F        F      BTUH   F-FT2
                                         ----    ----
                                         FT2     BTUH

 122.2      130.5      153.6     42.8    235     .36        .30


 HX EFFECTIVENESS

 COLL. SIDE          TANK SIDE     EFF
 INL.   OUT          INL.  OUT

130.5  122.2       121.6  122.7     .93

                  -----------------------------
```

```
TEST NUMBER      12          JULIAN DAY  42

TOTAL FLOW RATES, COLL. SIDE  4.0 GPM   TANK SIDE 16.0 GPM

MIDPOINT OF TEST INTERVAL, HOUR 13 MIN 25

COLIN      COLOUT      COLPLT      AMB      INSOL     X      COLEFF
  F          F           F          F       BTUH    F-FT2
                                            ----    -----
                                            FT2     BTUH

122.3      130.3       150.9      43.8      221     .37       .31

HX EFFECTIVENESS

COLL. SIDE           TANK SIDE      EFF
INL.   OUT           INL.   OUT

130.3  122.3         121.7  122.8      .93

                  ------------------------------


TEST NUMBER      12          JULIAN DAY  42

TOTAL FLOW RATES, COLL. SIDE  4.0 GPM   TANK SIDE 16.0 GPM

MIDPOINT OF TEST INTERVAL, HOUR 13 MIN 45

COLIN      COLOUT      COLPLT      AMB      INSOL     X      COLEFF
  F          F           F          F       BTUH    F-FT2
                                            ----    -----
                                            FT2     BTUH

122.4      129.9       147.3      43.7      204     .40       .32

HX EFFECTIVENESS

COLL. SIDE           TANK SIDE      EFF
INL.   OUT           INL.   OUT

129.9  122.4         121.8  123.0      .93

                  ------------------------------

END.
```

APPENDIX G

HEAT EXCHANGER INFORMATION

Testing of the heat exchanger was conducted simultaneously with the solar collector tests. Important information concerning these tests is summarized in Table F1. The necessary instrumentation needed to conduct these tests is discussed in Appendix C. Much of the data obtained which was not discussed in Table F1 was recorded by the data acquisition system. The computer program STES12A was used to analyze this data, and the results obtained are shown in Table F3 and Table F4, respectively.

APPENDIX H

BASEBOARD CONVECTOR INFORMATION

The testing of the baseboard convector was conducted simultaneously with the testing of Solar Habitat I and the storage tank from February 17 to March 9, 1977. The instrumentation used to obtain the necessary information to evaluate the baseboards is described in Appendix C. For the experimental analysis of the convectors the ambient air temperature in Solar Habitat I was assumed to be 65°F and the flow rate through each convector loop was chosen to be .89 gpm. A flow rate of .89 gpm was chosen because higher flow rates in the convector loops were not constant when more than one convector loop was in operation.

The sensor output of the appropriate channels in Appendix C were monitored and recorded by the data acquisition system. A sample of the data obtained is described in Table I1. From this sample the variables which are needed to evaluate the baseboard convectors are the time; the temperature of the water at the inlet and outlet of the basement, living area and bedroom convector loops; and the on-off signal for the basement, living area, and bedroom convectors. From the tests conducted, the data was transferred to a file and analyzed by the program HXSH1C (Table I2). One hundred and eighty-three data points were obtained for various loops and are shown in Table H1.

TABLE H1

BASEBOARD CONVECTOR RESULTS

First column - julian day
Second column - hour
Third column - location
Fourth column - rate of heat transfer to Solar Habitat I per linear foot of convector - Btu/hr-ft
Fifth column - inlet temperature to convector - °F
Sixth column - average temperature of the water through the convector - °F
Seventh column - product of the overall heat transfer coefficient and the surface area of the convector - Btu/hr °F

