A STUDY OF
A SOLAR HEATED HOUSE IN QUEBEC

Richard Gordon Kerr

A Thesis

in

The Centre

for Building Studies

Presented in Partial Fulfillment of the Requirements
for the degree of Master of Engineering (Building)
Concordia University
Montreal, Quebec, Canada

March, 1978

ABSTRACT

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This thesis is a study of the solar heating system in a house near La Macaza, Quebec. The system consists of a vertical air heating collector, which was built as part of the south wall of the house, a rock storage, partly manual control and partly passive heat transfer. Measurements of the solar radiation on the collector and temperatures in the collector, house and storage were recorded on a magnetic tape during the 1976-77 heating season. Studies of the collector efficiency curve, the storage, the daily efficiency of the system and the electricity consumption pattern in the house are presented. The contribution of the solar heating system to the heat requirements of the house for October 1, 1976 to March 31, 1977 is estimated to be 50%. The collector efficiency curve is similar to that of a factory-built collector. The thermal performance of the house and solar heating system has been simulated on a computer using an electric circuit analogy. The calculated temperatures in the collector, storage and house match the measured temperatures.

ACKNOWLEDGEMENTS

Financial support for this work was provided from a Central Mortgage and Housing Corporation Fellowship, from a Concordia University Fellowship, from National Research Council grant No. A4770, and from la Formation de Chercheurs et d'Action Concertée (FCAC) de Québec.

L'Institut de Recherche d'Hydro-Québec provided the Data Acquisition System, calibrated and installed the sensors and provided computer facilities to reduce the data. The Brace Research Institute provided a stipend for travel to the site and to support a resident in the house for three months.

Thanks to Dr. Paul Fazio, Director of the Centre for Building Studies of Concordia University for arranging the financial support and for his interest and encouragement. M. Jacques Beaudet, Chef de Projets de la Direction Services à la Clientèle de l'Hydro-Québec arranged to provide part of the Data Acquisition System, served as liaison with the owners of the property and was a willing source of assistance.

The assistance of Dr. Marvin Shapiro and Mal Turaga of the Centre for Building Studies and Dr. Robert McConnell of l'Institute de Recherche d'Hydro-Québec is gratefully acknowledged. Thanks to Alfredo Romana, who prepared some of the drawings in Appendix A, and Hagop Evrensel, who prepared the figures used in the text and some of the drawings in Appendix A, to Michel St.Jean of l'IREQ for computer work for Chapter 3, to those who typed this thesis and to my fellow graduate students, in the C.B.S., for maintaining a positive working environment.

Thanks to my wife, Pat, for her encouragement and patience.

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CHAPTER 1

INTRODUCTION

The direct use of the sun's energy to heat buildings has become a popular, and will soon be an essential aspect of the construction industry. An excellent introduction to the subject is contained in the book by Farrington Daniels[27]. More detailed considerations are given in ASHRAE GRP 170[28] and in the texts by Duffie and Beckman[18], and by Meinel and Meinel[29]. Practical guidance for builders can be found in the books by Anderson[30] and by Nicholson[31]. "Solar Energy", the journal of the International Solar Energy Society and the proceedings of the Solar Energy Society of Canada/ISES Conference in Winnipeg[2], and the ISES Conference in Orlando[3] contain many useful papers about the various aspects of solar energy.

Solar heating is an ancient art. It was revived on this continent in the decades between 1930 and 1950 by a few pioneers at the University of Wisconsin, M.I.T. and Colorado State University, who began experimenting with collectors and solar heated homes. Since the realization in 1974 that most countries were too dependent on a single energy source, the effort devoted to solar energy research and development has grown rapidly.

As part of its Energy Research Programme, the Centre for Building Studies, at Concordia University, has initiated several research studies in solar energy with the aim of developing cost effective solar heaters suitable for the Québec climate. At the outset, it was realized that before designing solar heaters for Québec, reliable data on the performance of the solar heating system already built here was needed. Since no such data existed, this project was begun to study an existing house located near the village of Macaza, 170 kilometers north of Montreal.

The house was designed and built as part of the "Quebec Indian Housing Project" by the School of Architecture and the Brace Research Institute, both of McGill University[1]. It was completed in February 1976 and was home for families of staff members of Manitou College. Some preliminary studies were presented by Hamilton and McConnell[2].

The author undertook to monitor the house during the 1976-77 heating season and to prepare this thesis for the M.Eng. (Building) programme in the Centre for Building Studies. The study was initially carried out in collaboration with the Brace Research Institute and l'Institut de Recherche d'Hydro-Québec, which supplied and installed the monitoring equipment and provided computer facilities to reduce the data. Investigations were later continued by the C.B.S. with the participation of I.R.E.Q. Preliminary analyses of part of the data have been presented at conferences[3,4].

The present thesis presents a more complete analysis of the data collected during the 1976/77 heating season. In addition, the thermal performance of the house and solar heating system has been simulated on the Concordia University CDC CYBER 172 computer using an electric circuit analogy. Comparisons are made between measured and calculated temperatures in the collector, storage and the living space. Values derived from the computer analysis and measured electricity consumption are used in a heat balance calculation to give an estimate of the contribution of the solar heating system towards the total heat supply to the house.

A number of computer programs have been developed by others to simulate the performance of both liquid and air heating solar energy systems of a standard type with parameters to represent certain characteristics of the system and the location. One such program is TRNSYS[5]. The f-chart program[6] was developed to correlate with TRNSYS as a design tool for the prediction of the contribution of a solar heating system to the heat requirements of a house.

The calculations of this study are based on a simulation program which originated at the MIT Electrical Engineering Department[7]. Modifications to the program were made in order to simulate the particular solar heating system in the Macaza house. The system used air for heat transfer from a vertical collector to a rock storage. Air heating systems have been extensively developed and tested, notably by Löf et al[8]. There are a number of unique features of the Macaza house. The solar collector was constructed as part of the south wall of the house. Snow in front of the south wall in winter serves as a reflector to increase the incident solar energy on the collector. The solar heating system was designed for partly manual control and for partly passive heat transfer.

The construction of the house and the site-built solar heating system are described in Chapter 2. The instruments used to monitor the house, the techniques of analysis of the data and the results of the analysis are presented in Chapter 3. In Chapter 4, the simulation model and the results of computer runs which match the measured performance of the house are given. The heat flows in the house, and the contribution of the solar heating system to the heat supply are also given in Chapter 4. Suggestions for changes in the solar heating system to improve performance and a discussion of the results of this study are presented in Chapter 5. Some economic analysis of costs are presented in Appendix F.

CHAPTER 2

THE HOUSE AND SOLAR HEATING SYSTEM

2.1 The House: Site and Design

In June 1975, the Shelter Systems Group of the Department of Architecture of McGill University started the construction of this house on the grounds of Manitou College, a community college for Indians, Inuit and Metis. It was one of four houses proposed for the Quebec Indian Housing Project supported financially by the Canadian Donner Foundation, the Ministry of State for Urban Affairs and the Department of Indian and Northern Affairs. The project was directed by Professor Bryan McClosky.[1]

The house was built on the college grounds, near La Macaza, a small village, 170 km north of Montreal in the Laurentians. It was planned to be "culturally and environmentally appropriate" through the use of a solar heating system, "local materials", and the employment of indigenous workers in the predominantly labour intensive construction.

Involved in the design of the house were architects Guy Courtois and Bryan McClosky. Tom Lawand of the Brace Research Institute was responsible for the heating system design.

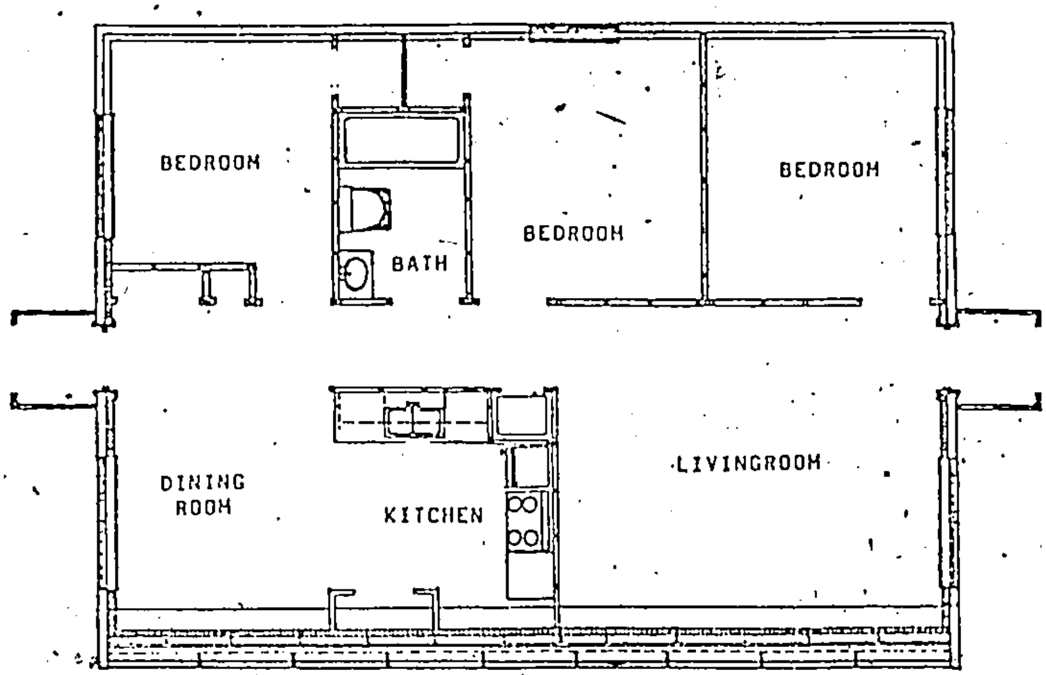
The house and solar heating system were designed for on-site construction of the system, and for simplicity of operation of the system. Pictures and a description of the house can be found in Reference 1.

The house is located in the Quebec Laurentians, a region with an average of 4850 Centigrade heating degree days. The location is at 46°24' North Latitude, 74°47' west, 250 metres above sea level. An important environmental aspect is the snow cover that reflects solar radiation well, making an important contribution to the amount of solar energy received on the vertical collector surface.

The house was designed from the outset for the climate of the region. It was oriented on an east-west axis, to maximize the southern exposure for heat collection. The northern exposure, through which much heat is lost, was minimized by a low profile and earth berm. The windows were concentrated on the east and west sides, where light and heat can be gained. Bedrooms are located in the northern half of the house, directly over the heat storage chamber, so heat stored during the day can rise at night to the bedrooms (Figure 1). The entire surface of the south wall is used for the solar collector. Frame construction is used in the south wall in order to accommodate the solar collector. The east, west and north walls are made of stacked 5" x 5" rough cut spruce timbers. The 5" x 5" dry spruce walls were built with a folded layer of building paper between each squared log to reduce water penetration. Additional oakum was wedged in from the outside where necessary. Two inches of styrene insulation covers the inside of the east and west walls. In the north wall, 4" thick panels of treated peat-moss insulation were used to achieve an overall heat loss factor similar to the other walls.

In the south wall, 2" of polystyrene insulation was used. The interior was finished with 3/16" prefinished wood panels. The

a) Main floor



b) Basement

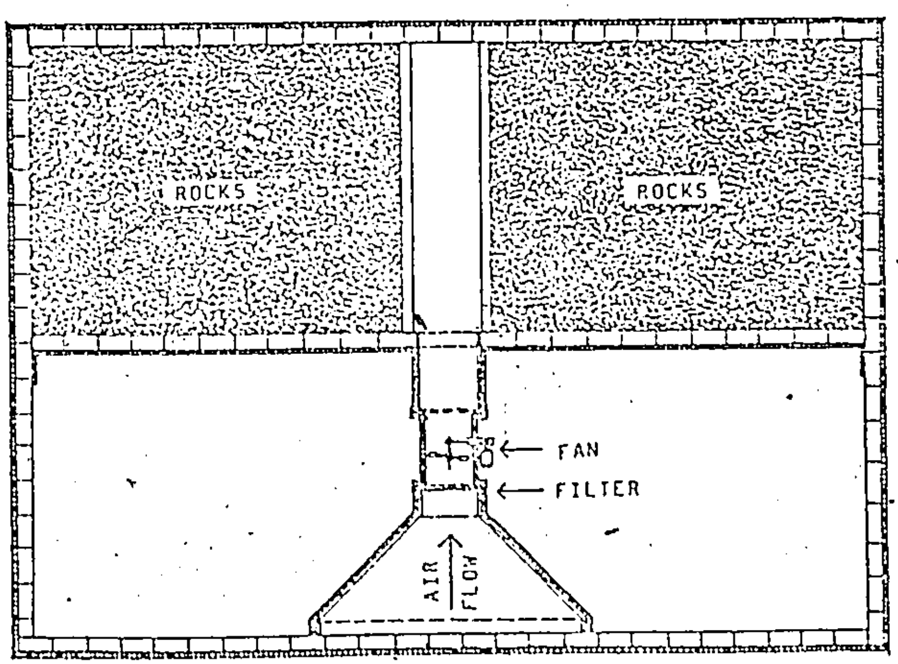


Figure 1 | Floor Plans

ceiling was covered with 4" of insulation (giving nominal R.20) and acoustic tiles. The foundation walls were coated with asphalt sealant and then covered with 3" of styrene insulation.

2.2 The Solar Heating System

(Refer to Appendix A for detailed drawings.)

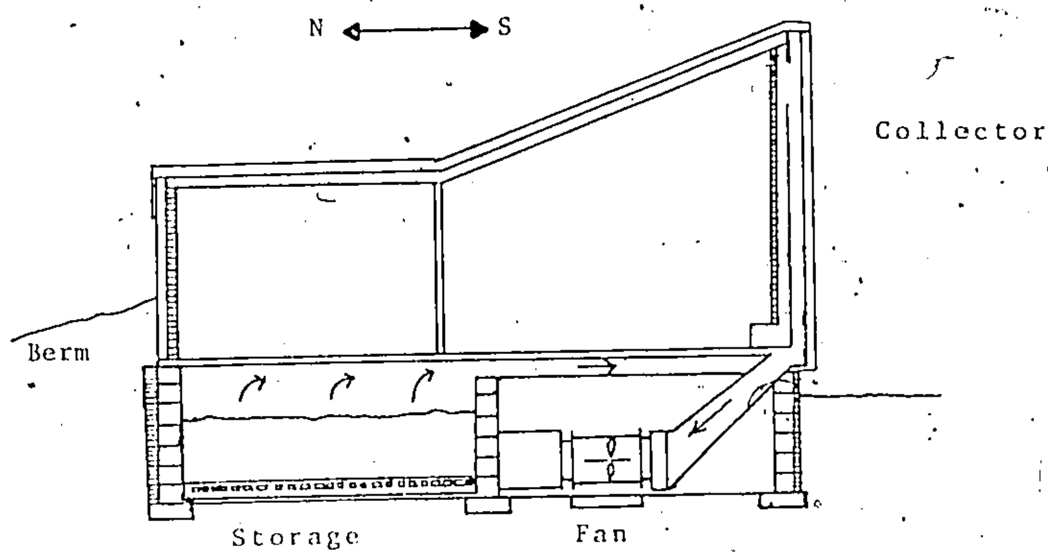
The solar heating system comprises two main components: a vertical solar energy collector on the south wall and a heat storage chamber located in the basement of the house, as shown in Figure 2. A fan in the basement draws warm air from the collector and distributes it to the storage chamber containing rocks that absorb the heat.

The use of air as a heat transfer medium has several advantages over alternative systems using various liquids in closed circuits for heat absorption. It avoids problems of leakage and freezing, as well as dependence on plumbing skills.

At the particular latitude of the site, the optimal tilt of the collector surface (for winter heating) is about 60° as measured from the horizontal. However, the solar energy reflected from the snow is utilized better with a vertical collector. The latter is also easier to construct and avoids snow accumulation problems.

A fan with a high air speed was used to lower the surface temperature of the absorber and thus reduce heat losses from the collector.