```
          **********  PROGRAM CONV      **********          PAGE  1
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 49   0          343.5 163.6 157.5  36670.4
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 49   0          399.7 163.9 155.8  34169.7
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 49   1          338.8 163.0 157.1  36496.2
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 49   1          395.7 163.4 155.3  34000.4
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 49   2          335.3 162.6 156.7  36350.4
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 49   2          393.5 163.0 155.0  33860.6
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 49   3          332.4 162.1 156.3  36174.6
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 49   3          389.0 162.5 154.6  33708.1
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 49   4          330.3 161.7 155.8  35999.6
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 49   4          382.3 162.0 154.2  33577.3
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 49   5          328.8 161.2 155.4  35810.0
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 49   5          380.1 161.6 153.8  33408.1
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 49   6          328.5 160.7 154.9  35594.3
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 49   6          378.0 161.0 153.3  33202.6
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 49   7          323.1 160.2 154.4  35427.5
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 49   7          376.4 160.5 152.8  33034.1
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 49   8          312.5 159.8 154.3  35378.4
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 49   8          366.7 159.7 152.2  32802.8
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 50   0          342.5 163.0 156.9  36431.3
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 50   1          340.4 163.3 157.3  36603.6
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 50   2          335.0 163.0 157.1  36523.1
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 50   2          396.2 163.4 155.3  33998.2
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 50   3          330.5 162.5 156.7  36349.9
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 50   3          387.9 162.9 155.0  33858.4
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 50   4          327.3 162.1 156.3  36182.4
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 50   4          383.2 162.4 154.6  33716.8
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 50   5          323.4 161.6 155.9  36017.2
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 50   5          378.9 161.9 154.2  33561.3
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 50   6          321.3 161.2 155.5  35852.4
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 50   6          375.8 161.5 153.9  33426.8
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DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 50   7          317.4 160.7 155.1   35704.6
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 50   7          371.9 161.0 153.5   33276.0
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 50   8          308.7 159.8 154.4   35401.5
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 50   8          370.3 160.9 153.3   33232.7
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 50  22          395.4 163.5 155.4   34029.9
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 51   0          386.5 163.3 155.4   34043.1
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 51   1          383.8 163.2 155.3   34007.2
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 51   2          382.4 163.0 155.2   33948.1
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 51   3          381.3 162.8 155.0   33885.1
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 51   4          380.9 162.7 154.9   33841.2
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 51   5          382.7 163.0 155.2   33940.4
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 51   6          326.2 161.7 156.0   36049.2
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 51   7          325.2 161.7 156.0   36046.4
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 51   8          321.1 161.6 156.0   36054.9
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 51   9          321.1 161.9 156.2   36165.8
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 51  10          315.9 161.6 156.1   36092.5
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 51  10          370.5 161.5 153.9   33447.9
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 51  16          384.6 162.2 154.4   33628.0
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 51  17          326.2 161.9 156.2   36137.5
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 51  17          374.7 162.2 154.6   33721.8
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 51  18          318.6 161.5 155.9   36022.8
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 51  18          368.4 161.8 154.3   33610.3
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 51  19          315.6 161.1 155.5   35854.2
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 51  19          364.2 161.5 154.0   33504.1
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 51  20          311.0 160.2 154.7   35532.8
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 52   0          322.7 161.1 155.4   35839.6
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 52   0          340.0 145.3 138.4   27379.7
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 52   1          317.6 160.7 155.1   35709.7
DAY  HR BEDROOM   Q/F    TI    ATEMP     UA
 52   1          367.6 161.0 153.5   33310.3
DAY  HR LIVING    Q/FT   TI    ATEMP     UA
 52   2          312.6 160.6 155.0   35675.3
```

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          **********  PROGRAM CONV      **********          PAGE  3
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 52  2          361.9 160.9 153.5  33287.5
DAY HR LIVING   Q/FT   TI    ATEMP     UA
 52  3          306.7 159.9 154.5  35436.7
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 52  3          359.2 160.6 153.3  33223.1
DAY HR LIVING   Q/FT   TI    ATEMP     UA
 52  4          307.5 159.5 154.1  35288.5
DAY HR LIVING   Q/FT   TI    ATEMP     UA
 52  5          308.9 159.6 154.1  35296.3
DAY HR LIVING   Q/FT   TI    ATEMP     UA
 52  6          308.9 159.3 153.8  35177.1
DAY HR LIVING   Q/FT   TI    ATEMP     UA
 52  7          310.5 159.3 153.9  35187.9
DAY HR LIVING   Q/FT   TI    ATEMP     UA
 52  8          309.9 159.4 153.9  35211.7
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 54  0          398.9 165.4 157.3  34770.1
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 54  1          395.3 165.3 157.3  34755.2
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 54  2          393.8 165.3 157.3  34774.6
DAY HR LIVING   Q/FT   TI    ATEMP     UA
 54  5          346.7 165.0 158.8  37227.3
DAY HR LIVING   Q/FT   TI    ATEMP     UA
 54  6          345.2 165.2 159.1  37319.3
DAY HR LIVING   Q/FT   TI    ATEMP     UA
 54  7          338.0 164.6 158.7  37156.2
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 54  7          395.0 164.9 156.9  34606.6
DAY HR LIVING   Q/FT   TI    ATEMP     UA
 54  8          332.4 164.3 158.4  37066.6
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 54  8          388.4 164.5 156.6  34503.6
DAY HR LIVING   Q/FT   TI    ATEMP     UA
 55  7          369.2 169.2 162.7  38813.7
DAY HR LIVING   Q/FT   TI    ATEMP     UA
 55  8          358.0 168.8 162.5  38713.6
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 55  8          418.1 169.1 160.6  36039.9
DAY HR LIVING   Q/FT   TI    ATEMP     UA
 55  9          352.6 168.4 162.2  38598.5
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 55  9          412.7 168.8 160.3  35949.7
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 55 16          419.9 168.9 160.3  35938.2
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 55 17          413.0 168.9 160.4  35985.7
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 55 18          410.7 169.0 160.6  36054.6
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 55 23          422.8 169.1 160.5  36016.1
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 56  0          413.7 169.0 160.6  36042.1
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 56  1          408.9 168.8 160.5  36002.3
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 56  2          409.5 168.8 160.4  35993.2
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 56  5          412.3 168.8 160.4  35955.6
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DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 56  6          407.1 168.6 160.3  35951.3
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 56  7          405.3 168.5 160.2  35895.4
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 56  8          400.7 168.2 160.0  35831.1
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 56  9          397.6 168.1 160.0  35819.9
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 57  7          435.4 172.5 163.6  37214.7
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 57  8          430.2 172.4 163.6  37212.7
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 59  6          438.7 173.0 164.1  37394.2
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 59  7          432.1 172.2 163.4  37130.5
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 60  5          395.0 161.9 153.9  33420.3
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 60  6          386.7 161.2 153.3  33213.0
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 60  7          380.1 160.5 152.7  32979.4
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 60  8          374.1 159.8 152.2  32763.9
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 61  1          354.0 153.0 145.8  30274.2
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 61  2          347.2 152.4 145.3  30088.7
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 61  3          343.7 151.7 144.7  29846.7
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 61  4          340.7 151.0 144.0  29595.6
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 61  5          337.9 150.3 143.4  29339.6
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 61  6          336.0 149.6 142.7  29099.8
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 61  7          332.3 148.9 142.2  28872.6
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 61  8          325.4 148.3 141.6  28664.5
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 61  9          320.0 147.7 141.2  28510.5
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 62  1          307.8 142.8 136.5  26668.7
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 62  2          300.5 142.3 136.2  26544.0
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 62  3          296.0 141.7 135.7  26343.6
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 62  4          294.3 141.1 135.1  26140.9
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 62  5          292.7 140.6 134.6  25931.2
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 62  6          291.7 140.0 134.1  25724.2
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 62  7          287.5 139.4 133.6  25534.4
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 62  8          281.4 138.9 133.2  25392.5
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 63  7          266.4 133.1 127.7  23225.2
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      **********  PROGRAM CONV     **********          PAGE  5
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 63  8         262.0 132.7 127.3  23096.2
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 63  9         259.3 132.1 126.9  22917.4
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 63 10         255.8 131.7 126.5  22771.3
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 63 11         251.6 131.2 126.1  22622.6
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 63 13         245.6 130.3 125.3  22319.1
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 63 14         242.2 129.9 124.9  22166.1
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 63 15         239.9 129.3 124.4  21979.3
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 63 16         238.8 128.9 124.0  21810.5
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 63 17         237.1 128.4 123.5  21625.4
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 63 18         233.3 127.9 123.2  21487.3
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 63 19         230.3 127.5 122.8  21339.0
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 63 20         228.9 127.1 122.4  21195.8
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 63 21         226.6 126.7 122.0  21049.1
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 63 22         225.4 126.3 121.7  20906.8
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 63 23         222.9 125.9 121.3  20765.1
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 64  0         220.3 125.5 121.0  20634.2
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 64  1         219.2 125.1 120.6  20485.0
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 64  2         217.5 124.7 120.3  20368.4
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 64  3         216.5 124.4 120.0  20235.8
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 64  4         215.3 124.0 119.6  20093.5
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 64  5         213.5 123.6 119.2  19950.5
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 64  6         212.7 123.2 118.9  19811.9
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 64  7         210.6 122.8 118.5  19678.8
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 64  8         206.7 122.5 118.2  19569.0
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 64  9         202.9 122.1 118.0  19468.0
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 64 10         200.8 121.8 117.7  19376.0
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 64 20         191.6 118.2 114.2  18011.5
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 64 21         187.0 117.8 114.0  17921.6
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 64 22         184.3 117.5 113.8  17821.1
DAY HR BEDROOM  Q/F   TI   ATEMP    UA
 64 23         181.8 117.1 113.4  17693.0
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```
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 66   4           178.2 114.8 111.1   16800.6
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 66   5           175.0 114.5 110.9   16710.0
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 66   6           174.0 114.2 110.6   16600.9
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 66   7           172.9 113.9 110.3   16492.8
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 66   8           171.2 113.6 110.1   16386.0
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 66   9           169.3 113.3 109.8   16288.0
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 66  11           162.1 112.6 109.3   16096.5
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 66  12           160.9 112.4 109.1   16001.1
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 66  13           158.8 112.0 108.8   15899.3
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 66  14           157.9 111.7 108.5   15783.3
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 66  15           156.7 111.5 108.3   15701.7
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 66  16           155.8 111.3 108.1   15618.9
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 66  17           154.6 111.0 107.8   15515.7
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 66  18           153.6 110.7 107.6   15426.2
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 66  19           152.2 110.5 107.4   15342.7
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 66  20           152.4 110.2 107.1   15238.9
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 66  21           150.8 110.0 106.9   15150.6
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 66  22           151.5 109.7 106.6   15054.4
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 66  23           150.9 109.5 106.4   14963.7
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 67   0           150.8 109.2 106.2   14870.9
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 67   1           150.9 109.0 105.9   14758.3
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 67   2           151.2 108.7 105.6   14656.5
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 67   3           152.5 108.5 105.4   14549.3
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 67   4           153.5 108.2 105.1   14435.3
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 67   5           154.1 108.0 104.8   14338.2
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 67   6           155.3 107.7 104.5   14228.1
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 67   7           154.4 107.5 104.3   14154.2
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 67   8           149.7 107.3 104.2   14103.5
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 67   9           145.4 107.1 104.1   14067.2
DAY  HR  BEDROOM  Q/F    TI    ATEMP     UA
 67  10           139.5 16.9 104.0  14041.9
```

```
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 68  6         150.4 105.1 102.0  13251.8
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 68  7         145.9 105.0 102.0  13233.4
DAY HR BEDROOM  Q/F    TI    ATEMP     UA
 68  8         143.3 104.7 101.8  13165.2
```

APPENDIX I

SOLAR HABITAT I INFORMATION

The testing of Solar Habitat I was conducted for a period of twenty days, February 17 to March 9, 1977. The necessary instrumentation used for this test is discussed in Appendix C and all data was recorded on the data logger system. A sample of the data obtained is shown in Table I1. All the variables in the table were necessary to evaluate Solar Habitat I. The data for the test was analyzed by program HXSH1C (Table I2) for each hour and these hourly results are shown in Table I3. From the hourly information the daily heating loads were obtained. The daily heating loads were based on a 24 hour period beginning at 6:00 a.m. to the following morning at 6:00 a.m. This period was chosen to incorporate into the analysis the effect the daily solar insolation rate has on the storage capacity of Solar Habitat I itself. The daily heating results obtained are based only on the energy delivered to Solar Habitat I and are summarized in Table I4. To compensate for the thermal energy gained from sources other than the storage tank, an estimation of Q_{ST}, Q_H, Q_{HW}, and Q_E were made. Calculations I1 discuss the estimation of these values, and Table I6 summarizes the results obtained when these sources of energy are included in the daily heating load of Solar Habitat I. From the data in Table I4 and Table I6, and using a canned regression analysis program (21) the desired results were obtained.

TABLE II

SAMPLE DATA

```
015:14:00:00
151.2 F    21.3 F    21.5 F    72.1 F    78.3 F
137.8 F    71.8 F   150.9 F    89.3 F    61.2 F
7.936 MV  0.011 V   0.138 V   4.792 V
015:14:03:00
151.4 F    21.2 F    21.5 F    73.4 F    78.5 F
137.8 F    71.7 F   151.2 F    89.3 F    62.2 F
7.930 MV  0.012 V   0.141 V   4.698 V
```

First row - julian day : hour : min : sec
Second row, first column - tank temperature - S14
Second row, second column - outside ambient air temperature - S43
Second row, third column - outside ambient air temperature - S44
Second row, fourth column - exit temperature for basement convector loop - S32
Second row, fifth column - exit temperature for living area loop - S33
Third row, first column - exit temperature for bedroom loop - S34
Third row, second column - inlet temperature for basement loop - S29
Third row, third column - inlet temperature for bedroom loop - S31
Third row, fourth column - inlet temperature for living area loop - S30
Third row, fifth column - temperature of 2000 gallon tank - S18
Fourth row, first column - pyranometer output - S22
Fourth row, second column - on-off signal for basement loop - S35
Fourth row, third column - on-off signal for living area loop - S36
Fourth row fourth column - on-off signal for bedroom loop - S37