Heat from the sun is absorbed by a black metal plate and by a black metal screen placed between it and the double glazing. The purpose of the expanded metal screen is to increase the efficiency of the system by increasing the heat absorption area. Theoretically, such a screen can



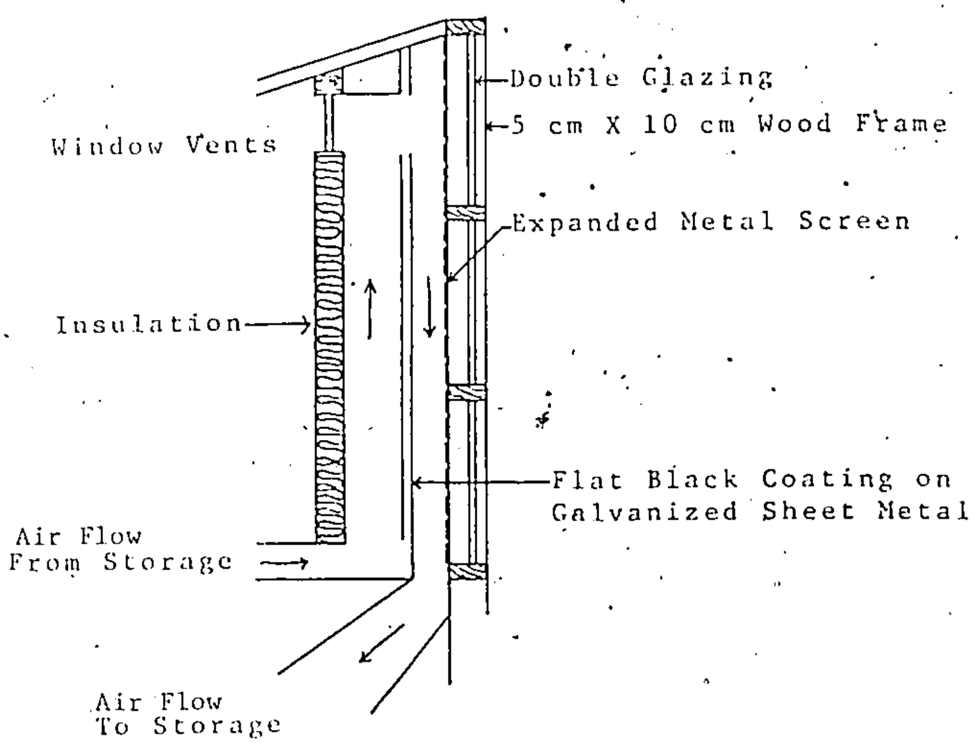


Figure 2 Sections of house and collector

almost double the absorber-to-air heat transfer coefficient of a flat black plate collector.[9] The total area of the collector is about 36' x 14' (504 ft^2). The net collector area of glazing is 42.5 m^2. To ensure even distribution through the collector, the warm air is channelled by means of vertical dividers placed across the surface with fixed horizontal wood strips to control the amount of flow in each channel.

Air is drawn from the collector through a 7" x 10' opening at the base of the central third of the south wall. The fan located in the basement duct draws the warm air through a filter and forces it into a plenum chamber. From the plenum, the hot air is distributed through a layer of hollow concrete blocks below the rocks aligned so as to form horizontal channels. The air rises through ½" gaps left between the blocks and then between the rocks. The air returns to the collector via horizontal ducts, between the floor joists, and vertical passages behind the collector. It re-enters the collector through two 7½" x 10' openings near the top of the collector.

A system of manually operated gates located near the base of the collector is used to direct the air flow either to the collector or to the kitchen and living room. When the sun is shining, the gates are opened to allow forced air flow from the storage to the collector and back again. At night and on cloudy days, the gates are closed, isolating the collector otherwise heat would be lost through the collector glazing. When the gates are closed, the fan can be used to circulate heat from the storage bin through the house. Fan air intake is through vents in the benches along the central third of the south wall of the house. After passing through the storage bin, warm air enters the house via vents in the benches along the outer thirds of the south wall, and via vents in the bedrooms. Even with the fan off, heat distribution can be obtained by allowing warm air from the storage to rise by natural convection into the bedrooms.

On a sunny day, the collector can also be operated passively (i.e., without fan) by opening the gates and the four windows at the top of the collector, creating a thermosiphon action through the collector to the living room and kitchen area.

Electric baseboard heating units totalling 9 kw provide auxiliary heat. They are placed at floor level under the windows of the house. Since they have been installed, it has been suggested that the heating units could have been located in the rock bin so as to allow storage of the electric heat in the rocks during off peak periods. This would be of interest in case of widespread use of such a storage system, since it could relieve the power demand load of the electric utility during peak hours.

2.3 Details of the Construction and Operation of the Solar Heating System

The solar collector is composed of an absorber plate, 22 gauge steel, a black expanded metal screen and sealed glass units supported by a wood frame wall. The collector is supported by 5" x 5" dry spruce studs resting on the foundation, 4' on centre. There are 5" x 43" spaces between the collector and the polystyrene insulation that separates the collector from the house. In the central third of the south wall, these spaces do not serve a special function, but in the two outer thirds they serve as cool air return ducts. Air circulation in the central space is blocked by a 1" thick wooden board at the bottom. On the outside, the studs are covered with sheets of chipboard. The absorber plate metal panels are fixed to vertical wood lathing strips on 16" centres nailed to the chipboard. This provided a 3/4" gap between the chipboard and the sheet metal for air circulation behind the absorber plate. In the central third of the collector, this warm air exits at the bottom to the fan, whereas in the two outer thirds this air circulates upwards with the returning cool air.

The absorber plate is composed of 4' x 8' galvanized sheet metal panels. These were predrilled on 16" centres to correspond to the lathing spacing. In all, eighteen sheets were used. Black latex paint (good to 180°F) with a dull finish was used. Because the sheet metal was galvanized, it was washed with naptha gas (to remove oil and dirt) and then etched with vinegar to ensure adhesion of the paint. A spray gun was used to provide a thin even surface of both a primer and the black paint. After the paint dried, the sheet metal was installed onto the lathing, using nails of slightly smaller diameter than that of the drilled holes to allow the sheet metal to expand when heated.

The 36' x 14' wood frame to hold the glazing was constructed in a garage at Manitou College, so work could continue during rainy weather. Dry spruce 2x4's were used for its construction. 3/4" blocks were installed to hold the stoppers for the glazing. The joints were strengthened with sheet metal plates nailed to the inside surface at each joint. The frame was then primed and carried to the house with the help of sixteen people. The frame was set on a wooden board suspended by brackets at the base of the 5" x 5" studs, and fixed in place with additional brackets bolted to the 5" x 5" studs at each joint of the frame. The ¼" thick metal brackets were made at the college shop.

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Boards and wood strips were installed to distribute the flow of air over the surface of the collector, as shown in Figure 3. Otherwise, all the air would take the path of least resistance: a straight line from the inlet to the outlet, and no circulation would go to the corners. Boards were placed vertically behind the 2" x 4" studs at the mid-height of the collector, forming 9 channels. A calculation was made of the path lengths and of the absorber surface area which was drained by each channel of air. The channels at the extreme ends of the collector were left open. All other channels were partially blocked, by a piece of wood strip placed horizontally behind the frame. The gap between the wood and the absorber in each channel was made proportional to the product of the ratios of the absorber surface area and path lengths with respect to the extreme channel as shown in Table 1.

TABLE 1

CHARACTERISTICS OF AIR PATHWAYS IN THE COLLECTOR

Air Path Number	Absorber Surface Area sq. ft.	Ratio of Area to #1	Length of Air Path ft.	Ratio of Length to Length of #1	Product of Ratios	Amount of Opening
1	66	1	18	1	1	3"
2	40	4/7	16	8/9	1/2	1½"
3	40	4/7	14	7/9	4/9	1-1/3"
4	40	4/7	12	2/3	1/3	1"
5	40	4/7	14	7/9	4/9	1-1/3"

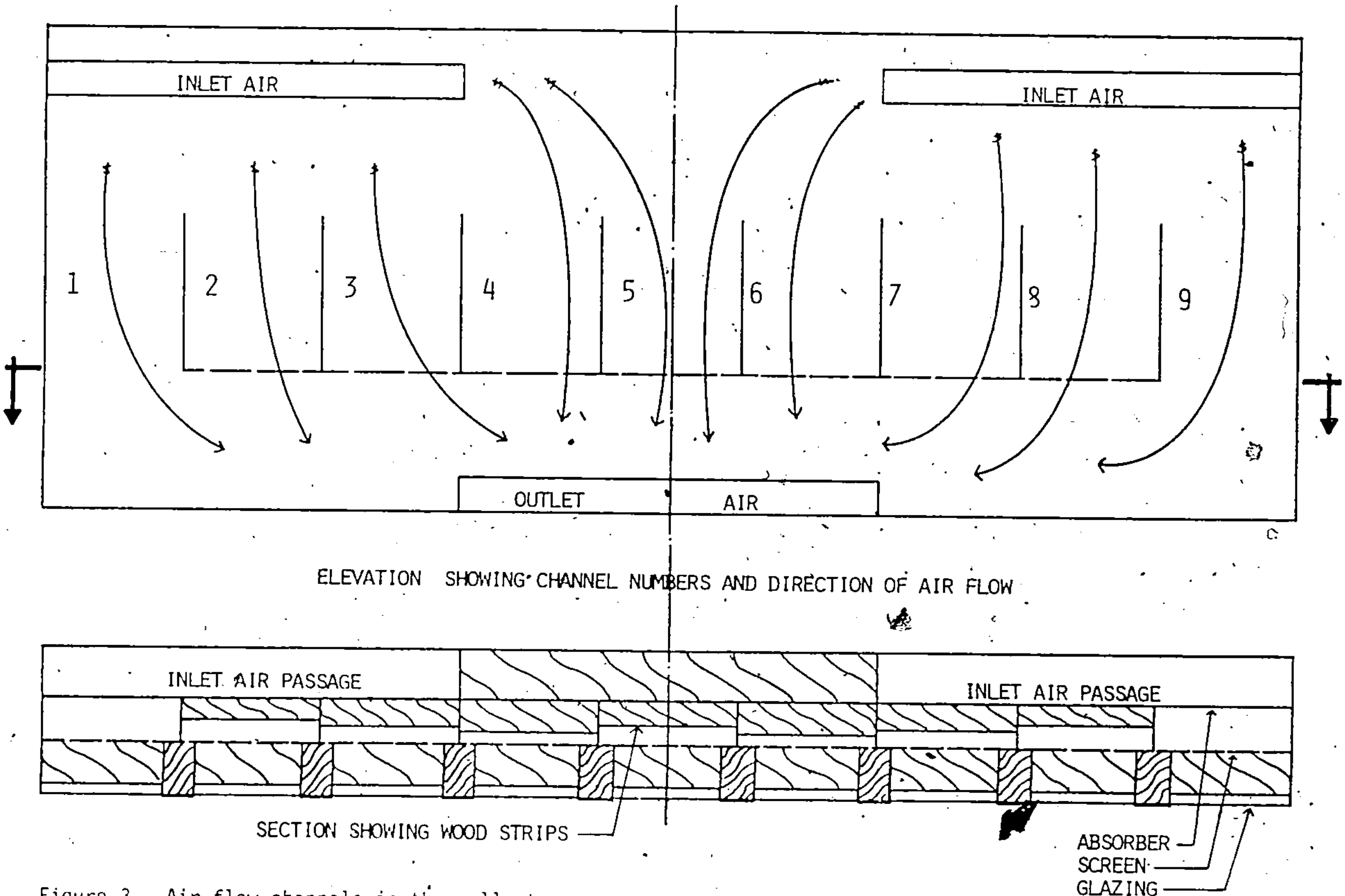

Figure 3 Air flow channels in the collector

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Channels 6 to 9 had openings identical to those of channels 1 to 4, in the reverse order.

The frame holds the expanded metal screen from Dramex (3/16" small diamond design #22, 50% open). This was painted with black Tremclad antirust paint. Eighteen sheets of screen were washed (by dipping them one by one into a 4' x 8' tray of gasoline), then scrubbed and dipped in a tray of the black paint and then hung to dry. Finally the sheets were cut to the size of the frame module (4' x 4½') and nailed on to it.

The sealed glass units are composed of two sheets of glass, of which the exterior sheet is tempered, set in an aluminum frame. The unit is 15/16" thick and measures 47" x 54". The installation of the glass units in the frame was difficult, since they weighed 100 lbs. and some were to be installed ten feet above the ground. Each unit was placed in a wooden jig, lifted by ropes, situated in front of the appropriate opening in the frame, rested on neoprene rubber blocks (allowing a ¼" gap for expansion), then sealed and fixed in place with pre-cut, pre-painted exterior stoppers. The size of the interior stoppers is 1-3/4" x 3/4", that of the exterior ones 1¼" x 3/4" and that of the rubber blocks ¼" x 3/4" x 2. The seals used were 440 Tremco tape and monolastomeric caulking.

The entire process of washing, transporting and installing the glazing involved three men full time for two days. Hours after completion it began to snow.

Air is circulated through a duct into the storage chamber by a 3,000 CFM Champion Fan (1 h.p., 110 volts motor). Although the fan is inside the duct, the motor is located outside so it is accessible from the basement.

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The duct is made of sheet metal held by a wooden frame. All ducts in the house are insulated to ensure the effectiveness of the heat transport circuit.

The storage bin is located under the bedrooms, thermally insulated but connected to the bedrooms by baseboard diffusers which allow control of the heat flow. Insulation of the storage chamber is on the outer side of the concrete walls and block floor, so the concrete will contribute toward the mass of the heat storage.

The gates controlling the heat flow in the system are located at the bottom of the south wall, behind the collector, supported and hidden by an 18" high bench running along the entire south wall. They are opened by a hand-winch requiring about five turns against the pressure of the spring-loaded gates. Each gate is connected to the winch by a wire strung over pulleys. One has access to the wires and gates by lifting the plywood top of the bench. The air vents for heating from storage are also located on the face of this bench.

Operation of the solar heating system by the inhabitant requires the manipulation of the gates controlling the air flow. The fan is turned on by a differential thermostat when a sensor in the collector is 20°F warmer than one in the storage chamber. Then the gates must be raised to allow air flow from the collector to storage. The gates are closed at dusk or when the sun is unlikely to reappear. However, when the fan cycles on and off during partially overcast days, the gates are not closed.

At night, the air vents allowing convection of warm air to the bedrooms are opened when required and then closed in the morning. If

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heat distribution by the fan at night is desired, then the fan has to be turned on manually. If there is a power failure on a sunny day, the two windows and the two plywood flaps at the top of the collector must be opened to prevent a heat build-up in the collector that might crack the glass.

Checking the proper working condition of the gates, greasing the fan, changing the pulley belts of the fan and changing or cleaning the air filter are the maintenance requirements of the heating system.

2.4 Comments on House and Heating System Design

The collector glazing is a sealed unit of two glass panes mounted in a wooden frame. The interior pane is ordinary glass, the exterior one is tempered glass. The units were installed at the end of November 1975.

Three cracks in the inner panes occurred in the winter of 1975 and three more in January 1977 when the house was unoccupied. Most of the cracks are short, but two of the year-old cracks have enlarged to the point where some condensation between the panes can be observed. Although the cracks have not apparently affected the performance of the collector, in time, there will be greater heat loss through the sealed unit.

The cracks occurred on clear, sunny days when the fan was not operating because it was not yet connected, or because there was a power outage in the electricity supply to the house.

When the air is not circulated, it rises by natural convection. If there were large enough air inlets and outlets, the hot air could move out of the collector at the top to be replaced by cooler air at the bottom. However, it appears that the collector is not adequately vented. The

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temperature of the glass surface rose to 66°C. The high temperature alone may not be enough to crack the glass. "The construction of a sealed unit is such that the thermal resistance of the air space is greater than the resistance of the edge spacer. In cold weather the mean temperature of the inner pane will be warmer than the edge temperature."[26] Therefore, tensile stress is produced at the edge of the glass pane which, added to other edge stresses due to the frame, may exceed the edge strength of the glass, causing breakage.

There was no pattern to the cracked panes. The particular panes which cracked may have been under more stress due to the frame than the others, or possibly there were slight defects in their manufacture.

The breakages in January 1977 are likely due to the same cause during a power failure, when there was no one in the house to open the vents.

It was observed on February 7 that there was snow drifted up to a level of about one foot above the bottom edge of the lowest units, which could have contributed to the cracking of two lower panes during the power outage. This suggests that collectors should be above the maximum snow level, or some control of snow drifting be provided. The frame is subject to thermal expansion and contraction, which may have contributed to the stress on the edge of the glass. It is not known whether this factor is sufficient by itself to have caused the cracking if ventilation of the collector was better. The wood used was the dryest available. It is possible that the 2" x 4" framing members were not sufficiently stiff to prevent closure of the air gap which surrounds the unit.

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The choice of a large vertical collector on the south wall and a low northern exposure to the wind determined that the roof be a shed roof. A combination of an incline on the south half with a flat roof on the north half saves some space but presents some problems. The "cathedral" ceiling on the south half can be criticized as a waste of space and heat (heat rises and is trapped in the peak). Possible solutions are a loft in part of the space and the use of a ceiling fan to circulate warm air down to the living room floor.

The architect's wish to have the ceiling beams exposed to interior view has been appreciated by the residents; however, it has led to a condensation problem. In order for the beams to be exposed, the insulation and ceiling tiles were placed just below the roof deck, leaving no space for ventilation. Moisture which penetrates the vapour barrier, or from the wood in the roof, is frozen in winter. In the spring thaw, the water leaks through the insulation onto the ceiling tiles. The tiles are currently discoloured in a number of places. If the insulation and ceiling were applied onto the beams, there would have been about nine inches of ventilation space. However, the cavity would only have had an opening on the south side above the collector, because the north end is blocked by the flat roof. This may not have been adequate ventilation. A possible solution would have been a full shed roof with a truss and an attic space above a flat ceiling.

The house has the whole south wall as a collector. There are two openable windows near the top of the wall which serve as emergency vents and allow in some light. Generally, on a sunny day, the light in the house is adequate, but on an overcast day it is not, according to the inhabitants.

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Since heat is not wanted in the house during the summer months and the system is not designed to store summer heat, the collector must be made inoperative during the summer. There are a number of alternatives:

1. Shading by an eave;
2. Covering the collector with shutters or canvas:
3. Venting the heat to the outside by openings in the top of the collector.

The present design requires that in the summer, the collector air be vented by the fan to the outside.

In order to increase insulation of the house, the earth was piled up three feet above ground level on the north, east and west sides. In the winter, the snow drifted up to the level of the windows and partially blocked the light and view (the screen trapped the snow). Also, the snow melts and freezes in the sliding window tracks, which prevents them from being opened. This is a problem because it prevents emergency escape through the windows.