TABLE I2

COMPUTER PROGRAM

HXSH1C

```
PROGRAM HTLOSS (INPUT,TAPE1,OUTPUT,TAPE3)
DIMENSION N(1560,5),S(1560,5)
REAL MBA,MU,MBE
F=221.1545
READ,X,X1,X2,X3,K
E=8.18
CPV=14443.
QBAL=14.67
QUL=14.5
QBEL=15.92
MBA=6.8402
MU=6.8402
MBE=6.5065
REWIND 1
DO 9 I=1,K
READ (1,3)NDAY,NHOUR,NMIN,NSEC
READ (1,4)TT,TA1,TA2,BAR,UR
READ (1,5)BER,BAI,BEI,UI,TT2
READ (1,6)PYR,SBA,SU,SBE
IF (X1.EQ.1.) GO TO 95
READ (1,83) WIND
83 FORMAT (6X,F9.3)
3 FORMAT(6X,I3,1X,I2,1X,I2,1X,I2)
4 FORMAT(6X,5F9.1)
5 FORMAT(6X,5F9.1)
6 FORMAT(6X,4F9.3)
95 A=A+1.
NNMIN=NMIN+NNMIN
STT=TT+STT
STA1=TA1+STA1
STA2=TA2+STA2
SPYR=PYR+SPYR
STT2=TT2+STT2
IF (NDAY.GE.59.AND.SBA.LT.1.AND.SU.LT.1.AND.SBE.LT.1.AND.X2.
+EQ.1.) 84,85
85 H=0.
G=0.
GO TO 91
84 G=G+1.
IF (A.NE.G) GO TO 200
STT1=TT+STT1
IF (G.EQ.20.) GO TO 86
GO TO 9
86 ATT=STT1/G
H=H+1.
IF (H.GE.2.) GO TO 87
Q1=CPV*ATT
TT1=ATT
G=0.
A=0.
STT1=0.
GO TO 9
87 Q2=CPV*ATT
TT2=ATT
QT=Q1-Q2
TTT=(TT1+TT2)/2.
88 FORMAT (6X,I2,1X,I2,5X,F6.2,5X,F10.1)
PRINT 88,NDAY,NHOUR,TTT,QT
WRITE (3,88) NDAY,NHOUR,TTT,QT
TT1=TT2
```

```
00610 Q1=Q2
00620 STT1=0.
00630 G=0.
00640 A=0.
00650 GO TO 9
00660 91 IF (SBA.GT.1.) GO TO 11
00670 IF (SBA.LT.1.) AB=0.
00680 12 IF (SU.GT.1.) GO TO 13
00690 IF (SU.LT.1.) AC=0.
00700 14 IF (SBE.GT.1.) GO TO 15
00710 IF (SBE.LT.1.) AD=0.
00720 16 IF (A.GE.20.) GO TO 10
00730 GO TO 9
00740 11 B=B+1.
00750  AB=AB+1.
00760 IF (Z1.EQ.1.) GO TO 51
00770 AMB=A-B
00780 Z1=1.
00790 51 IF (AMB.LT.16.) 31,32
00800 31 IF (AB.LE.20.) GO TO 34
00810 SBAI=BAI+SBAI
00820 SBAR=BAR+SBAR
00830 GO TO 12
00840 32 IF (AB.LE.4.) GO TO 12
00850 SBAI=BAI+SBAI
00860 SBAR=BAR+SBAR
00870 IF (A.EQ.20.AND.AB.GT.4.) GO TO 33
00880 GO TO 12
00890 33 QBA=MBA*AB*3.*(SBAI/(AB-4.)-SBAR/(AB-4.))
00900 B=0.
00910 Z1=0.
00920 GO TO 12
00930 34 IF (AB.LE.4.) GO TO 12
00940 SBAI=BAI+SBAI
00950 SBAR=BAR+SBAR
00960 IF (A.EQ.20.) GO TO 33
00970 GO TO 12
00980 13 C=C+1.
00990 AC=AC+1.
01000 IF (Z2.EQ.1.) GO TO 52
01010 AMC=A-C
01020 Z2=1.
01030 52 IF (AMC.LT.16.) 35,36
01040 35 IF (AC.LE.20.) GO TO 37
01050 SUI=UI+SUI
01060 SUR=UR+SUR
01070 GO TO 14
01080 36 IF (AC.LE.4.) GO TO 14
01090 SUI=UI+SUI
01100 SUR=UR+SUR
01110 IF (A.EQ.20.AND.AC.GT.4.) GO TO 38
01120 GO TO 14
01130 38  QU=MU*AC*3.*(SUI/(AC-4.)-SUR/(AC-4.))
01140 C=0.
01150 Z2=0.
01160 GO TO 14
01170 37 IF (AC.LE.4.) GO TO 14
01180 SUI=UI+SUI
01190 SUR=UR+SUR
01200 IF (A.EQ.20.) GO TO 38
```

```
01210 GO TO 14
01220 15 D=D+1.
01230 AD=AD+1.
01240 IF (Z.EQ.1.) GO TO 50
01250 AMD=A-D
01260 Z=1.
01270 50 IF (AMD.LT.16.) 39,40
01280 39 IF (AD.LE.20.) GO TO 41
01290 SBEI=BEI+SBEI
01300 SBER=BER+SBER
01310 GO T_ 16
01320 40 IF(AD.LE.4.) GO TO 16
01330 SBEI=BEI+SBEI
01340 SBER=BER+SBER
01350 IF (A.EQ.20.AND.AD.GT.4.)  GO TO 42
01360 GO TO 16
01370 42 QBE=MBE*AD*3.*(SBEI/(AD-4.)-SBER/(AD-4.))
01380 D=0.
01390 Z=0.
01400 GO TO 16
01410 41 IF (AD.LE.4.) GO TO 16
01420 SBEI=BEI+SBEI
01430 SBER=BER+SBER
01440 IF (A.EQ.20.) GO TO 42
01450 GO TO 16
01460 10 TT=STT/A
01470 TA1=STA1/A
01480 TA2=STA2/A
01490 ATA=(TA1+TA2)/2.
01500 PYR=SPYR/A
01510 TT2=STT2/A
01520 SI=PYR*F/E
01530 IF (B.EQ.0.) GO TO 20
01540 QBA=MBA*B*3.*(SBAI/B-SBAR/B)
01550 QBAPFT=B/20.*QBA/QBAL
01560 QBAPFT=QBAPFT*4,0./B**2
01570 TBAI=SBAI/B
01580 ATBA=(SBAI/B+SBAR/B)/2.
01590 B8=ALOG((SBAI/B-68.)/(SBAR/B-68.))
01600 UBA=20./B*QBA/B8
01610 20 IF (C.EQ.0.) GO TO 21
01620 QU=MU*C*3.*(SUI/C-SUR/C)
01630 QUPFT=C/20.*QU/QUL
01640 QUPFT=QUPFT*400./C**2
01650 TUI=SUI/C
01660 ATU=(SUI/C+SUR/C)/2.
01670 UU=C/20.*QU/ALOG((SUI/C-68.)/(SUR/C-68.))
01680 UU=UU*400./C**2
01690 21 IF (D.EQ.0.) GO TO 22
01700 QBE=MBE*D*3.*(SBEI/D-SBER/D)
01710 QBEPFT=D/20.*QBE/QBEL
01720 QBEPFT=QBEPFT*400./D**2
01730 TBEI=SBEI/D
01740 ATBE=(SBEI/D+SBER/D)/2.
01750 D7=20./D*QBE
01760 D8=ALOG((SBEI/D-68.)/(SBER/D-68.))
01770 UBE=D7/D8
01780 22 CONTINUE
01790 IF (NDAY.LT.57.) 80,81
01800 80 QHAH=1130.
```

```
01810 81 IF (NDAY.EQ.57.AND.FHOUR.LE.16.) 102,103
01820 102 QHAH=1130.
01830 103 IF (NDAY.LT.58.) 100,101
01840 100 QIH=2529.
01850 101 IF (NDAY.EQ.58.AND.NHOUR.LE.20.) 104,105
01860 104 QIH=2529.
01870 105 CONTINUE
01880 QTL=-4720.76+68.59*TT
01890 QT=QBA+QU+QBE+QHAH+QIH+QTL
01900 IF (X.EQ.1.) GO TO 60
01910 IF (X3.EQ.1.) GO TO 67
01920 IF (B.EQ.0.) GO TO 61
01930 PRINT 62
01940 WRITE (3,62)
01950 PRINT 63,NDAY,NHOUR,QBAPFT,TBAI,ATBA,UBA
01960 WRITE (3,63) NDAY,NHOUR,QBAPFT,TBAI,ATBA,UBA
01970 61 IF (C.EQ.0.) GO TO 64
01980 PRINT 65
01990 WRITE (3,65)
02000 PRINT 63,NDAY,NHOUR,QUPFT,TUI,ATU,UU
02010 WRITE (3,63) NDAY,NHOUR,QUPFT,TUI,ATU,UU
02020 64 IF (D.EQ.0.) GO TO 67
02030 PRINT 68
02040 WRITE (3,68)
02050 PRINT 63,NDAY,NHOUR,QBEPFT,TBEI,ATBE,UBE
02060 WRITE (3,63) NDAY,NHOUR,QBEPFT,TBEI,ATBE,UBE
02070 GO TO 67
02080 60 PRINT 25,NDAY,NHOUR,TT,QT,ATA,SI,TT2
02090 WRITE (3,25) NDAY,NHOUR,TT,QT,ATA,SI,TT2
02100 25 FORMAT (2X,I2,1X,I2,3X,F6.2,3X,F9.2,3X,F5.2,3X,F6.2,3X,F5.2)
02110 67 QBA=0.
02120 QU=0.
02130 QBE=0.
02140 QT=0.
02150 STT=0.
02160 STA1=0.
02170 STA2=0.
02180 SPYR=0.
02190 STT2=0.
02200 A=0.
02210 B=0.
02220 C=0.
02230 D=0.
02240 SBAI=0.
02250 SBAR=0.
02260 SUI=0.
02270 SUR=0.
02280 SBEI=0.
02290 SBER=0.
02300 62 FORMAT (*  DAY HR BASEMENT Q/FT  TI    ATEMP     UA*)
02310 63 FORMAT (3X,I2,1X,I2,9X,F5.1,1X,F5.1,1X,F5.1,1X,F8.1)
02320 65 FORMAT (*  DAY HR LIVING    Q/FT  TI    ATEMP     UA*)
02330 68 FORMAT (*  DAY HR BEDROOM   Q/F   TI    ATEMP     UA*)
02340 200 IF (A.EQ.20.) 201,9
02350 201 G=0.
02360 A=0.
02370 H=0.
02380 STT1=0.
02390 9 CONTINUE
02400 END
```

TABLE I3

HOURLY HEAT LOSS DATA FOR SOLAR HABITAT I

Column one - line number

Column two - julian day

Column three - hour

Column four - average storage tank temperature - °F

Column five - thermal energy added to Solar Habitat I based on $\dot{Q}_C$, $\dot{Q}_T$, $\dot{Q}_{HA}$, and $\dot{Q}_{VC}$ ($\dot{Q}_{HA}$ and $\dot{Q}_{VC}$ are defined in Calculations I1) - BTU/hr

Column six - average ambient temperature - °F

Column seven - solar insolation rate on a south facing vertical surface - BTU/ft^{2}hr

Column eight - average water temperature of the 2000 gallon storage tank - °F

```
00001   48 15   164.32   10208.95   20.01   161.22   64.43
00002   48 16   164.69   10234.33   19.01    81.94   64.45
00003   48 17   165.08   10261.08   17.48     4.59   64.49
00004   48 18   165.41   10284.05   16.19      .29   64.47
00005   48 19   165.69   10303.26   15.67      .35   64.46
00006   48 20   165.99   10323.49   14.38      .34   64.41
00007   48 21   166.28   10343.39   13.40      .38   64.40
00008   48 22   166.57   10363.28   13.25      .38   64.40
00009   48 23   165.95   20037.64   12.96      .41   64.36
00010   49  0   165.26   21617.47   12.86      .42   64.37
00011   49  1   164.65   21443.50   12.07      .41   64.35
00012   49  2   164.12   21320.71   11.46      .51   64.45
00013   49  3   163.62   21175.11   10.84      .53   64.45
00014   49  4   163.09   21000.61   10.44      .53   64.48
00015   49  5   162.61   20909.64    8.15      .52   64.44
00016   49  6   162.15   20840.80    7.43     1.48   64.32
00017   49  7   161.71   20707.61    8.63    41.59   64.31
00018   49  8   161.33   16974.88   13.09   135.04   64.28
00019   49  9   161.43   10011.07   16.91   221.41   64.29
00020   49 10   161.88   10041.59   21.41   267.08   64.28
00021   49 11   162.27   10068.68   25.42   287.51   64.25
00022   49 12   162.64   10093.72   28.39   287.42   64.21
00023   49 13   163.04   10121.15   29.60   265.42   64.18
00024   49 14   163.39   10145.16   30.64   198.17   64.12
00025   49 15   163.73   10168.82   30.00   132.40   64.18
00026   49 16   164.12   10195.23   28.01    56.60   64.21
00027   49 17   164.43   10216.49   25.37     3.07   64.20
00028   49 18   164.69   10234.67   23.42      .23   64.16
00029   49 19   164.99   10254.90   23.13      .28   64.16
00030   49 20   165.24   10272.05   22.64      .26   64.11
00031   49 21   165.56   10294.00   21.27      .29   64.17
00032   49 22   165.85   10313.89   20.40      .31   64.13
00033   49 23   166.05   12421.05   19.74      .32   64.11
00034   50  0   165.78   15275.42   19.25      .33   64.09
00035   50  1   165.33   18784.17   18.90      .33   64.09
00036   50  2   164.63   21394.53   19.39      .37   64.04
00037   50  3   164.09   21161.05   20.91      .38   64.05
00038   50  4   163.60   21005.82   21.88      .38   64.06
00039   50  5   163.15   20849.52   22.77      .37   64.03
00040   50  6   162.69   20738.39   23.41      .68   64.02
00041   50  7   162.24   20589.66   24.12    13.64   64.01
00042   50  8   162.03   13704.14   27.05    53.66   64.01
00043   50  9   162.29   10070.05   30.69    68.61   64.02
00044   50 10   162.71   10098.52   31.35    29.04   63.96
00045   50 11   163.06   10122.53   32.03    29.10   63.92
00046   50 12   168.40   10150.00   32.50    28.80   63.95
00047   50 13   163.83   10175.34   33.91    28.59   63.95
00048   50 14   164.19   10200.38   37.20    71.39   63.93
00049   50 15   164.57   10226.44   36.53    91.45   63.94
00050   50 16   164.88   10247.36   34.94    13.55   63.92
00051   50 17   165.21   10269.99   32.50     1.68   63.91
00052   50 18   165.55   10293.31   31.63      .15   63.94
00053   50 19   165.83   10312.86   30.94      .16   63.90
00054   50 20   166.15   10334.47   29.12      .16   63.87
00055   50 21   166.23   13308.87   28.02      .18   63.85
00056   50 22   165.84   16608.24   28.75      .23   63.81
00057   50 23   165.57   16475.05   28.02      .19   63.83
00058   51  0   165.42   16436.94   26.90      .21   63.81
00059   51  1   165.22   16380.63   25.98      .22   63.85
00060   51  2   165.08   16349.21   25.43      .26   63.80
```

```
00061    51  3    164.89     16318.61    24.92        .26     63.76
00062    51  4    164.73     16301.78    24.62        .26     63.77
00063    51  5    164.26     18753.41    24.00        .27     63.81
00064    51  6    164.13     14926.26    24.60        .45     63.80
00065    51  7    164.11     14910.18    24.96       4.08     63.80
00066    51  8    164.19     14856.16    25.67      10.16     63.84
00067    51  9    163.63     20027.84    26.34      15.44     63.76
00068    51 10    163.20     17176.31    2[illegible].81      10.33     63.75
00069    51 11    163.20     10132.13    [illegible].32      13.55     63.78
00070    51 12    163.59     10158.86    28.12      19.74     63.79
00071    51 13    164.06     10191.46    28.69      18.50     63.80
00072    51 14    164.46     10218.89    28.47      13.23     63.81
00073    51 15    164.57     12771.78    28.78       8.62     63.79
00074    51 16    164.15     18258.04    27.48       5.90     63.78
00075    51 17    163.56     20851.98    27.29        .69     63.81
00076    51 18    163.10     20610.41    26.68        .30     63.83
00077    51 19    162.63     19887.03    26.20        .31     63.87
00078    51 20    162.51     12114.29    25.96        .29     63.91
00079    51 21    162.86     10109.15    26.03        .29     64.00
00080    51 22    163.29     10138.30    26.17        .27     64.03
00081    51 23    163.44     13504.46    26.26        .30     64.10
00082    52  0    162.77     20194.43    26.85        .30     64.03
00083    52  1    162.29     20526.82    26.77        .28     64.02
00084    52  2    161.92     20339.83    26.79        .40     64.24
00085    52  3    161.61     16757.91    25.89        .40     64.26
00086    52  4    161.63     14483.57    25.21        .41     64.25
00087    52  5    161.72     14510.26    23.99        .39     64.26
00088    52  6    161.75     14512.32    23.34       1.53     63.98
00089    52  7    161.74     14534.55    24.48      15.20     63.99
00090    52  8    161.86     11837.82    26.39      84.05     63.99
00091    52  9    162.17     10061.48    27.60      83.25     64.00
00092    52 10    162.55     10087.54    28.24     154.57     64.07
00093    52 11    162.87     10109.49    28.84     241.53     64.12
00094    52 12    163.18     10131.10    29.72     296.46     64.12
00095    52 13    163.60     10159.91    29.85     252.66     64.15
00096    52 14    163.96     10184.60    29.48     222.78     64.12
00097    52 15    164.27     10205.52    27.98     172.11     64.08
00001    53 13    165.58     10295.72    32.65      31.83     63.97
00002    53 14    165.93     10319.38    32.37      28.60     64.03
00003    53 15    166.20     10338.24    35.18      92.56     64.05
00004    53 16    166.57     10363.28    32.98      64.66     64.12
00005    53 17    166.90     10386.25    30.01       3.61     64.08
00006    53 18    167.15     10403.40    28.80        .19     64.06
00007    53 19    167.50     10427.06    27.56        .19     64.04
00008    53 20    167.79     10446.96    27.68        .23     64.03
00009    53 21    168.10     10468.56    27.24        .23     64.05
00010    53 22    168.36     10486.40    27.02        .26     64.03
00011    53 23    167.84     17650.48    28.11        .29     64.00
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00013    54  1    167.53     16722.55    29.98        .30     64.02
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00017    54  5    167.45     15451.53    25.21        .39     64.18
00018    54  6    166.80     21560.60    24.96       1.42     63.99
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00023    54 11    166.87     10384.20    37.36      45.54     64.10
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00028     54 16    168.44     10491.88    38.31      21.03     63.97
00029     54 17    168.76     10513.49    36.37       2.38     64.00
00030     54 18    169.09     10536.47    35.04        .17     63.97
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00032     54 20    169.65     10574.88    32.30        .22     63.91
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00045     55  9    170.11     14694.88    31.57       6.94     63.78
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00083     56 23    174.11     10880.44    38.40        .21     63.99
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          **********  PROGRAM RD4868   **********          PAGE  4
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00292    65 16   117.52      3340.28   38.13     9.45   64.74
00293    65 17   117.41      3332.73   37.63     1.29   64.74
00294    65 18   117.29      3324.50   37.20      .16   64.85
00295    65 19   117.22      3319.36   36.95      .18   64.76
00296    65 20   117.10      3311.13   36.75      .18   64.72
00297    65 21   117.00      3304.61   35.97      .19   64.67
00298    65 22   116.91      3298.44   35.50      .21   64.67
00299    65 23   116.77      3288.49   35.10      .19   64.69
00300    66  0   116.65      3280.61   34.92      .20   64.69
00301    66  1   116.53      3272.03   34.71      .20   64.65
00302    66  2   116.41      3263.80   34.35      .28   64.74
00303 0  66  3   116.16      5044.74   34.24      .29   64.67
00304    66  4   115.67      6049.57   33.65      .22   64.54
00305    66  5   115.37      5977.90   33.29      .22   64.50
00306    66  6   115.02      5938.62   33.15     1.62   64.49
00307    66  7   114.68      5897.39   33.88     5.74   64.46
00308    66  8   114.37      5849.14   34.76    11.36   64.44
00309    66  9   114.06      5798.60   36.43    22.55   64.40
00310    66 10   113.74      5688.96   38.07    30.09   64.35
00311    66 11   113.44      5640.91   39.61    33.78   64.33
00312    66 12   113.15      5601.16   39.18    22.99   64.30
00313    66 13   112.86      5548.08   38.12    11.98   64.28
00314    66 14   112.58      5515.56   38.16    14.68   64.23
00315    66 15   112.33      5478.55   37.68    11.65   64.25
00316    66 16   112.07      5447.39   37.21     7.04   64.26
00317    66 17   111.81      5409.70   36.13     2.11   64.24
00318    66 18   111.55      5376.25   35.58      .15   64.22
00319    66 19   111.25      5332.59   35.22      .16   64.21
00320    66 20   110.98      5317.63   34.79      .16   64.20
00321    66 21   110.74      5276.14   34.62      .19   64.20
00322    66 22   110.49      5270.70   34.79      .20   64.18
00323    66 23   110.20      5240.71   34.26      .19   64.19
```

```
00324    67   0    109.96      5222.64    33.45        .16     64.16
00325    67   1    109.71      5207.44    32.91        .18     64.15
00326    67   2    109.48      5195.23    32.89        .21     64.11
00327    67   3    109.24      5200.24    32.73        .20     64.11
00328    67   4    108.98      5198.02    32.36        .20     64.06
00329    67   5    108.76      5192.69    31.42        .19     64.06
00330    67   6    108.49      5194.03    30.73       8.74     64.01
00331    67   7    108.21      5159.21    32.60      75.22     64.05
00332    67   8    107.98      5069.26    34.45     144.41     64.08
00333    67   9    107.75      4985.17    35.93     182.57     64.22
00334    67  10    107.56      3545.26    37.51     211.27     64.45
00335    67  11    107.50      2653.01    39.98     224.03     64.77
00336    67  12    107.46      2650.26    42.02     224.20     65.03
00337    67  13    107.41      2646.49    43.34     207.24     65.23
00338    67  14    107.35      2642.72    43.93     173.87     65.14
00339    67  15    107.30      2638.95    44.71     126.24     65.04
00340    67  16    107.22      2633.46    44.73      70.91     65.02
00341    67  17    107.16      2629.69    43.44      13.50     64.97
00342    67  18    107.11      2626.26    42.09        .03     64.92
00343    67  19    107.09      2624.54    39.22        .06     64.88
00344    67  20    107.03      2620.77    37.96        .10     64.79
00345    67  21    106.98      2617.00    36.13        .10     64.76
00346    67  22    106.86      2609.11    34.48        .12     64.70
00347    67  23    106.81      2605.68    33.94        .15     64.67
00348    68   0    106.77      2602.94    33.58        .16     64.62
00349    68   1    106.71      2598.82    33.31        .16     64.59
00350    68   2    106.65      2594.71    32.74        .24     64.70
00351    68   3    106.59      2590.59    32.88        .29     64.73
00352    68   4    106.52      2585.45    33.22        .28     64.70
00353    68   5    106.39      3443.54    32.75        .27     64.68
00354    68   6    105.92      4939.34    33.10       8.41     64.48
00355    68   7    105.67      4850.31    36.34      26.46     64.47
00356    68   8    105.45      4793.89    38.04      77.73     64.43
```