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CHAPTER 3

MONITORING, ANALYSIS AND RESULTS

3.1 Objectives

The first objective is an estimate of the performance of the solar heating system in order to assess the suitability of this kind of system for the climate of Quebec. The collector, the storage and the interactions of the parts are studied in order to estimate the performance that could be achieved if the components were well matched to each other and to the solar input.

The performance of the collector is judged primarily by the heat output from it and by the efficiency of conversion of incident solar radiation to output heat. Instantaneous and daily efficiencies and an efficiency curve are calculated. Thermal inertia which can delay start up in the morning and can affect the performance during cloudy periods is another aspect of collector performance.

The performance of the rock storage is judged by its response to inputs of heat from the collector, to demands of heat from the house, and by its effect on the collector efficiency. The heat distribution ducts and dampers must pass heat into the house when needed, but not pass heat when it is not needed. The control scheme for the system consists of the automatic control of the fan by a differential thermostat and the manual opening and closing of air flow gates by the inhabitant. Did the

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manual control of the gates cause any significant heat losses because they were not opened or closed co-incident with the fan operation?

The second objective of the analysis is the study of the contribution of the solar heating system to the heat requirements of the house. The questions to be answered are: Of the total heating required by the house, what part was supplied by the solar heating system (called solar fraction) month by month and for the whole heating season? At what time of day does the peak heating demand of the house occur? At what time does the peak demand on the electric auxiliary heaters occur?

3.2 Monitoring Instruments and Data Collection

In order to assess the thermal performance of the house, various temperatures, incident solar radiation and electricity inputs were measured.

The temperatures were sensed by copper - constantin thermocouples which give a signal in the millivolt range, dependent on the temperature at the junction of the two different metals. The thermocouples were connected to a reference junction which provides a fixed reference voltage representing 0 Celsius.

Fifteen thermocouples were placed in various locations, as shown in Table 2.

All the thermocouples, solarimeters, electrical sensors and data acquisition systems were furnished, calibrated and installed by Hydro-Québec.

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TABLE 2

THERMOCOUPLE LOCATIONS

Collector Screen:	Top centre
	Mid-height centre
	Bottom centre
	End channel mid-height
Collector Air:	Inlet at top of supply duct
	Inlet at bottom of supply duct
	Outlet
	Mid-height in each of 5 air channels in the centre and 4', 8', 12' 16' away from centre
Outside Air:	In a shielded tube 4' from north wall of centre of house
Inside Air:	North bedroom 4' above floor
	East bedroom 8' above floor

Those in the collector were shielded from radiation by a small paper tube. Fourteen thermocouples were placed in the storage, as shown in Figure 4.

The solar radiation was measured by three Kipp and Zonen solarimeters, Model #CM5. The solarimeters, also called pyranometers, were of the thermopile type with two glass dome covers. One of the solarimeters was mounted in the centre of the south wall with its receiving plane

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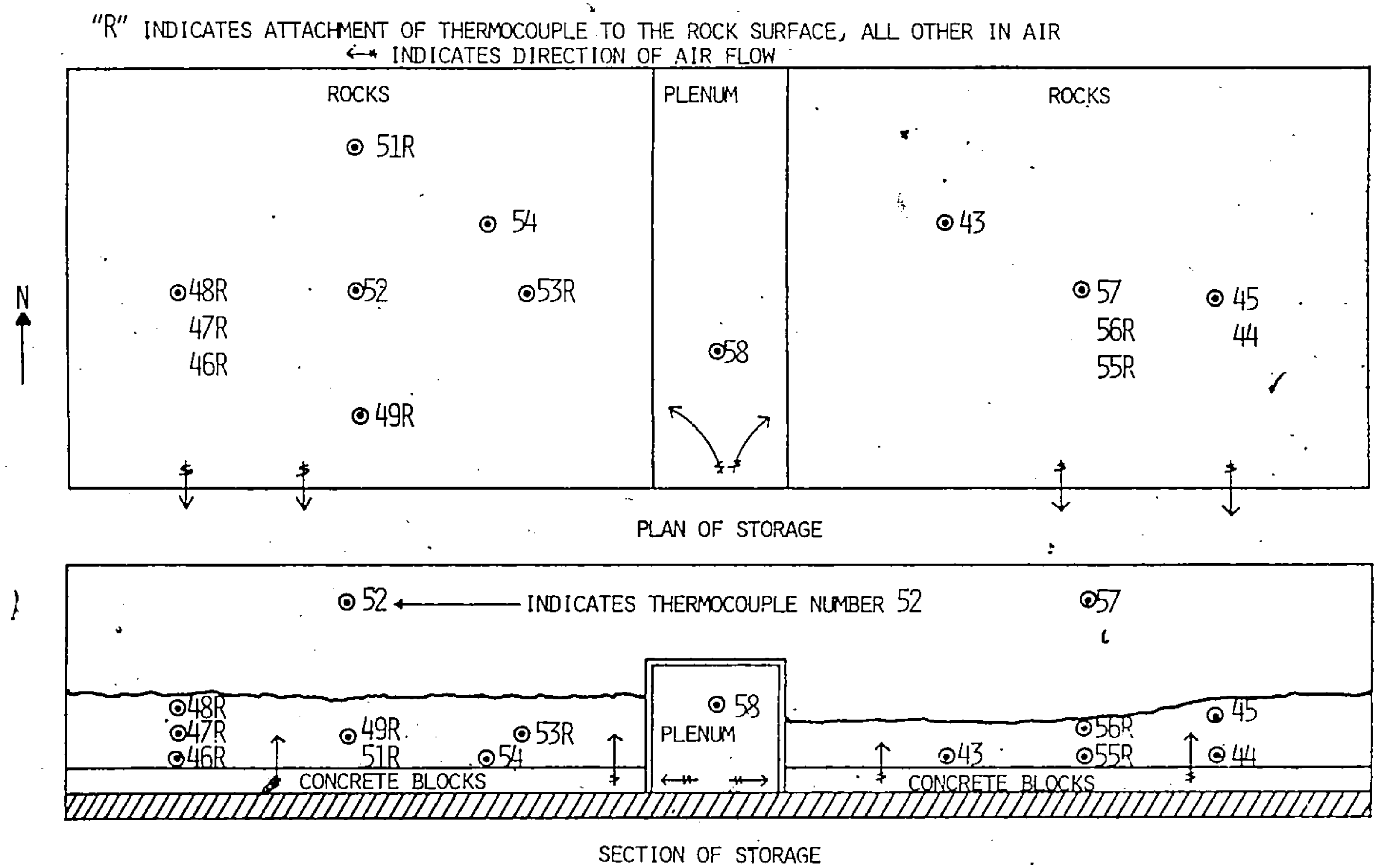

Figure 4 Location of thermocouples in the storage

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vertical. The other two were mounted on the top of the roof with their receiving planes horizontal. One of these was shielded from the direct rays of the sun with a metal band which occluded 14 degrees of the sky in a band on a great circle centred on the solarimeter.[10] The elevation of the shadow band was adjusted in order to follow the seasonal changes of the noon altitude of the sun.

The 32 measurements above, plus 7 electrical measurements, were recorded on magnetic tape at 15 minute intervals, using an I.R.E.Q.'s Monitor Labs Data Acquisition System. The electrical measurements were taken from the secondaries of current transformers inserted in various circuits in the house. The purpose of these electrical measurements was to obtain estimates of the "occupancy" internal heat gains to the house, and of the heat losses from the vented appliances: the dryer, water heater, and electric toilet.

A second data acquisition system of a type commonly used by Hydro-Québec was used to obtain readings of the energy supplied to the baseboard heaters, to the fan, and to the entire house, using ordinary household kilowatthour meters in each circuit. A pulse was produced for each revolution of the meter and the number of pulses in a fifteen minute interval was recorded on a magnetic tape cassette. Each cassette has a capacity of one month of readings. The printout of the data can show each fifteen minute total to permit detailed calculations for a short period. In addition, totals can be obtained for longer periods and plotted for quick inspection. A sample of the graph of fan energy consumption of kilowatt-hours totalled over a three hour interval is shown in Appendix B. There is a small battery in this unit which permits up to four hours of operation

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in the event of a power failure, so that subsequent readings are taken at the correct time.

The Monitor Labs system consists of a number of components:

i) A John Fluke Model 8400A Digital Voltmeter which measures DC voltages with up to 1 microvolt of resolution. The input is sampled periodically and digitized.

ii) A Model 1200 Analog Scanner which is used to switch sequentially through all the channels and transfer each analog input signal in turn to a single pair of output lines which connect to the voltmeter. The scanner uses integrated circuits and plug-in circuit cards, so it is very reliable.

iii) A Model 3100 Digital Clock which provides a signal at pre-set intervals - 15 minutes for the present study - to initiate each scan, and provides the current time in day of year, hour, minute and seconds as a label for each group of data.

iv) A Model 4200 Data Coupler, which transfers a block of 100 BCD characters from the voltmeter to the recording devices. The data stream is arranged into programmed word groups in the coupler.

v) A Pertec 1000/2000 Series Tape Transport, used to record the data on magnetic tape.

vi) A Hewlett Packard 5055A paper tape Printer.

vii) A Voltage Regulator which maintains a constant voltage for all the other devices.

This system was not protected against power failures. The clock and recording devices had to be reset after a blackout.

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The system, as a whole, records a sequence of data samples. No integration or averaging of a continuous measurement is done on site. The magnetic tapes were taken to IREQ, where the data was transferred to a computer tape in Fortran compatible format. A program was written which translated the thermocouple and solarimeter data from millivolts to degrees Celsius and watts per square centimeter, using the calibration equation of the thermocouples and the solarimeter constants. The program could perform some averaging of the data and it displayed the results graphically. Samples of the output are shown in Appendix B.

A summary of the data for ten days in November is shown in Figure 5.

There were some problems in data gathering:

i) On one occasion, the battery of the reference junction compensator was not replaced soon enough, so that the absolute values of the thermocouple readings were inaccurate for a period of three months. However, the difference between two thermocouples readings was accurate, so that the data for October - December was recovered by normalizing it to an assumed constant indoor temperature.

ii) On a few occasions, condensation was found in the dome of the pyranometer which was used to measure diffuse radiation. The dome was removed, dryed and resealed. This was a minor inaccuracy which affected a few days only.

iii) The measurements of current in the dryer, waterheater and electric toilet were limited in usefulness because the currents were sufficiently variable that the fifteen minute sample interval did not give an accurate indication of the total energy used by these appliances.

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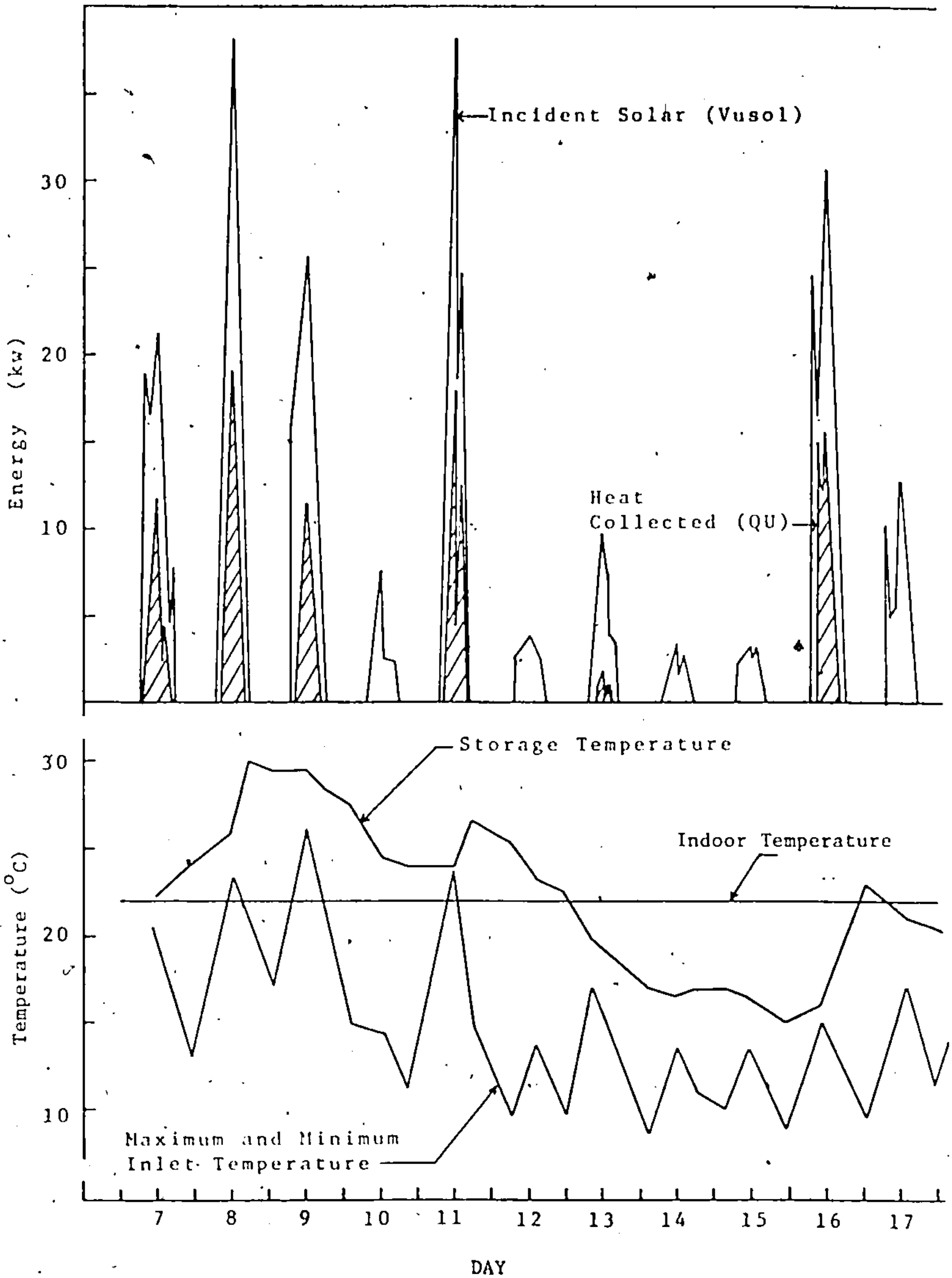

Figure 5 Summary of data for ten days in November 1976

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iv) There was a faulty connection on the voltmeter which sometimes produced noise instead of information. This caused a loss of data for a number of days before the problem was corrected.

v) There were temporary blackouts of electricity supply to the house. There were some delays before the Monitor Labs system was restarted.

vi) The outside thermocouple had been connected backwards.

The periods for which the data is complete, unreliable or not available are shown in Table 3.

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TABLE 3

SUMMARY OF DATA AVAILABLE

	October	November	December	January	February	March
Monitor Labs						
Solarimeters	XXXX ___	X ___	XXX ___ XXXXXX	___ XX ___	XXX ___	X ___
Thermocouples	XXXX - - -	-X - - - - -	XXX- -XXXXXX-	-XX-	-XXX ___	X ___
Household Electric Meters						
Fan	___	___	___	___	XX ___	___
Heaters	___	___	___	___	XX ___	___
Total entry	___	___	___	XXXXXXXXXXXX	___	- - - - -
Weather Stations						
Ambient Temperature	___	___	___	___	___	___
Wind	___	___	___	___	___	___
House Log	- - -	- - -	- - -	XXXXXXXXXXXX	___	___

___ Data Reliable

\- - - Data Unreliable

XXX Data not Available

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A part of the monitoring of the house was the log which was kept by the inhabitants. The log records the times when the gates were opened or closed. The log also records some weather information, whether or not the house was occupied, and anything unusual. For a particular period, when the heat flows in the house were being studied, the log records when the shower, range and dryer were used and when dishwashing was done.

Measurements of air flow rate were taken by Blair Hamilton. They are explained in his thesis.[11] The flowrate was measured with a hot wire anemometer at a number of different locations. The air flow in the collector-storage loop is used in the calculation of heat gain from the collector. A series of measurements was made in the ducts leading to the collector. The total flow into the collector was 2661 m^3/hr. Measurements in the duct at the outlet of the collector gave a result of 2582 m^3/hr. These values agree within the accuracy of the measurements. The value 2600 m^3/hr is used in the calculation of the heat gained from the collector in Section 3.3.

Outside Temperatures

A check was made to be certain that the outside thermocouple was measuring the air temperature accurately. Each day the temperature was read visually from a standard outdoor thermometer in the shade near the north window. These spot measurements agreed within 0.5°C. The outdoor temperature record is incomplete, and degree day data is needed for heat load calculations. Weather data was obtained from the Atmospheric Environment Service, Canada[12] for two weather stations at Ste. Agathe and Maniwaki, which are about 52 km southeast and 93 km due west of the site respectively. A correlation between the measured temperatures at the

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site and at nearby weather stations was attempted. The ambient temperature measured at the house site was compared to the maximum and minimum temperatures measured at the weather stations.

The average over twenty-four hours of the site hourly temperatures matches the average of the mean daily temperatures at the weather stations as shown in Figure 6. The maximum at the site generally falls between the maxima at the two weather stations.

Figure 6 shows traces of hourly dry bulb temperatures for Ste. Agathe and for the Macaza house site. The house is at a lower elevation than Ste. Agathe, which may account for the lower night-time temperatures.