TABLE I4

DAILY THERMAL ENERGY SUPPLIED TO SOLAR HABITAT I FROM THE STORAGE TANK

```
**********  PROGRAM TANKDATA **********                  PAGE   1

49        163.79    188506.76    21.61   1901.04      64.03
50        164.62    181044.88    29.36    432.74      63.81
51        163.19    224376.62    26.56    124.63      64.26
54        168.89    135235.42    33.36    432.66      63.81
55        171.23    190928.69    33.56     71.62      63.80
56        172.68    136081.05    39.20    341.98      63.90
57        176.91    135561.26    35.93    646.41      63.86
58        180.23    127218.27    37.63    232.37      63.82
59        169.67    124478.55    32.06   1426.15      64.49
60        158.06    143564.18    30.16   1091.19      64.49
61        146.95    123031.10    32.27   1536.04      64.43
62        138.21     80409.75    36.20   1660.41      64.21
63        129.63    142115.78    33.28    149.12      63.99
63        121.83     55597.03    41.81    972.85      63.77
65        117.51     56771.21    36.75    579.60      64.50
66        111.73     85308.56    35.31    177.78      64.06
67        107.20     29479.70    37.32   1664.16      64.68
```

Column one	- julian day
Column two	- average storage tank temperature - °F
Column three	- thermal energy supplied to Solar Habitat I from the storage tank ($\dot{Q}_C$ and $\dot{Q}_T$) - BTU/day
Column four	- average daily ambient air temperature -°F
Column five	- total daily solar insolation rate on a south facing vertical surface - BTU/dayft^2
Column six	- average daily temperature of the 2000 gallon storage tank - °F

CALCULATION I1

CALCULATION OF THE THERMAL ENERGY GAINED FROM SOURCES OTHER THAN THE STORAGE TANK

The thermal energy gained by Solar Habitat I from electricity dissipated through appliances and laboratory equipment, $\dot{Q}_E$, was estimated by finding the difference between the average daily electrical consumption and the amount of electricity used as shaft work. From the kilowatt-hour meter data, the average electrical consumption rate was estimated to be 40 kwh/day or 136520 BTU/day. Of this daily electrical energy use it is estimated that 62730 BTU/day is shaft work (16). An explanation of the energy used and the shaft work by specific appliances and equipment is summarized in Table I5.

The amount of thermal energy gained by Solar Habitat I due to heat loss from the two residents living in Solar Habitat I, $\dot{Q}_H$, was estimated by assuming the people were present fourteen hours/day and added thermal energy to Solar Habitat I at a rate of 370 BTU/hr per person (16). Thus, on a daily basis it is estimated that the thermal energy gained from the residents of Solar Habitat I was 10360 BTU/day.

Another source of thermal energy was the gas stove. It was estimated that the stove was in operation 1 1/2 hr/day and released thermal energy at a rate of 4500 BTU/hr or 6750 BTU/day (16).

Thermal energy was also added to Solar Habitat I continuously from the hot water heater, $\dot{Q}_{HW}$. For this analysis, it was assumed the inside water temperature was 140°F, the ambient air temperature was 65°F, and the overall heat transfer coefficient was .1713 $BTU/hrft^2{}^\circ F$. The overall heat transfer coefficient was estimated from the capacity and dimensions of the storage tank (20). From the above information and the measured surface area of the storage tank (31.62 ft^2) it was estimated the storage tank released energy to Solar Habitat I at a rate of 379 BTU/hr or 9100 BTU/day. Summing the values of $\dot{Q}_E$, $\dot{Q}_{ST}$, $\dot{Q}_H$, and $\dot{Q}_{HW}$ it is estimated that there are 100,000 BTU/day of thermal energy added to Solar Habitat I from sources other than the storage tank.

For the acutal testing of Solar Habitat I, there were two other sources of thermal energy which have not been discussed previously. They include the energy used by the hot air heater, $\dot{Q}_{HA}$, for the pilot light and the electrical energy dissipated in a voltage controller, $\dot{Q}_{VC}$, which decreased the line voltage to a level which was compatible with the immersion heaters. It was estimated that from February 17 at 2:00 p.m. until February 28, 1977 at 5:00 p.m. the hot air heater added thermal energy to Solar Habitat I at a rate of 1130 BTU/hr or 27120 BTU/day and the voltage controller added thermal energy to Solar Habitat I from February 17 at 2:00 p.m. until February 27, 1977 at 8:00 p.m. at a rate of .8 kw or 2730 BTU/hr or 65520 BTU/day. Table I6 summarizes the total thermal energy used ($\dot{Q}_C$, $\dot{Q}_T$, $\dot{Q}_E$, $\dot{Q}_{HW}$, $\dot{Q}_{ST}$, $\dot{Q}_{VC}$, and $\dot{Q}_{HA}$) to supply the heating load of Solar Habitat I for various weather conditions.

TABLE I5

THERMAL ENERGY ADDED TO SOLAR HABITAT I FROM APPLIANCES AND EQUIPMENT

Appliance or equipment description	Electrical energy needed to operate - BTU/hr	Estimated shaft work - BTU/hr	Time in operation - hr	Daily shaft work - BTU/day
1 HP pump used continuously to stir storage tank - 115 V, 13 A	5102	1881	24	45142
Ventilation fan - 1/8 HP, 115 V, 2 A	785	206	24	4960
Bedroom baseboard convector pump - 1/8 HP, 115 V, 3 A	1177	649	7.25	4708
Living area baseboard convector pump - 1/12 HP, 115 V, 2.4 A	942	509	2.20	1120
Other appliances used: fan on recorders and teletypes, hairdryer, refrigerator, mixers, drills, saws, etc.	—	—	—	estimated 6800

Total

62730 BTU/day of the total electricity supplied is shaft work.

TABLE I6

TOTAL THERMAL ENERGY SUPPLIED TO SOLAR HABITAT I

```
 **********   PROGRAM TOTALQ    **********               PAGE   1

49         163.79    381146.76    21.61   1901.04     64.03
50         164.62    373684.88    29.36    432.74     63.81
51         163.19    417016.62    26.56    124.63     64.26
54         168.89    327875.42    33.36    432.66     63.81
55         171.23    383568.69    33.56     71.62     63.80
56         172.68    328721.05    39.20    341.98     63.90
57         176.91    328201.26    35.93    646.41     63.86
58         180.23    292558.27    37.63    232.37     63.82
59         169.67    236908.55    32.06   1426.15     64.49
60         158.05    243564.18    30.16   1091.19     64.49
61         146.95    223031.10    32.27   1536.04     64.43
62         138.21    180409.75    36.20   1660.41     64.21
63         129.63    242115.78    33.28    149.12     63.99
63         121.83    155597.03    41.81    972.85     63.77
65         117.51    156771.21    36.75    579.60     64.50
66         111.73    185308.56    35.31    177.78     64.06
67         107.20    129479.70    37.32   1664.16     64.68
```

Column one - julian day

Column two - average daily storage tank temperature - °F

Column three - thermal energy supplied to Solar Habitat I from all sources of energy ($\dot{Q}_T$, $\dot{Q}_C$, $\dot{Q}_{HW}$, $\dot{Q}_H$, $\dot{Q}_{ST}$, $\dot{Q}_E$, $\dot{Q}_{HA}$, and $\dot{Q}_{VC}$) - BTU/day

Column four - average daily ambient air temperature - °F

Column five - total daily solar insolation rate on a south facing vertical surface - BTU/hrft^2

Column six - average daily temperature of the 2000 gallon storage tank - °F

APPENDIX J

INFILTRATION RATE INFORMATION

The total infiltration rate is comprised of infiltration due to natural convection and infiltration due to the ventilation system installed in the basement of Solar Habitat I. Only the infiltration rate due to the ventilation system was experimentally measured. This was done by obtaining a velocity profile at the exit of the exhaust duct of the ventilation system. The wind velocity was measured at twenty-five locations in 9 inch by 4 1/2 inch exhaust duct by an electronic manometer. Figure J1 shows the data obtained. From this data the average pressure (inches of water) was obtained and the estimated average velocity calculated by the following equation (22)

$$V_d = \left[2g_c h \frac{(\rho - \rho_a)}{\rho_a} \right]^{1/2} \tag{J1}$$

where

ρ_a = Density of air = .075348 #m/ft^3

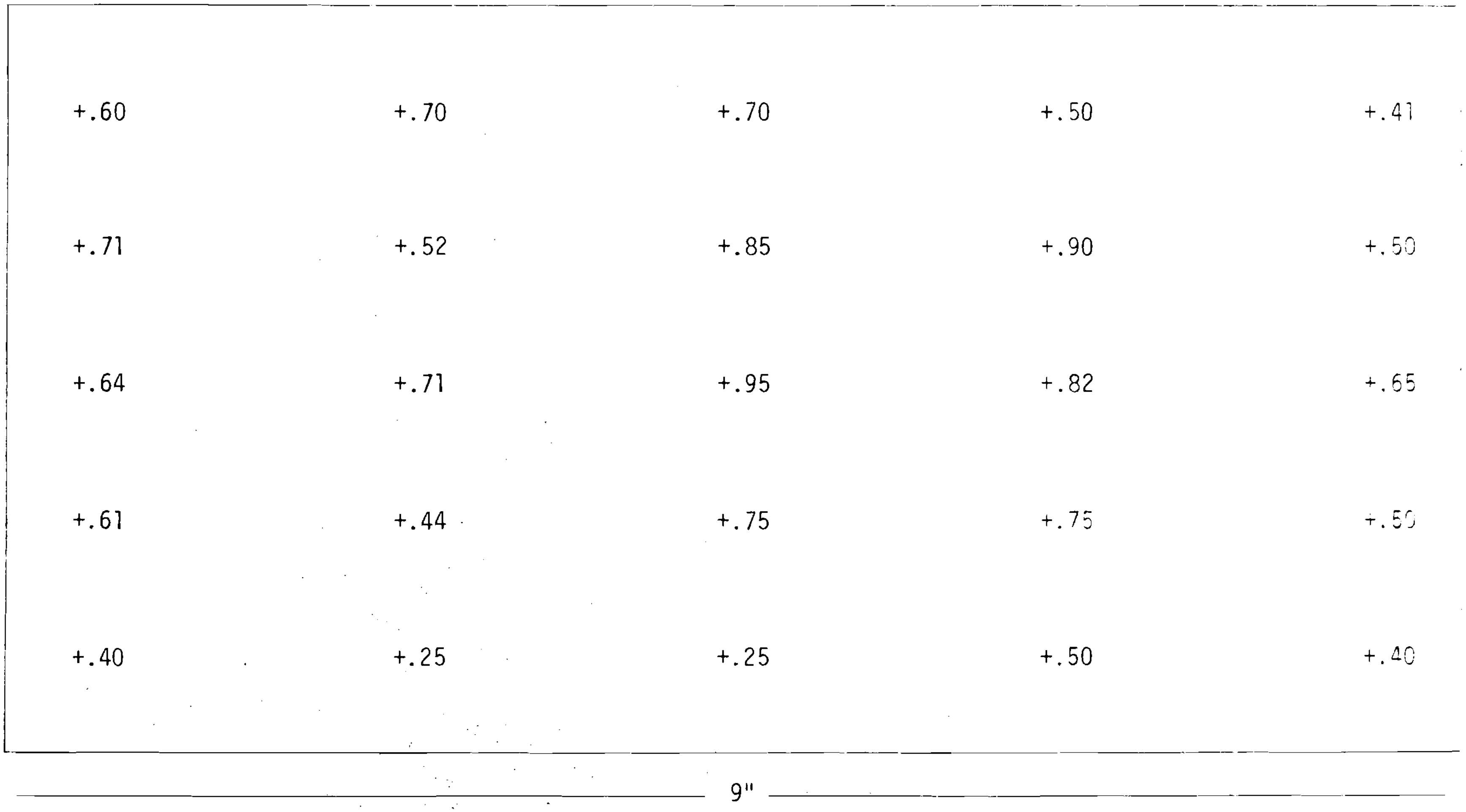
ρ = Density of water = 62.37 #m/ft^3

g_c = Gravitational constant = 32.2 ft/sec^2

h = Height of water = 1.5×10^{-4} ft of water

V_d = Average velocity at the exit of the ventilation duct = 2.826 ft/sec

By knowing the value of V_d the volumetric flow rate can be calculated (2848 ft^3/hr), from which the infiltration rate due to the ventilation system can be obtained (.11 air changes/hr).