The correlation is good. The degree day data for Ste. Agathe-des-Monts is used to represent the degree days at the house site for calculations in Section 4.5 and in Table 4.

A comparison of the sunshine hours and the heating degree days during the 1976-77 season, with the average sunshine hours and heating degree days during the previous 10 years, is shown in Table 4. The heating degree days for October 1976 - March 1977 were above average and the sunshine hours were below average. Thus, the 1976-77 season was a severe test for the house and the solar heating system.

A comparison of the average heating degree days for the same six month period, between Ste. Agathe-des-Monts, Montreal and Ottawa, is also shown in Table 4. Ste. Agathe-des-Monts is about 10% and 15% colder than Ottawa and Montreal respectively.

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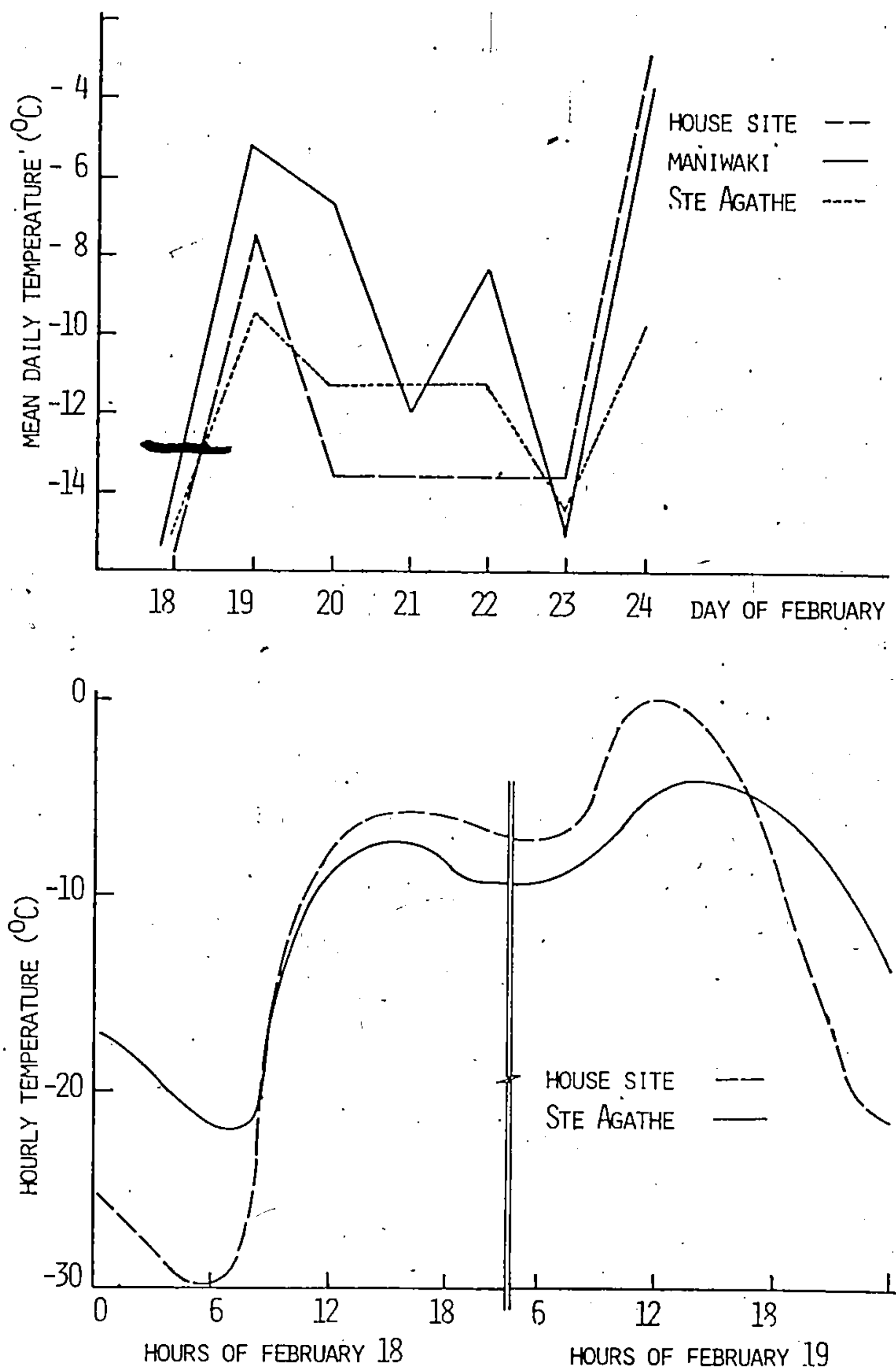

Figure 6 Comparisons of temperatures at the house site and at nearby weather stations

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TABLE 4

COMPARISON OF 1976-77 WEATHER WITH 10 YEAR AVERAGE
FOR STE. AGATHE-DES-MONTS

	1976-77 Hours of Sunshine	12 Year Average Hours of Sunshine	1976-77 Degree Days	10 Year Average Degree Days
October	105.8	135	458	382
November	65.7	60	646	592
December	79.4	81	1020.4	879.9
January	92.3	96	1040.5	968.7
February	82.8	125	793.5	851.6
March	141.7	151	605.1	736
Total	568	648	4563	4410

Normal degree days for same 6 month period: OTTAWA 4037 MONTREAL 3842

3.3 Heat Output of the Collector

The heat output of the collector was not measured directly, but was calculated from the temperatures of the air passing through the inlet and outlet ducts. The net heat gain of the air going through the collector is proportional to the difference between the inlet and outlet air temperatures. It is calculated using the expression:

$$Qu = 26000\,(T_2 - T_1)/(T_2 + 273.2)$$

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where:

QU is the sensible heat gain (watts)

T_2 = collector outlet temperature (°C)

T_1 = collector inlet temperature (°C).

This expression was derived using the procedure described in Chap. 5, Ref. 13. but converted to the SI system of units as follows:

The heating of moist air is described by $QU = ma(h_2 - h_1)$

where: ma is mass flow of air ($kg\ hr^{-1}$)

h_1 is enthalpy before heating (watt hours kg^{-1})

h_2 is enthalpy after heating (watt hours kg^{-1})

$$ma = \frac{f}{v}$$

$$v = \frac{287.1\ (1 + 1.6078W)\ (T_2 + 273.2)}{p}$$

$$h_2 - h_1 = (.279 + .51\ W)\ (T_1 - T_2)$$

where: f is air flow rate (m^3hr^{-1})

v is specific volume of the moist air mixture (m^3kg^{-1}).

W is humidity ratio (kg water per kg air)

p is total pressure (atmosphere)

Combining the above expressions yields:

$$QU = \frac{f.p.\ (0.279 + 0.51\ W)\ (T_2 - T_1)}{287.1\ (T_2 + 273.2)\ (1 + 1.6078W)}$$

taking: p = 1 atmosphere

= 10.13×10^4 Newtons/meter^2

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and: W = .00663 kg of water per kg of dry air from Reference 11.

yields

$$QU = \frac{98.4\, f(T_2 - T_1)}{T_2 + 273.2}$$

Using a flow rate from Reference 11, $f = 2600\ m^3 hr^{-1}$ yields:

$$QU = \frac{260000\ (T_2 - T_1)}{T_2 + 273.2}$$

This quantity QU was calculated at each 15 minute interval. A profile of QU for three days in November 1977 is shown in Figure 7. The total heat collected during the day, called Q, is the integral of QU. Values for Q were obtained using Simpson's rule for each day for which there was sufficient data.

On several occasions, when the Monitor Labs Data Acquisition System was not functioning correctly, QU could not be obtained by the method described above. However, in most cases the electrical consumption of the fan was available from the three channel cassette recorder. The total consumption in kilowatt hours of the fan for the day, called QFAN, was calculated. Using the data for days when measured values of both Q and QFAN were available, a least squares regression line was calculated. The line Q = A * QFAN + B is used for interpolation for the days when QFAN was measured but Q was unavailable. To minimize possible effects due to the variation in the noon elevation of the sun, three separate interpolation lines for the months of October, of November and December together, and of February were calculated (e.g., for February: B = -43.9; A = 34.6). The line for February is shown in Fig. 8. The results of the interpolation are shown in Table 5. Data in the region of low daily QFAN was not used

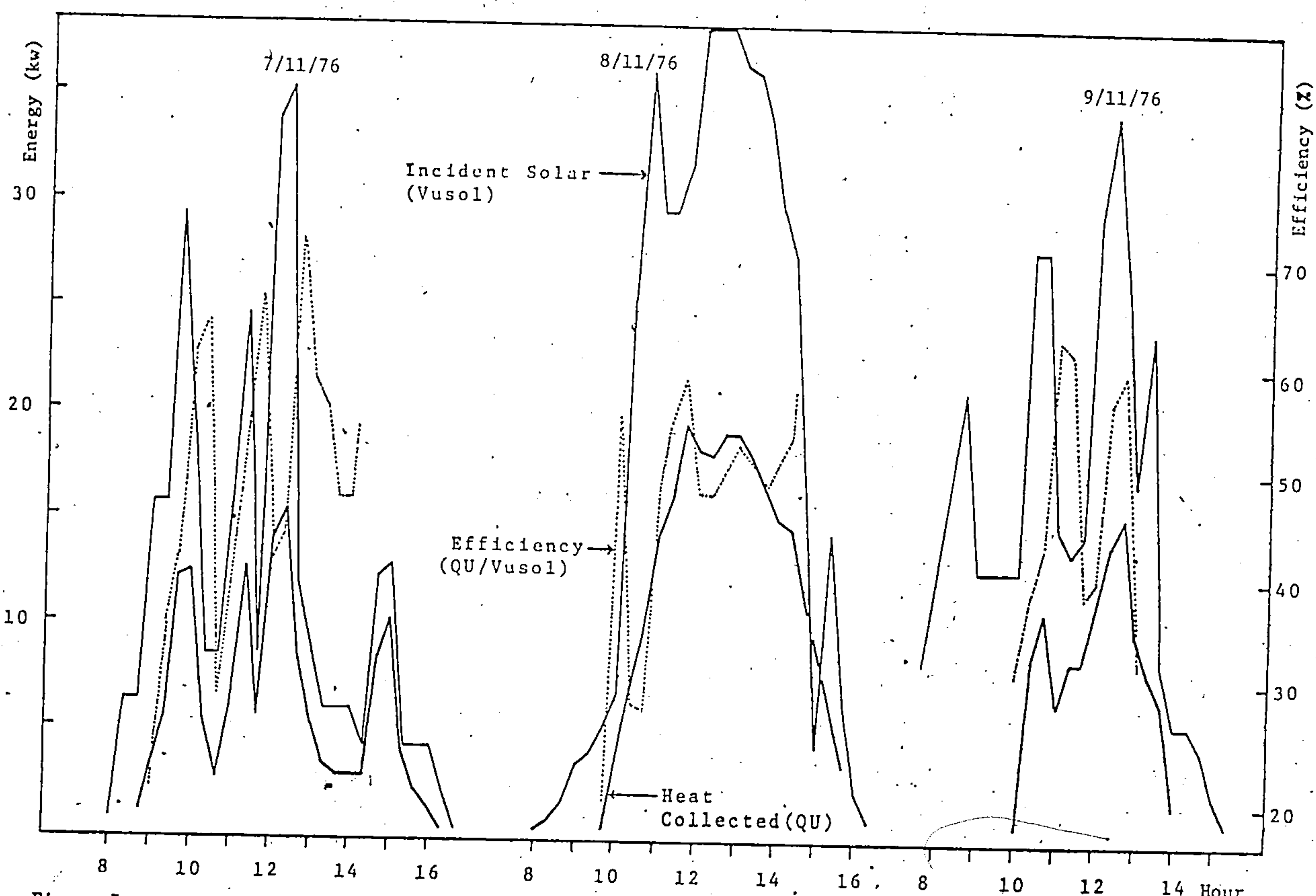

Figure 7 Collector performance for 3 days in November 1976

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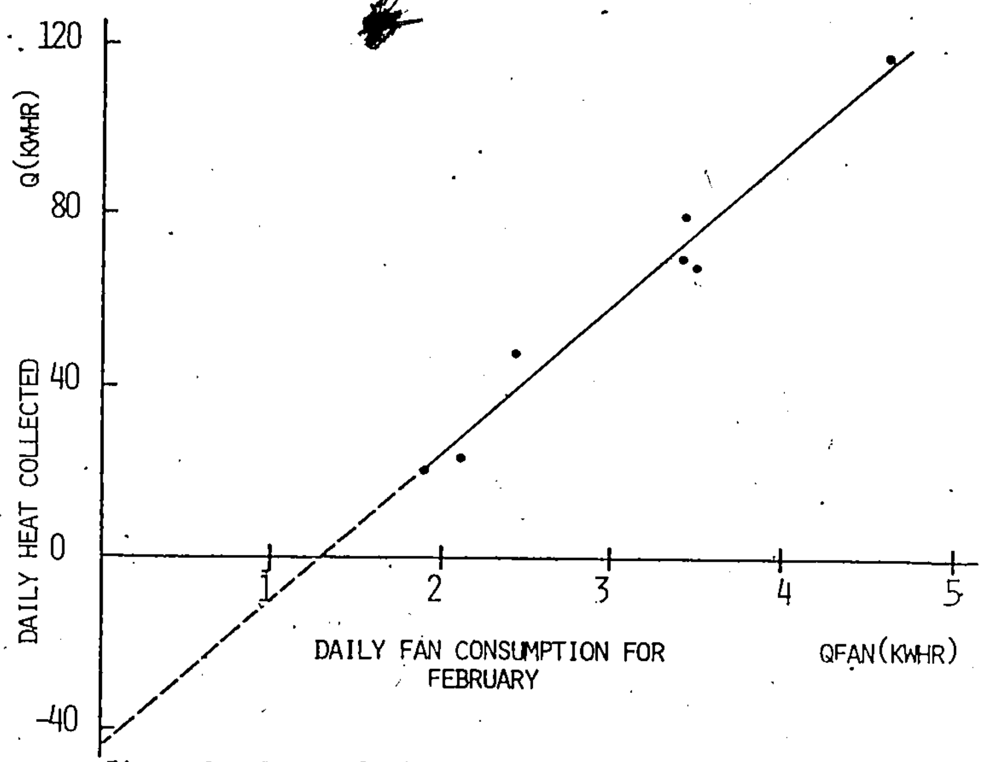

Figure 8 Interpolation line for collector heat gain

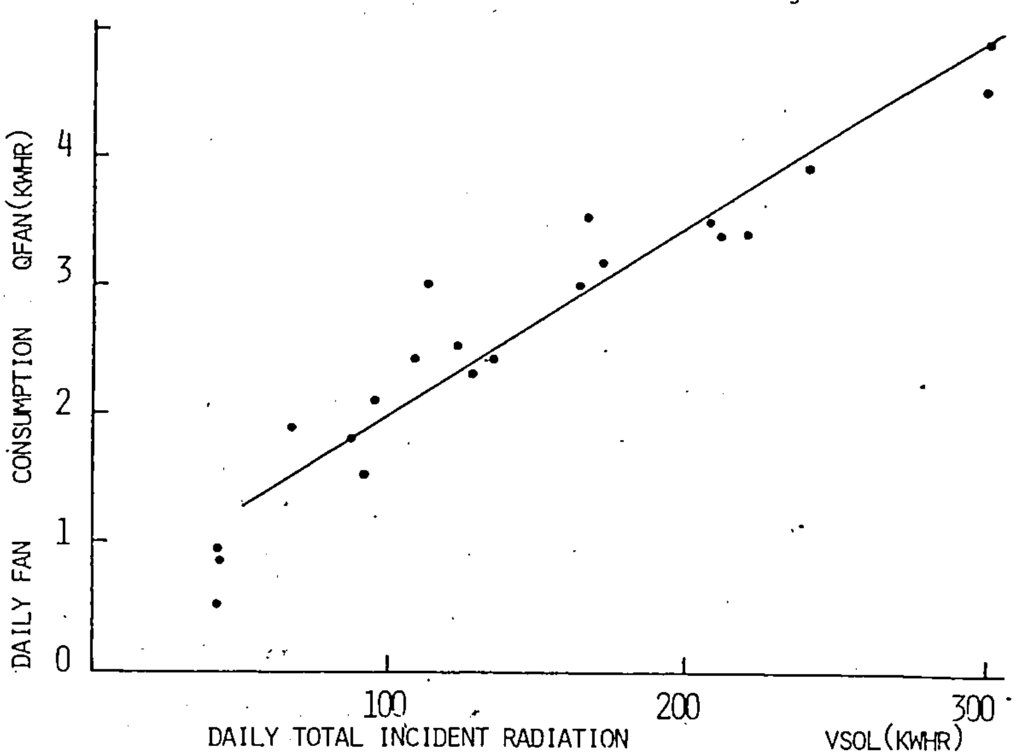

Figure 9 Interpolation line for QFAN vs VSOL

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for the interpolation lines because the physical process of heat collection is different. On days when the fan cycles on and off, such as partly cloudy or lightly overcase days, heat stored in the heat capacity of the collector when the fan is off can distort the value of Q. Losses are higher because the dampers were not closed when fan was off. Also, the start-up power surges of the fan can add significantly to the value of QFAN. The result is that the Q versus QFAN curve has a different slope at low Q than at high Q.

The daily values of heat collected both measured and interpolated for October 1, 1976 through March 31, 1977 are shown in Table 5.

TABLE 5

DAILY TOTAL HEAT COLLECTED Q (kwhr)

Day	October	November	December	January	February	March
1	67*	7	52*	0	N/A	22
2	101*	66*	0	40*	N/A	71
3	108*	23*	77*	33*	0	117
4	106*	0	43*	0	7*	0
5	98*	0	17*	50*	82*	0
6	32*	0	54*	25*	28*	0
7	0	48	8*	0	108*	7
8	0	83	81*	97*	140*	42
9	0	38	88*	93*	0	52
10	0	0	0	0	15*	106
11	122*	68	80*	8*	0	98
12	22*	0	0	83*	0	53
13	10*	8	74	85*	0	0
14	7*	0	0	65*	0	0
15	11*	0	67	0	22	16
16	9	60	0	47*	79	0
17	0	0	0	88*	48	41
18	14	11	96	0	23	8*
19	10	0	0	24*	1	98*
20	8	33	0	62*	69	77*

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TABLE 5 (cont'd)

Day	October	November	December	January	February	March
21	0	0	7*	15*	119	62*
22	0	0	47*	14*	2	0
23	8	0	0	55*	69	6
24	44	4	58*	0	9	59
25	21	0	0	2	0	20
26	60	0	7	26*	0	101
27	0	0	77*	24*	11	79
28	0	0	66*	0	19	65
29	55	33*	19*	18*		5
30	0	29*	40*	32*		68
31	0		16*	0		82
Total for Month	913	511	1074	986	851	1355

*Interpolated values N/A-not available

A measurement of the radiation incident on the vertical solarimeter was taken every 15 minutes. For a radiation density of one watt per square centimeter, the output of the solarimeter was 8.85 volts. The reading obtained was multiplied by the collector glass area of 42.5 square meters to give a value for the total radiation incident on the collector. The result is called VUSOL. A profile of VUSOL for 3 days in November 1977 is shown in Figure 7. Again, an integration was performed to obtain the total incident radiation for the day - called VSOL. For those days when there was partial cloud cover, there were large variations in solar intensity with periods shorter than 15 minutes. For those days, VSOL is only an estimate of the total radiation for the day. However, both low and high readings are equally probable, so that the accuracy of the calculated seasonal total radiation is not much affected by this error.

For the days when the solarimeter readings were not recorded properly by the Monitor Labs System, an interpolation line has been drawn using least squares regression analysis, as shown in Figure 9. The daily values of solar radiation on the vertical surface, both measured and interpolated, are shown in Table 6. The monthly total radiation and the monthly totals divided by the collector glazing area of 42.5 m^2 are also shown in Table 6.

TABLE 6

DAILY SOLAR RADIATION ON VERTICAL (kwhr)

Day	October	November	December	January	February	March
1	160*		135*		N/A	112
2	237*	170*		120*	N/A	188
3	250*	65*	195*	105*		274
4	248*		115*			
5	230*		50*	140*	210*	
6	87*		140*	90*	96*	45
7		109			265*	69
8		173	205*	245*	330*	151
9		128	220*	230*		157
10					60*	229
11	282*	126	205*			257
12	65*			210*		172
13		43	208	215*		
14				175*		
15			164		94	74
16	40	113		135*	219	
17				225*	130	151
18	40	43	240		135	
19	75			85*		300*
20		88		165*	165	247*
21				62*	300	205*
22			127*	50*	86	46

TABLE 6 (cont'd)

Day	October	November	December	January	February	March
23	40			155*	212	78
24	90	70*	148*			190
25	50					132
26	130			68		279
27			195*	105	43	216
28			175*	46	90	171
29	140	90*	55*	69		47
30		80*	107*	130		220
31			50*	44		241
Total	2164	1298	2734	2869	2435	4251
(kwhr/ m^2)	50.9	30.5	64.3	67.5	57.3	100

Daily values of VSOL less than 40 kwhr are not shown because the interpolation procedure is unreliable for days of low QFAN and low VSOL.

* Interpolated values N/A - not available

The monthly totals of Q and VSOL and an average monthly efficiency are shown in Table 7. The average efficiency of the collector is about 35% over the five months of November 1976 - March 1977. This efficiency is based on those days for which there was at least 40 kwhr of radiation on the vertical collector surface, which was sufficient to turn on the collector at least for a short period of the day. Estimates of the probable errors in the monthly heat collected and incident radiation, which are shown in Table 7, were obtained as explained in Appendix G.

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TABLE 7

MONTHLY TOTAL HEAT COLLECTED, INCIDENT SOLAR RADIATION AND AVERAGE EFFICIENCY

	Total Q (kwhr)	Total VSOL (kwhr)	Average Efficiency (%)
October	913 ±19	2164 ±11	42
November	511 ±12	1298 ±7	39
December	1074 ±19	2734 ±12	39
January (except 27 to 31)	986 ±18	2869 ±12	34
February (except 1 and 2)	851 ±19	2435 ±13	35
March	1355 ±23	4251 ±16	32
	5690 ±45	15751 ±30	35 ±.003

A comparison between the calculated value of the heat collected by the collector (Q) and the measured consumption of electric resistance heating in the house (A) is shown in Table 8. The sum of Q and A represents the total heat supplied to the house except that supplied by occupants and appliance use. The solar fraction is defined as $\frac{Q}{Q + A}$. The value of the solar fraction is 50% over the 6 month period. Estimates of the probable errors in the monthly heat collected and solar fraction, which are shown in Table 8, were obtained as explained in Appendix G.

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TABLE 8

MONTHLY SOLAR FRACTION

	Total Q (kwhr)	Total Baseboard (kwhr)	Solar Fraction f	Degree Days Re 18°C Ste. Agathe-des-Monts
October	919 ±19	662	58 ±.02	458
November	511 ±11.5	1254	29 ±.01	646
December	1074 ±19	1490	42 ±.01	1020
January	986 ±17.5	1181	45 ±.01	1041
February	851 ±19	588	59 ±.02	792
March	1355 ±23	430	76 ±.02	605
	5690 ±45	5605 ±29	.50 ±.01	4563

3.4 Collector Efficiency

The ratio QU/VUSOL is taken as the instantaneous efficiency of the collector. Detail is shown for three days with different weather patterns in Figure 7. On days with alternate sunny and cloudy periods, like November 7 and 9, the thermal inertia of the collector can distort the instantaneous efficiency curve considerably. On each of the days in Figure 7, there was a sunny period at about noon. The collection efficiency for radiation striking the collector at the time of the peak of VUSOL is virtually the same on all three days: just above or below 50%. However, there is a time lag before that collected heat exits from the collector: i.e., the QU curve lags the VUSOL curve. Because of the

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particular time sequences of the cloud cover, this lowers the calculated efficiency curve near noon on November 7, but raises it near noon on November 9. The apparent peak efficiencies of 70% on November 7 and over 60% on November 9 are spurious artifacts of this time delay. Note also that during the passage of a cloud near 15 hours on November 8, the calculated efficiency would have gone to 200% because of the integrating effect of this thermal inertia.

For a comparison of different types of solar heating systems, the integrated daily efficiency can be of more interest than the maximum instantaneous efficiency. Q and VSOL are the daily integrals of QU and VUSOL, and the ratio Q/VSOL is taken as the integrated daily efficiency. Thermal inertia effects do not distort it. Integrated daily efficiencies for November 7, 8 and 9 were 44%, 48% and 30% respectively.

Figure 10 is a plot of Q compared to VSOL for 28 days in February and March, during which heat was collected. There is approximately a linear relationship between the solar radiation incident on the collector and the total heat collected during the day.

In order to account for the variation of the values from the line, a daily efficiency curve is plotted in Figure 11, by analogy with the instantaneous efficiency curve. In Figure 11, daily efficiency is plotted against the (peak inlet temperature - peak ambient temperature) / radiation on the collector per square meter of surface area.

Efficiency Curve

Efficiency is not the ultimate criterion for comparison of solar collectors. The heat output per dollar of the collector purchase and operating cost could be considered to be more meaningful, see Shurcliff[14].

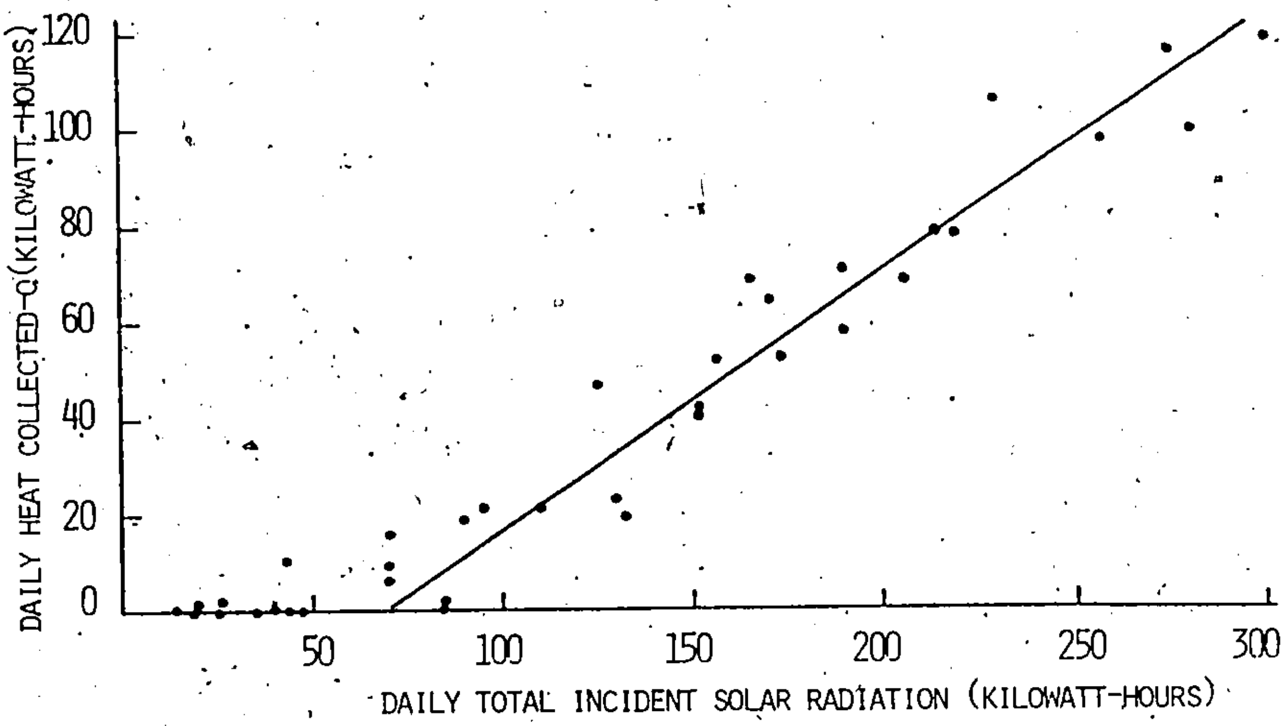

Figure 10 Heat collected vs incident solar radiation for February and March

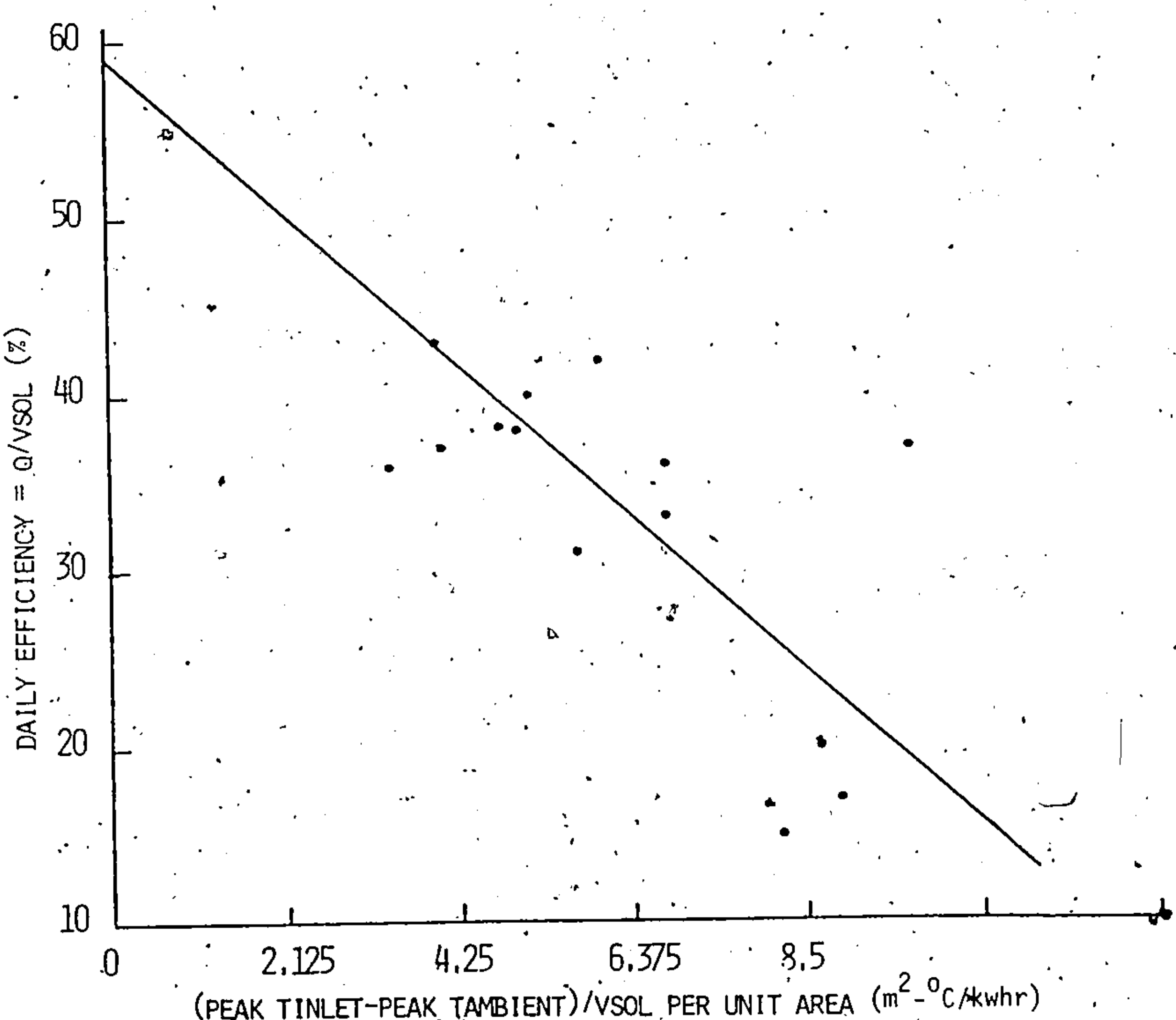

Figure 11 Daily thermal performance of solar heating system during February and March 1977

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Some of the economic considerations for the La Macaza Solar Heating System are treated in Appendix F.

The efficiency curve is presented here for a comparison of the thermal performance of different collectors.

Ashrae has published Standard 93-77, entitled "Methods of Testing to Determine the Thermal Performance of Solar Collectors".[15] Their method involves keeping the air entering the collector at constant conditions which can not be guaranteed in a real heating system. Nevertheless, we present our results in a form similar to Ashrae 93-77, to facilitate comparison.

In particular, the instantaneous efficiency of the collector is plotted vs. a function:

$$(t_i - t_a)/I \text{ in } [^{\circ}C\,m^2/Watt]$$

where:

t_i is collector inlet temperature

t_a is ambient temperature outside collector

I is radiation on collector per square meter of collection surface

i.e: $I = VUSOL/area$

For a collector operating under steady state conditions, the efficiency of the collector can be described by:

$$\eta = F_R \tau\alpha - F_R U_L (t_i - t_a)/I$$

where: τ is the transmissivity of the collector glazing

U_L is the heat loss coefficient of the collector

α is the absorptance of the collector surface

η is the efficiency

F_R is the solar heat removal factor

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Thus, when η is plotted vs $(t_i - t_a)/I$ a straight line will result where the slope is equal to $F_R U_L$ and the intercept is equal to $F_R \tau\alpha$.

The standard, Ashrae 93-77, sets forth requirements for the testing of solar collectors. Most of these requirements were met in the measurements and analysis. However, because of the fixed nature of the collector, an incident angle less than 30° was not always maintained. Corrections for this are described below. In addition, the standard calls for wind velocity measurements near the surface of the collector to be able to calculate the augmentation of the convective losses from the collector caused by wind. Such measurements were not made at the site, although a report from a nearby weather station is shown in Table 9.

Calculations were made according to the method of standard 93-77 for three clear days of steady solar radiation. The result is shown in Figure 12. Also shown are results for two other types of collector.

One curve shown in Figure 12 is taken from Gupta and Garg.[16] The collector tested was 1.23 m x .76 m. It had one glazing cover of 3 mm glass with extinction coefficient 0.077/cm, and a wire mesh screen inclined between the glass cover and the corrugated galvanized absorber, both painted flat black. ~~The weather~~ was clear and calm. Also shown on Figure 12 are the test results of a Solaron Collector, Reference 17. The Solaron Collector is a double glazed air heater with a flat black absorber. The air passes behind the absorber. Figure 12 shows that the efficiency curves of the Macaza collector and the Solaron Collector are similar. The smaller slope for the Macaza collector represents a smaller heat loss coefficient.