+.60	+.70	+.70	+.50	+.41
+.71	+.52	+.85	+.90	+.50
+.64	+.71	+.95	+.82	+.65
+.61	+.44	+.75	+.75	+.50
+.40	+.25	+.25	+.50	+.40

Value x .003 is the pressure difference in inches of water - scale, 1 inch = 1 inch

Figure J1. Velocity Profile for Ventilation Duct

APPENDIX K

NOMENCLATURE

A_B = Surface area of the bottom of the storage tank - ft^2

A_c = Aperture area of the collector array - ft^2

A_E = Surface area of the east wall of the storage tank - ft^2

A_N = Surface area of the north wall of the storage tank - ft^2

A_s = Surface area of the storage tank - ft^2

A_S = Surface area of the south wall of the storage tank - ft^2

A_T = Surface area of the top of the storage tank - ft^2

A_W = Surface area of the west wall of the storage tank - ft^2

A_I = Experimental average daily solar insolation rate - BTU/ft^2 day

C = Specific heat of water - BTU/#m°F

C_1 = $U_E A_E + U_W A_W + U_N A_N + U_T A_T + U_B A_B + U_S A_S$ = constant - BTU/hr°F

C_2 = $-[(U_E A_E + U_W A_W + U_N A_N + U_T A_T)\, T_a + U_B A_B T_b + U_S A_S T_g]$ = constant - BTU/hr

$C_{h\ell}$ = constant which describes the heat loss through the doors, walls, windows, ceiling, and floor of Solar Habitat I - BTU/°F day

C_i = Experimental constant which describes the heat lost from Solar Habitat I due to infiltration - BTU/°F day

C_{min} = Smaller of the $\dot{m}_p C_p$ and $\dot{m}c$ magnitudes - BTU/hr°F

C_p = Specific heat of the propylene-glycol-water mixture - BTU/#m°F

C_s - Experimental constant which describes the heating load of Solar Habitat I for an average daily solar insolation rate - BTU/°F day

C_w = Experimental constant which describes the heat gain through the windows of Solar Habitat I due to solar insolation - $\dfrac{\text{BTU/°F day}}{\text{BTU/ft}^2\text{ day}}$

DI = Experimental values for the daily solar insolation rate - BTU/ft^2 day

F' = Collector efficiency factor = $\frac{\text{actual useful energy collected}}{\text{useful energy collected if the entire collector surface were at the average fluid temperature}}$

I = Solar insolation available on a south facing vertical surface - $BTU/hrft^2$

ℓ_1 = Length of the bedroom, kitchen, and bathroom convectors - ft

ℓ_2 = Length of the living area convectors - ft

ℓ_3 = Length of the basement convectors - ft

$\dot{m}$ = Flow rate of water through the heat exchanger on the tank side (tube side) - gpm

$\dot{m}_c$ = Flow rate through all convector loops - gpm

$\dot{m}_p$ = Flow rate of the propylene-glycol-water mixture through the collector - gpm

$\dot{Q}_1$ = Rate of heat transfer from the bedroom convector loop to Solar Habitat I per linear foot of convector - BTU/hrft

$\dot{Q}_2$ = Rate of heat transfer from the living area convector loop to Solar Haibtat I per linear foot of convector - BTU/hrft

$\dot{Q}_3$ = Rate of heat transfer from the basement convectors to Solar Habitat I per linear foot of convector - BTU/hrft

Q_{AH} = Amount of thermal energy supplied to Solar Habitat I from the auxiliary heating system - BTU/day

$\dot{Q}_C$ = Thermal energy supplied to Solar Habitat I from the baseboard convectors - BTU/day

$\dot{Q}_{ch}$ = Amount of energy supplied to Solar Habitat I per hour by means of the baseboard convector - BTU/hr

$\dot{Q}_E$ = Thermal energy added to Solar Habitat I from dissipating electricity through appliances - BTU/day

$\dot{Q}_H$ = Thermal energy gained to Solar Habitat I from human habitation - BTU/day

$\dot{Q}_{h\ell}$ = Heat losses from Solar Habitat I through walls, windows, doors, roof and floor - BTU/day

$\dot{Q}_{HW}$ = Thermal energy lost from the domestic hot water system to Solar Habitat I - BTU/day

$\dot{Q}_i$ = Rate of energy losses from Solar Habitat I due to infiltration - BTU/day

$\dot{Q}_L$ = Heating load of Solar Habitat I - BTU/day

$\dot{Q}_S$ = Rate at which thermal energy is supplied to Solar Habitat I - BTU/day

$\dot{Q}_{SS}$ = Amount of energy supplied to Solar Habitat I from the storage tank - BTU/day

$\dot{Q}_{ST}$ = Thermal energy gain to Solar Habitat I from the daily use of the gas stove - BTU/day

$\dot{Q}_t$ = Rate of heat transfer from the storage tank - BTU/hr

$\dot{Q}_T$ = Thermal energy lost from the storage tank to the basement - BTU/day

$\dot{Q}_w$ = Rate of energy gain to Solar Habitat I from solar insolation - BTU/day

t = Time - sec, hr

T_a = Ambient basement and main floor temperature - °F

T_{avg} = Average temperature of the water passing through the convectors - °F

T_b = Temperature of the ground below the tank - °F

T_e = Temperature of the fluid at the exit of the collector - °F

T_{e1} = Exit temperature from the bedroom convectors - °F

T_{e2} = Exit temperature from the living area convectors - °F

T_{e3} = Exit temperature from the basement convectors - °F

T_g = Average temperature of the ground on the south wall of the storage tank which is assumed to be $\left(\frac{\text{average ambient temperature} + 55°\text{F}}{2}\right)$ - °F

T_i = Temperature of the fluid at the inlet to the collector - °F

T_{i_1} = Inlet temperature to the bedroom convectors - °F

T_{i_2} = Inlet temperature to the living area convectors - °F

T_{i_3} = Inlet temperature to the basement convectors - °F

T_o = Outside ambient temperature - °F

T_{oa} = Average daily ambient air temperature - °F

T_s = Temperature of the water in the storage tank - °F

T_x = Experimental value for the average daily temperature at which there is a demand for thermal energy from the storage tank - °F

U_B = Overall heat transfer coefficient of the bottom of the storage tank - $\text{BTU/hrft}^2\text{°F}$

U_c = Overall heat transfer coefficient for baseboard convector - $\text{BTU/hrft}^2\text{°F}$

U_{cc} = Overall heat transfer coefficient throughout the solar collector cover system - $\text{BTU/hrft}^2\text{°F}$

U_E = Overall heat transfer coefficient of the east wall of the storage tank - $\text{BTU/hrft}^2\text{°F}$

U_ℓ = Overall heat transfer coefficient from the collector absorber plate to the ambient air - BTU/hrft^2°F

U_N = Overall heat transfer coefficient of the north wall of the storage tank - BTU/hrft^2°F

U_o = Overall heat transfer coefficient for the heat exchanger - BTU/hrft^2°F

U_S = Overall heat transfer coefficient of the south wall of the storage tank - BTU/hrft^2°F

U_t = Overall heat transfer coefficient of the tank - BTU/hrft^2°F

U_T = Overall heat transfer coefficient of the top of the storage tank - BTU/hrft^2°F

U_W = Overall heat transfer coefficient of the west wall of the storage tank - BTU/hrft^2°F

V = Volume of water in the storage tank - ft^3

$\overline{\Delta T}$ = Logarithmic mean overall temperature difference between the convector fluid and the inside ambient air temperature - °F

ΔT_c = Temperature difference between the convector fluid temperature and the ambient air temperature - °F

ε = Effectiveness of the heat exchanger

ρ = Density of water #m/ft^3

η = Efficiency of the collector = $\frac{\text{actual useful energy collected}}{\text{solar energy intercepted by the collector}}$ - %

$(\tau\alpha)_e$ = Effective transmittance - absorptance product