The solarimeters have two globes which permit sunlight to enter the instrument with a minimum of reflection losses for

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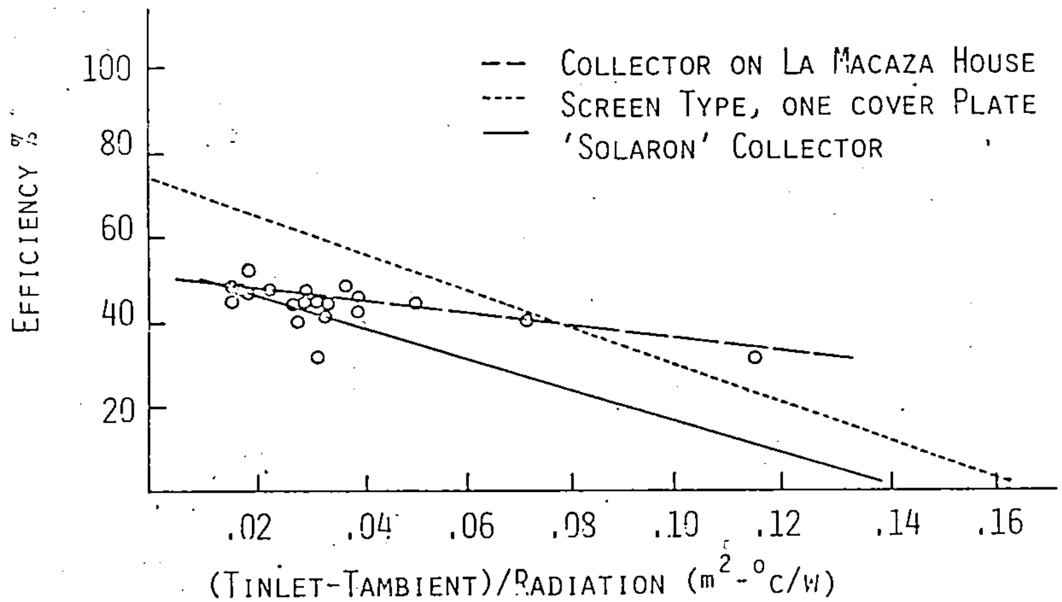

Figure 12 Thermal Efficiency for three air heating collectors with flat black absorber.

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all angles of incidence. However, the collector has two plane glass surfaces which have greater reflection losses than the globes for large angles of incidence. The transmittance of light considering both reflection and absorption in the glass is described in Figure 6.2.1 of Reference 18. For 5 mm glass plates with extinction coefficient 0.161/cm the transmittance for incident angles between 0^o and 45^o is about 0.75.

At an incidence angle of 70^o the transmittance is about 0.5. For latitude 46^oN, the angle of incidence of the sun on a south facing vertical surface varies from 44^o at noon on September and March 21 to 34^o on February 21 and October 21 to about 20^o at noon on December 21.[15] During most of a sunny day between October 21 and February 21, the angle of incidence is less than 40 degrees, with no difference between the solarimeter and collector covers. However, before 10.00 a.m. and after 2.00 p.m., the angle is greater than 40 degrees on February 21. This affects the efficiency calculations which are presented in Figure 12 . The actual radiation transmitted by the cover is less than the measurement of the pyranometer by a few percent for the data points at 2.00 p.m. and 3.00 p.m. Figure 12 has been corrected for this effect in order to make a comparison with Ashrae standard tests, which are made with incident angles less than 50 degrees.

The wind velocity across the collector must be known and reported for a standard test.. For the days used in Figure 12, the wind speed and direction at the Ste. Agathe station are shown in Table 9.

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TABLE 9

WIND SPEED AND DIRECTION AT THE TIMES OF THE EFFICIENCY CURVE ANALYSIS

Date	Hour of the Day					
	10	11	12	13	14	15
February 21	24 SSW	13 SW	20 WSW	32 W	32 WNW	33 WNW
March 3	30 WNW	32 WNW	24 WNW	26 NW	19 W	26 WNW
March 10	15 W	9 WNW	19 W	19 W	19 W	15 W

The normal mean wind speeds for the month are 13 km/hr.

It is clear from the Table that the wind speeds during the test periods were higher than normal. It is not a simple matter to account for the effect of the wind on the surface. The losses from the collector are increased by the wind. If these days had been calm, the test efficiency curve would have been flatter and possibly higher due to the lower heat loss coefficient.

3.5 The Storage

There are eight thermocouples attached to stones at various locations in the storage. There are others to measure air temperatures. The locations of all thermocouples are indicated in Figure 4 . The temperature profiles at these points were printed out in order to show the flow of heat within the storage. Some of these profiles are shown in Figure 13. By an inspection of these temperature profiles, the following observations can be made:

i) The smaller volume of rock in the east bin compared to the west bin results in higher average temperatures on the east side because there is more air flow through the east side.

ii) The north side of the storage is hotter than the south side because there is more air flow there, due to the construction of the duct. The plenum downstream from the fan has passageways opening to the rock pile at the bottom. The fan pushes most of the air to the back of the plenum, where it enters the northern side of the storage.

iii) The rocks at the bottom of the storage are near or in contact with the concrete blocks which form the air passageways. The temperature profiles show that these rocks lose their heat faster than others at night time because they are in contact with the air of the plenum, which is in contact with the cold basement.

iv) The profiles show the transfer of heat upwards from the lower rocks to the upper rocks and to the air above the storage. This transfer is accomplished by natural convection and radiation when the fan is off.

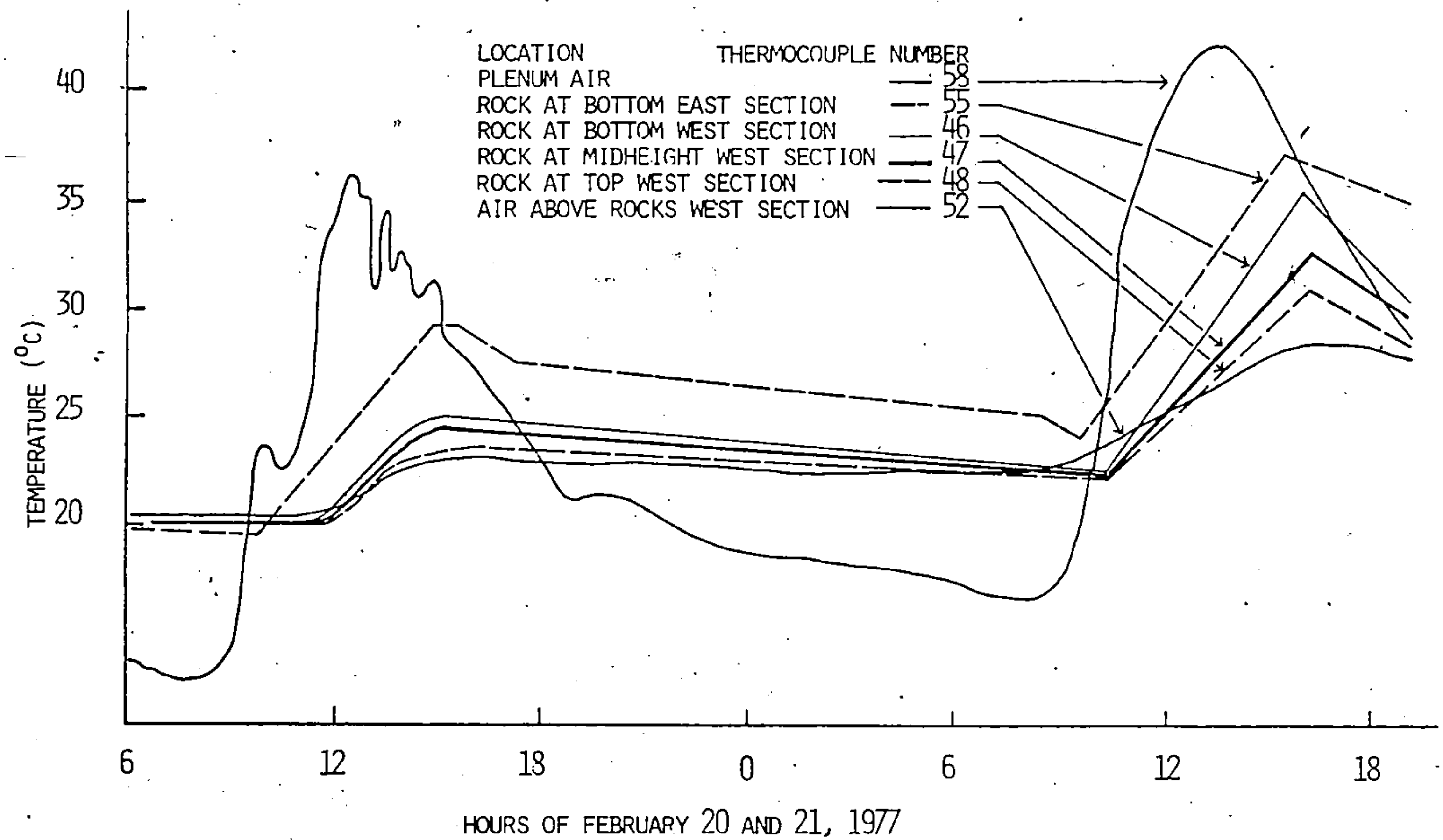

Figure 13 Temperature profiles in the storage

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v) The difference in temperature between air entering the storage and air leaving the storage at noon on February 21 is 40° - 24°C = 16°C. The difference becomes smaller later in the day when T inlet to collector rises to 27°C. In contrast, a stratified storage can absorb temperatures up to 60°C at inlet and return air at no more than 20°C to the collector (Ref. 17) - a difference of 40°C. The result is that the collector will operate more efficiently at the lower temperatures available from a stratified storage.

vi) In the case of the storage under study, the outlet air from the storage is circulated under the floor of the house in the space between the joists. The duct space is sufficiently insulated that there is negligible loss of heat between storage outlet and collector inlet. (Thermocouples 41 and 52 are similar.) However, when the collector fan is turned off, there is hot air directly under the floor. This hot air is not delivered to the house in a controlled way with the existing system, but rather the heat diffuses through the insulation and the baseboard diffusers.

In contrast, a stratified storage has hotter air at the top, which is a more effective heat source. In addition, if the storage hot air is blown into the rooms above, it will be used more fully in the living area when needed before it leaks out of storage through the storage walls.

3.6 Discussion of Errors

There are two classes of errors: those due to the imprecision of the measuring instruments in their representation of the true value of the variable being measured, and those errors due to the analysis techniques

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such as interpolation and assumptions of linearity in heat flow, averaging assumptions, and sampling techniques.

Measurement Errors

Temperatures were measured with copper constantin thermocouples (type T). The thermocouples were calibrated to a precision of 0.7°C, using an ice bath. The reference junction was calibrated with a precision of 0.1°C.

From the reference tables of temperature and corresponding voltage for the particular copper constantin thermocouples used, a cubic equation was obtained by regression analysis.[19] The correlation was good to 0.05°C for t between -100°C and 200°C.

$$t = 25.8714\,(V) - 0.696773\,(V)^2 + 0.0267611\,(V)^3$$

where: t = temperature, degrees Celsius

V = voltage, millivolts.

Errors of the test planning variety arise because the measurement taken by one thermocouple may not be a representative sample of the variable that is being tested. This condition arises in varying degrees for the temperature measurement points in the collector and in the house. For example, one point in the collector outlet duct is assumed to represent the average temperature in the duct.

The three solarimeters were calibrated by the manufacturer with a stated accuracy of 1%. For one of them, a light flux of 1 $w.cm^{-2}$ produces an EMF of 113 mv. The solarimeter located in the centre of the collector is representative of the average radiation incident on the whole surface of the collector. Sources of error for this type of solarimeter have been discussed in References 20 and 21. Hamilton in 11 concludes that the accuracy of the pyranometer readings is $\pm$ 5%.

Normally, air flow measurement in ducts requires a reasonably laminar air flow in a long, straight run of duct with constant cross section. In this system, there was no such practical measurement point. However, measurements were made at three different locations: in a short section of duct in the flow from the collector to the fan; in the plenum between the fan and storage, and in the entrance to the return ducts from the storage to the collector. The flow downstream from the fan was too turbulent to permit a reliable measurement. However, in the other two locations, turbulence was less.

A lateral traverse of the duct was made with a hot wire anemometer. However, the main limitation on the accuracy of the value used to represent the air flow rate is the location of the measurement. Non-representative values, due to turbulence, occur at points of change of duct size, and shape.

The variations in the measured values and an estimate that the probable error of the measurements of air flow in the duct between the collector and the fan is 560 m^3/hr or about 20% of 2600 m^3/hr is shown below.

Sample of air speed measurements at one point of the traverse:

x (meters/second) = (.92, .96, .9, 1.02, .94, .93, 1.0, .92, 1.05, .84, 1.09, .98)

$\bar{x}$ = .96 n = 12

$$S_x^2 = \sum_{(=)}^{n} \frac{(x_i - \bar{x})}{n - 1} = .00565$$

$$\sigma = \sqrt{S_x^2} = .071$$

Probable error: PE = .675 σ = .0479 m/sec = a.

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Twelve measurements were taken at each of 24 points in the traverse. Assuming that the probable error is the same for each traverse point with a value a_i = .0479 m/sec, then PE of total of all measurement = $\left(\sum_{i=1}^{24} a_i^2\right)^{\frac{1}{2}}$ so PE $=\sqrt{24}\, a$ = .235m/sec. For the cross section of duct = 0.66 m^2. PE = .235 m/sec x.66 m^2 x 3600 sec/hr = 557 m^3/hr.

The value of air flow indicated here is the flow from collector to storage and storage to collector when the control gates are opened. When the gates are open, there is a small crack around the gates which allows some air from the house to mix with the collector outlet air. However, the amount is difficult to estimate because the air flow at the outlet is complex. Nevertheless, the measurement provides an estimate of the air flow from collector to storage, which is a slight over-estimate of the total air flow through the collector.

Another type of error is due to the nature of the recording instrument. All thermocouples and solarimeters are sampled by the data acquisition system each 15 minutes. There is no averaging or integrating circuit. For the slowly varying temperatures, sampling is accurate enough, however on a partly cloudy day, the solar radiation and collector temperatures may vary substantially in a 15 minute interval. Over the period of a month, the measured Q and VSOL should be accurate enough, because the measured values of QU and VUSOL are randomly high as often as they are low.

Error due to Interpolation

Consider, for example, the interpolation line shown in Figure 8. The deviations ϵ of the measured Q values from the regression

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line in the y direction are $\epsilon_i = (0, -6, 8, 6, -4, -6, 3)$ $n = 7$.
$\bar{y} = \frac{\sum \epsilon i}{7} = 0.14$ kwhr

$$S^2 y/x = \frac{\sum \epsilon i^2}{n-2} = \frac{197}{5} = 39.4.$$

The variance of the mean value of y, called $\bar{y}$, is given by:

$$S^2 \bar{y}/x = \frac{S^2 y/x}{n} = 5.62 \; \& \; \sigma = \sqrt{S^2 y/x} = 2.37$$

Referring to the t-distribution for a 90% confidence level and degrees of freedom = 5, t = 2.015. The true value of $\bar{y}$ lies within $\bar{y} \pm t\sigma$ = .14 ± 4.77. The 90% confidence interval is - 4.63 to 4.91. There is a 90% probability that the mean of the Q values will be within about 5 kwhr of the interpolated value on the regression line.

3,7 Electricity Consumption Pattern of the House

In a paper entitled, "Off-Peak Use of Electricity for Solar Heated Homes"[22] concern is expressed on the impact of solar-heated houses on the electricity generation requirements of the utility if those houses used electric resistance heating in addition to solar heating. If the peak heating requirements of such a house were the same as a 100% electrically heated house, the utility would make the same investment in equipment, but the revenue obtained from the solar-heated house would be less because it uses less electricity on average. In this section, the overall and peak consumption of electricity in the La Macaza solar house is considered. Some conclusions on the effect of this house on the utility are presented.

Records of the electricity in kilowatt hours used in the resistance heaters (called "auxiliary"), and in the house as a whole (called "entry") were obtained for part of spring 1976 and for the 1976-1977 heating season. When the kilowatt hours of auxiliary energy is subtracted from the kilowatt hours of total entry energy, the result called "appliances" represents all other use of electricity in the house, which includes: range, water heater, lights, dryer, electric toilet (until the end of 1976), data acquisition systems and fan in the solar heating system. The refrigerator and data acquisition systems used together about 470 watts continuously. The fan used about 750 watts during a sunny day. For part of March 1976, when the house was occupied by a family, the profiles of "auxiliary" and "entry" are shown in Figure 14. The peak of entry is more than twice the peak of auxiliary. The peaks of entry occur near 9.00 a.m. and 6.00 p.m., whereas the peaks of auxiliary occur between 3.00 a.m. and 6.00 a.m. For part of February 1977, when the house was occupied by a bachelor, profiles of 4 hour averages of "auxiliary" and "appliances" are shown in Figure 15. Over the period shown, the average rate of "auxiliary" and of "appliances" use was 1 kilowatt and 2 kilowatts respectively.

The peaks of "entry", "auxiliary" and "appliances" were 7.8 kw and 3.6 kw and 6.3 kw respectively during the period. In the past, December has been the month of peak load for Hydro Quebec, corresponding to cold temperatures and pre-Christmas activities. For 1976, the peak load occurred on December 13 at 5.30 p.m. During December 1976, the measured peaks of "entry" for the solar house are shown in Table 10. The auxiliary heat during the same time period is also indicated in the Table.

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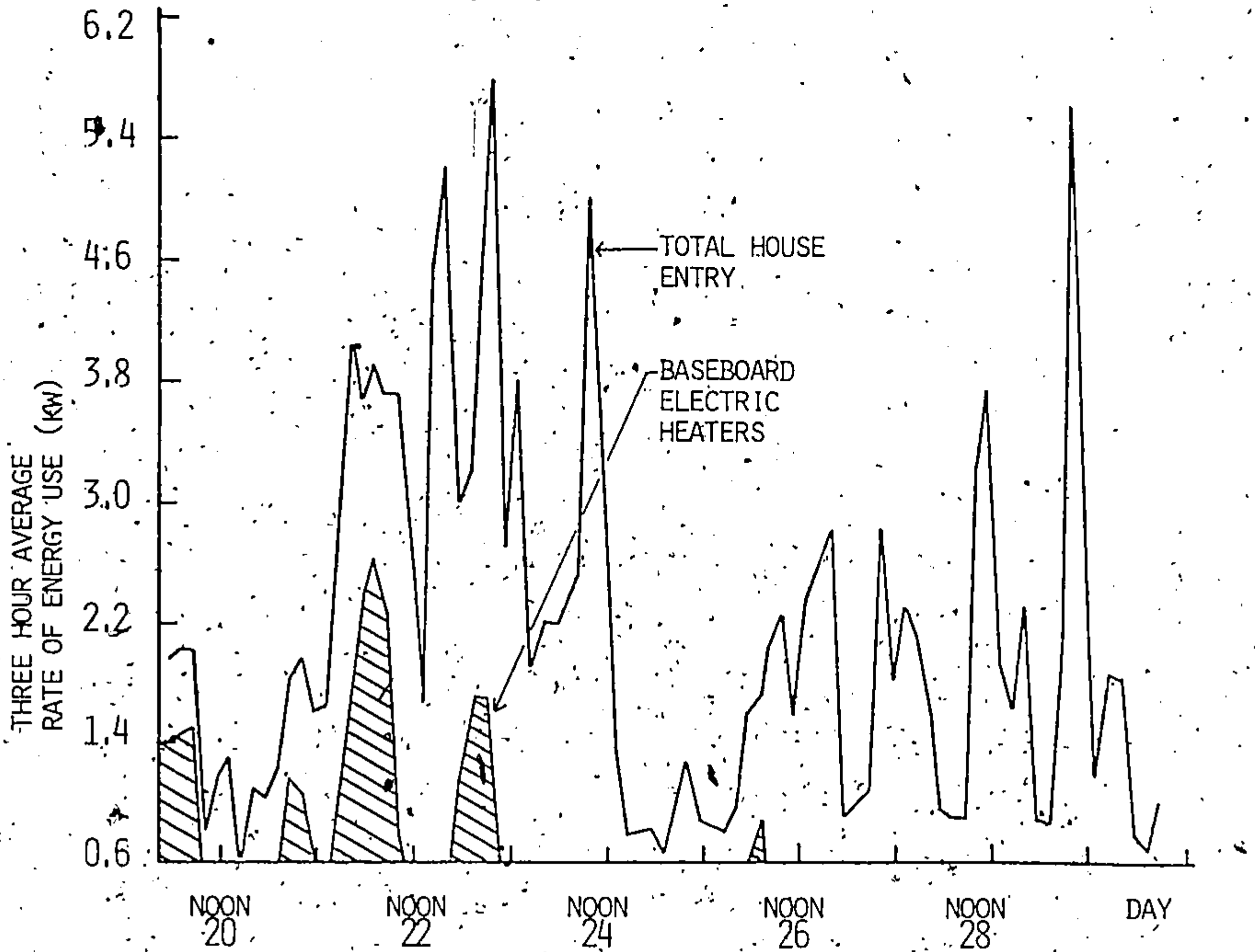

Figure 14 Electricity use in March 1976

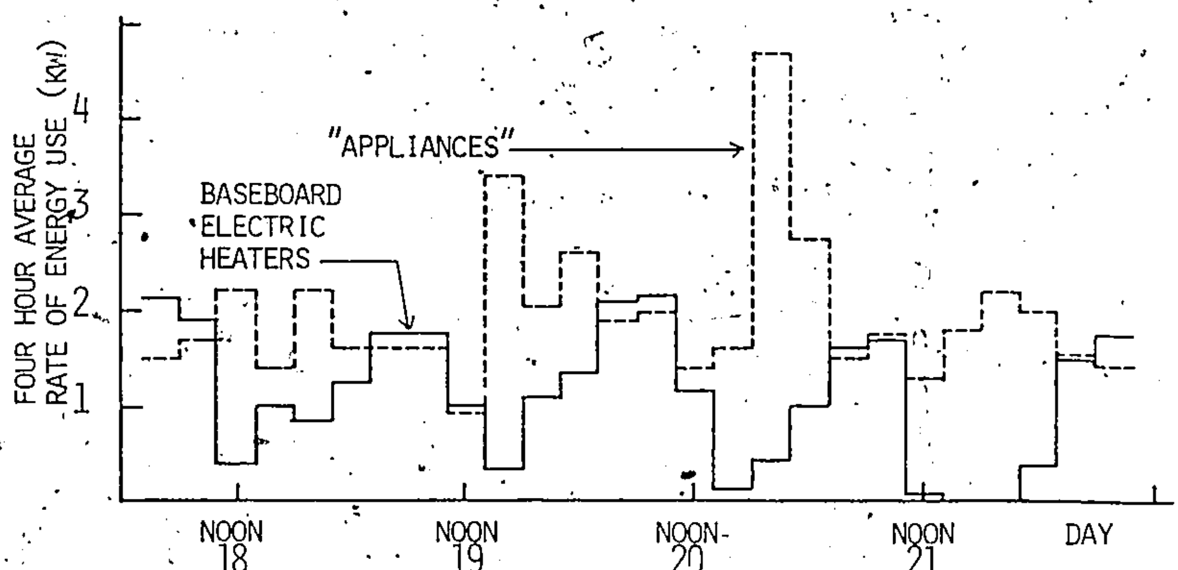

Figure 15 Electricity use in February 1977

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TABLE 10

PEAKS OF ELECTRICITY USE IN THE HOUSE

December Occurrence of peak of total entry		Total entry (kw)	Auxiliary heat at the time (kw)
Hours	Day		
9-12	3	12	3.6
15-18	5	11.5	2.7
12-15	7	12	1.4
12-15	12	12	.9

During December, the peak use of auxiliary electric heat was 5.2 kw on December 3, between 0 and 6.00 a.m., when the minimum outside temperature recorded at Ste. Agathe was -30°C. The previous day had been cloudy with no heat collected. Peak auxiliary was 4.8, 4.4, 4.2, 4.0, 4.0, 4.1 between 0 and 6.00 a.m. for December 4, 5, 6, 8, 9, 14 respectively. The solar heat collected during those days is shown in Table 5. The occurrence of the peaks of auxiliary use appears to have no relation to the occurrence of the peaks of entry shown in Table 10. On the contrary, the peaks of entry occur at the times when the range, water heater and dryer are in use.

When solar heat can be collected, it reduces the requirement for auxiliary heat. The coldest nights are clear nights, which frequently follow clear sunny days when solar heat can be collected. The pattern for some days in February 1977 is shown in Table 11.

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The minimum temperature was used to make a comparison of one night with another.

TABLE 11

CORRELATION OF CLEAR DAYS AND CLEAR NIGHTS FOR FEBRUARY 1977

Transition one day to next	Cold night followed by colder night	Cold night followed by warmer night
Cloudy day followed by sunny day	14-15 4- 5 20-21 22-23 27-28	19-20
Sunny day followed by cloudy day	18-19	8- 9 21-22 23-24

In summary, the La Macaza solar house has the following electricity use characteristics.

a) The house is an off-peak heater, because the maximum use of auxiliary electric heat is out of phase with the maximum demands on the utility.

b) The use of electricity in appliances is relatively large compared to the use in the auxiliary heaters. This is due both to the heat conservation design of the house and the solar heating system.

c) The house has lower peak heating requirements than most other houses because it is less sensitive to the minimum outside temperatures. This is due to the larger thermal storage in the house than in other typical houses.

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d) With the solar heating system, the house has fewer days of maximum heating demand on the utility than does a 100% electrically heated house. This is because many of the coldest nights are preceded by sunny days when heat is collected. When there is a series of cloudy days, the maximum demand on the utility coincides with that of the 100% electrically heated house.

e) When peak demand on the utility is met by fossil-fuel generating stations, the solar-heated house will require the consumption of less fuel because of (d) above, although the installation costs are similar except because of (c) above. Hydro-Quebec expects that gas turbines will be installed soon to meet peak demands on the electricity network.

Thus, the La Macaza solar house and similar houses would lower both heating costs for the owner and fuel costs for the utility.

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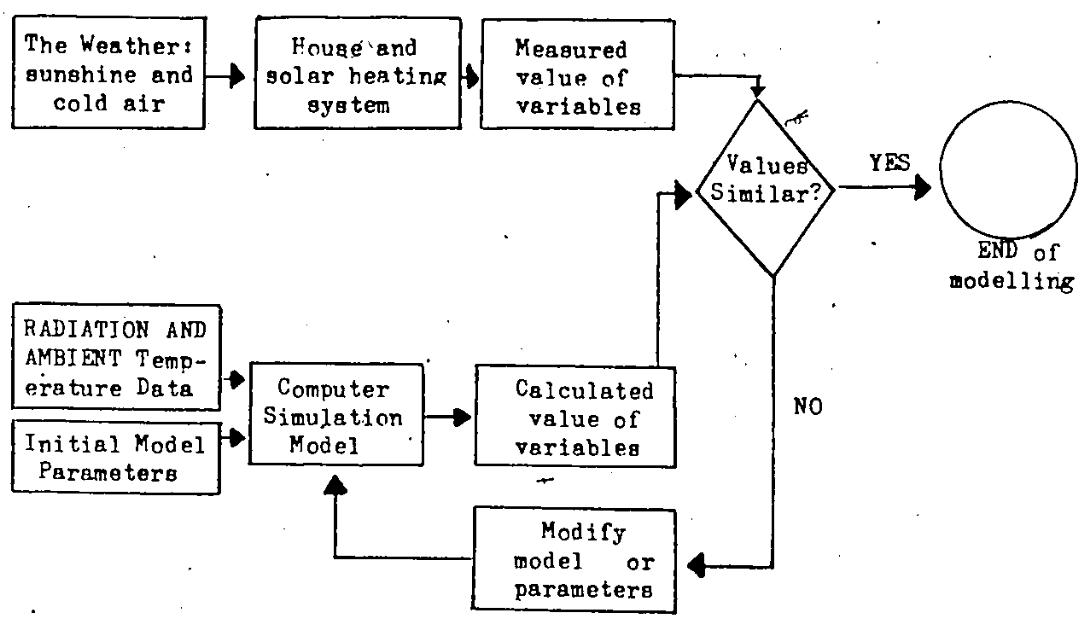
CHAPTER 4

COMPUTER SIMULATION STUDY

4.1 Objectives

The purpose of the study is to find a reliable set of parameters to represent the solar heating system and the heat loss mechanisms in the house. The procedure of the simulation study is to create a model of the heating process, which can be programmed on a computer, so that the output behaviour of the model is similar to a corresponding set of measurements of the heating process. The simulation procedure is illustrated schematically below.



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4.2 Model of the House and Solar Heating System

The basic model developed at the MIT Electrical Engineering Department, is shown in Figure 16 [a]. It was programmed, in its original form, in Basic Version 3 for a CDC 6400 computer. The thermal behaviour of the house and system is represented by an electrical analogue. This representation is reliable when the heat flows in the components of the house and system can be represented by linear equations: $Q = UA\Delta T$ where $UA = \frac{1}{R}$. This equation corresponds to Ohm's law of electricity: $I = CV$ where $C = \frac{1}{R}$, so an analogy exists with $Q \leftrightarrow I$ $T \leftrightarrow V$ and $R_{thermal} \leftrightarrow R_{electrical}$.

TABLE 12

MODEL COMPONENTS

Component	Definition	Units
Switches		
S1	The on/off switch for the fan in the collection circuit	
S2	The on/off switch for the fan of a forced air heat distribution system between the storage and the house	
S3	The on/off switch of auxiliary electric base-board heaters	
Input Variables		
I1	Solar radiation	kBTU/hr
I3	Auxiliary heating	kBTU/hr
Output Variables		
V1	Average collector temperature	°F
V3	Average storage temperature	°F
V5	Average house temperature	°F

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TABLE 12 (cont'd)

Component	Definition	Units
K1	$\frac{\text{Solar energy at absorber}}{\text{Solar energy incident on cover}}$	None
K2	Window solar heat gain factor	None
Resistances		
R1	Collector heat loss	^oF-hr/kBTU
R2	Collector heat transfer to outlet air	^oF-hr/kBTU
R3	Storage - basement heat loss	^oF-hr/kBTU
R4	Storage - ground heat loss	^oF-hr/kBTU
R5	Storage - house heat transmittance	^oF-hr/kBTU
R7	House - ambient heat loss	^oF-hr/kBTU
R8	House - ground heat loss	^oF-hr/kBTU
Capacitances		
C1	Rock storage heat capacity	kBTU/^oF
C2	House material heat capacity	kBTU/^oF

Revised Model

Figure 17 shows a schematic of the house and heating system with parameters corresponding to those used in the modified version of the model, which is shown in Figure 16(b). The modifications were made to the computer program, which was then used on the terminal of Concordia University's computer. A copy of that version of the program, which most closely matches the house, is included in Appendix D. The changes are:

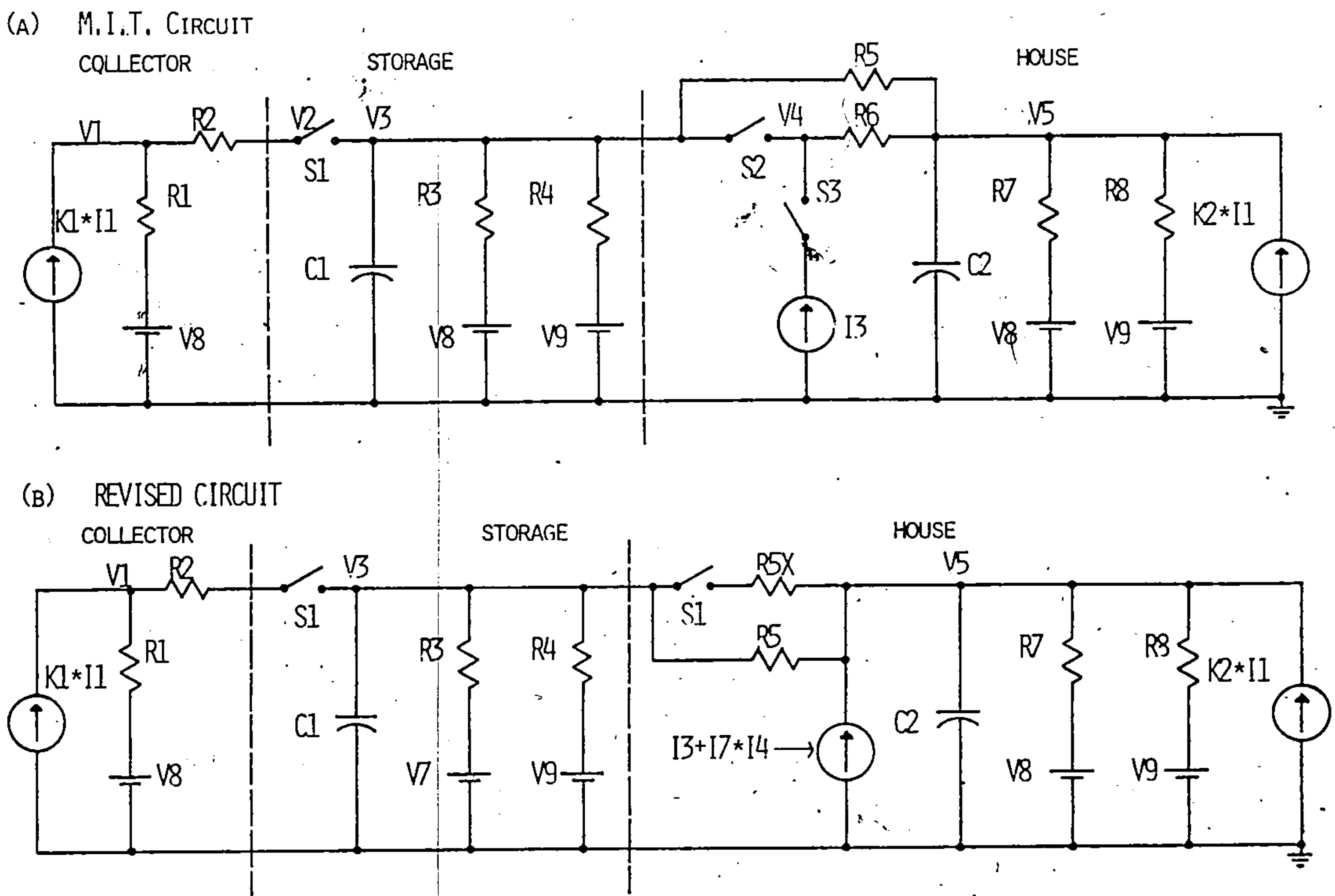

Figure 16 (a) M.I.T. Circuit Model for a general Solar House
(b) Revised Circuit Model for the La Macaza House

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i) During one period under study, a forced air heat distribution system was not used. The fan was not activated to blow air from storage into the house. Therefore, the model omits S2. The actual heat distribution between the solar heating system and the house is represented by two resistors in parallel. The first, R5, represents both heat transmission resistance and resistance to convective air flow between the storage and the rooms above. The second, R5X, is in parallel to R5 when the collector switch, S1, is closed. R5X represents the additional path of heat flow which is due to the effect of forced air circulating in the collector and storage in contact with the floor and the south wall of the house. The forced air is able to carry additional heat from the ducts into the house by way of cracks around control gates and cracks in the baseboard diffusers.

ii) Use of a new parameter, "V7", which represents the temperature of the unheated basement.

iii) Operation of the model each 15 minutes in order to give a more stable behaviour. It was observed that the calculated collector temperature oscillated a great deal when the status of switch S1 was only changed by the program on an hourly basis.

iv) The original MIT program was written in English Units. It was modified to accept inputs and print outputs in SI units. However, the resistances and capacitances remain in English Units.

v) For the revised model, there are four input variables and four output variables.

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Input:

a) I1 = VUSOL (kilowatts) - the solar radiation incident on the collector each fifteen minutes.

b) V8 (^{o}C) - the hourly average outdoor temperature each hour.

c) I3 (kilowatts) - the hourly average power used by the baseboard heaters each hour.

d) I4 (kilowatts) - the hourly average power used by the appliances each hour.

Output:

a) S1 = 1 collector on; S1 = 0 collector off.

b) V1 - the collector area average temperature.

c) V3 - the storage volume average temperature.

d) V5 - the temperature inside the living space.

These variables are shown in the sample of computer print-out in Appendix E.

vi) A modification of the program which created a deadband for the control of switch S1. Thus, S1 will close when $V1 > V3 + 20^{o}C$, but will not open again until $V1 < V3 + 3^{o}F$. The values are chosen to correspond to those used by the differential thermostat Rho Sigma Model RS12, which was installed in the house to control the power to the fan.

vii) A change of program to allow a variation in a parameter for a specific time interval to account for special effects. This was necessary to account for extra losses when collector gates were left open on February 19, 1977.

viii) In the first runs of the model, an attempt was made to match the auxiliary heat used by the model with the measured values of I3.

However, there remained too many variables in the model to be manageable. The program was then modified so that the values of I3 and I4 were input each hour from a file of measured values.

The program calculated the heat from the grid into the house by the equation: I3 + I7 x I4, where I7 is a factor corresponding to the fraction of appliance electricity that is released as heat in the house.

4.3 Calculation of Parameters Used in the Model

The following parameters were used in the model: K1, K2, R1, R2, R3, R4, R5, R5X, R7, R8, C1, C2. Figure 17 shows schematically the location of each parameter. Initial values of the parameters were calculated for use in the initial run of the computer program. Values for R1 and R2, which represent the characteristics of the collector, were calculated by using the measured data for the performance of the collector. Values for the other resistance parameters were based on theoretical heat loss coefficients for the appropriate partitions, walls or floors of the building. The techniques of Chapter 22 of Ashrae Handbook[13] were used.

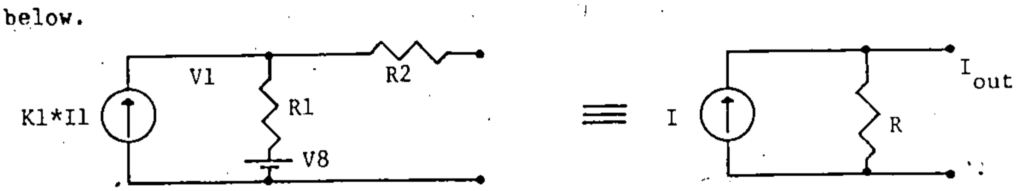
Collector Parameters

R1 Collector heat loss coefficient

R2 Collector heat transfer coefficient

Consider the collector portion of the model circuit shown in Figure 16(b). In order to determine R1 and R2, the electrical equivalent of the collector efficiency was used.

The collector portion of the circuit can be redrawn as shown below.



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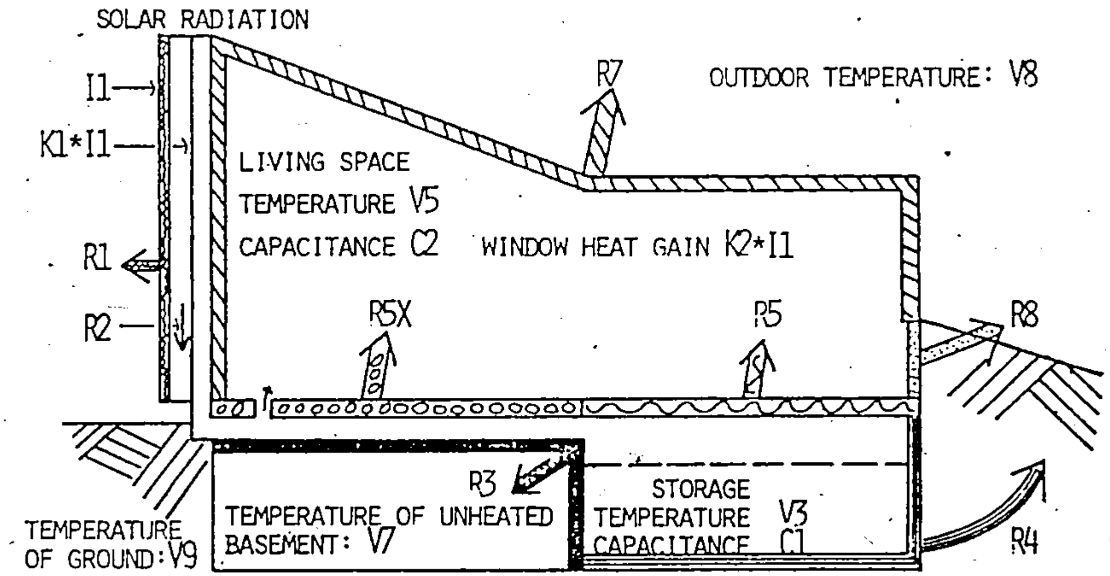

Figure 17 Schematic of the house heat flow pathways showing the parameters in the model

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Where V1 is the average temperature of collector air

V8 is the outside air temperature

K1 is the transmission of the collector cover.

Using Norton's theorem, the two circuits are equivalent[23]

when: $I = K1 \times I1 \times R1/(R1 + R2)$

and $R = R1 + R2.$

Using Ohm's Law:

$I_{out} = I - (V1 - V8)/R$

substitution

and $I_{out} = K1 \times I1 \times R1/(R1 + R2) - (V1 - V8)/(R1 + R2)$

I_{out} represents the heat flow out of the collector and I1 represents the radiation incident on the collector. Efficiency = $I_{out}/I1 = K1 \times R1/(R1 + R2) - (V1 - V8)/I1\,(R1 + R2)$. Measured values of the efficiency of the collection are plotted with respect to measured values of (V1 - V8)/I1 in Figure 18. Thus, the intercept and slope of the line are $K1 \times R1/(R1 + R2)$ and $-1/(R1 + R2)$ respectively. R1 and R2 can be determined when K1 is known. Using K1 = 0.8, the transmission of 2 panes of 5 mm ordinary plate glass, the values R1 = 5C°/kw or $2.5\frac{F^{o}hr}{kBTU}$ and R2 = 1C°/kw or $0.5\frac{F^{o}hr}{BTU}$ were obtained.

House and Storage Parameters

Calculations of the following values are presented in Appendix C.

Name	Description	Value	Units
R3	Storage-basement	13	°Fhr/kBTU

i) The duct space and storage temperatures are assumed to be equal.

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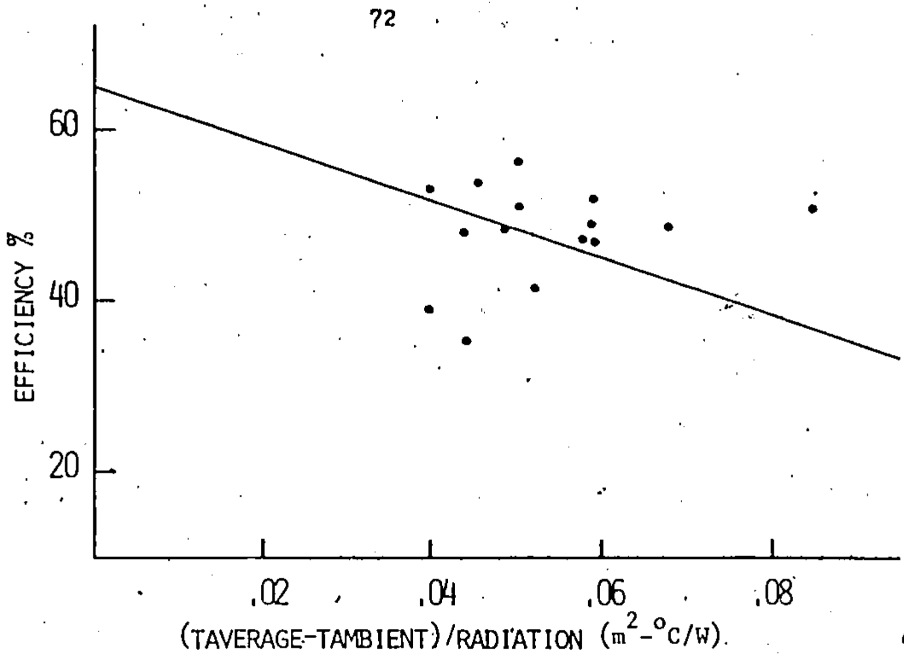

Figure 18 Thermal efficiency with respect to average collector temperature

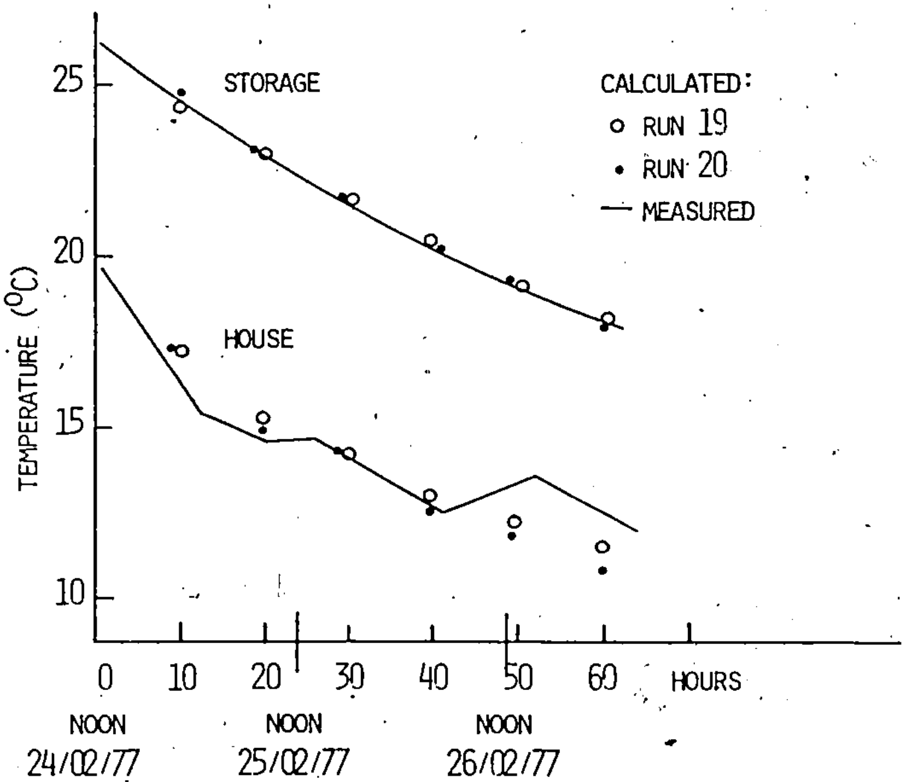

Figure 19 Measured and calculated temperatures in house and storage

ii) The unheated basement temperature is calculated from the weighted average of surrounding temperatures, Chapter 24.2 (Ref.13).

Name	Description	Value	Units
R4	Storage-ground	36.4	°F-hr/kBTU

i) The storage area is below grade and thus is similar to a heated basement with respect to the losses of heat to the soil.

ii) Heat loss can be calculated for walls and floors according to Chapter 24.4 (Ref. 7).

Name	Description	Value	Units
R5	Storage-bedrooms	14	°F-hr/kBTU

i) An estimate can be obtained from the U-values of the materials of the floor and insulation.

ii) For an initial value, convection through diffusers and radiation by the floor can be neglected.

Name	Description	Value	Units
R5X	Additional heat flow path when fan is operating	12	°F-hr/kBTU

i) When the fan operates on a sunny day, there is a forced convection of air through the openings between the ducts and the living spaces.

ii) With R5X in parallel to R5, the effective resistance to heat flow is reduced. This reflects the additional path for heat flow from the ducts to the house through the building materials.

Name	Description	Value	Units
R7	House - ambient	5	°F-hr/kBTU

i) Resistance can be calculated by techniques of Chapter 22 of Ref.13, using the heat conductivity of the building materials and infiltration air by the crack method.

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Errors in heat loss calculations are due to assumptions of uniformity of material and linearity of conductivity of building materials, and to the neglect of thermal bridging and discontinuities of construction. Errors in infiltration calculations are due to assumptions of uniform wind speed, estimates of crack length and of crack size.

ii) Because of the unusual construction of the house, with the south wall integrated with the collector, the wall does not always act as a pathway for heat loss from the house. When the sun shines, there is no heat loss through the wall. On a cloudy day, the collector may warm up enough to block heat loss from the house and, on a bright day, the collector is hot enough to provide some heat gain to the house through the insulation between the collector ducts and the living space. However, for calculation of the U value of the south wall, the collector is treated as an additional dead air space and double glazed cover of the wall of the house.

iii) The effect of stratification of heat in the peak of the ceiling on the heat losses is neglected.

iv) The heat flow resistance of the 5" thick wood walls is assumed to be linear with thickness of the wood.

Name	Description	Value	Units
R8	House-ground	72.5	hr-F^{o}/kBTU

The house is surrounded on three sides by a soil berm which covers the lower three feet of the wall.

Assumption: The berm soil temperature is the same as the soil temperature 2 feet below grade.

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Name	Description	Value	Units
C1	Heat capacity of rock storage	18	kBTU/°F

i) The specific heat of rock is 0.2 BTU/lb°F, as for quarried stone.[13]

ii) The rocks have a uniform density. One was measured to be 140 lb/cu. ft.

iii) Rocks pack with a void fraction of 0.42 if all the rocks are the same size.[24]

iv) The concrete wall storage container contributes to the thermal storage because it is covered on the exterior by insulation.

Name	Description	Value	Units
C2	Heat capacity of the rest of the house	4.8	kBTU/°F

i) The interior wood and other materials store heat.

ii) Although the exterior wood walls are not at room temperature, they contribute to the heat storage capacity of the house as if they were, because they delay the outflow of heat from the building.

Name	Description	Value	Units
K2	Window solar heat gain factor	0.01	

i) Chapter 26 of Ref. 13 gives an estimate of the solar heat gain through east and west exposures and of the shading coefficient for blinds and curtains. In the model K2 is the ratio of heat gain through the 10 m^2 of the windows to the solar radiation I1 on the 42.5 m^2 of the collector.

I3, heat supplied by the Utility company, is the heat supplied to the house by the baseboard electric heaters.

I4 is the difference between the total electric power that enters the house from the grid and that used by the heaters. Thus I4

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represents the power used by the appliances, lights, fan and data acquisition system. About 80% of I4 enters the house as heat. The remainder is lost in hot water down the drain, hot air up the dryer vent and excess heat rising immediately to the peak of the roof to escape.

Figure 15 shows the average over 4 hours of the values of I3 and I4 for February 18 until 21, 1977. The peaks of the the I4 curve were reduced, so that no hourly average values were greater than 4 kw. This was done because the cooking heat was wasted as excess heat in the house when it rose to the ceiling, and also because the heating of water in the hot water tank did not make heat available to the space immediately.

4.4 Results of Simulation

Simulation Runs for the Vacant House, February 24-26

During this period, the response of the house to the ambient weather conditions provides a measure of the heat loss and capacity parameters of the house and rock storage. From noon February 24, 1977 until midnight of February 28, the house was vacant, the thermostats were turned down and the gates of the solar heating system were left open in case there would be sunshine. However, the weather was cloudy enough that there was no input of energy to the house from the collector. The mean wind speed was 15 km/hr. The cassette recorder showed that the baseboard heaters were off, and that the average rate of electricity use in the vacant house was 600 watts. Of this, about 130 watts were used by the water heater to make up for heat losses through the tank insulation.

The simulation program was run in order to duplicate the changes in temperature which occurred in the house and storage for the first 60 hours after noon of February 24.

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Figure 19 shows both the measured and computed temperatures for the storage and the house respectively for two simulation runs. Table 13 shows the values of the parameters which were used in various runs of the computer program. In this section R1, R2, K1, K2, R5X are irrelevant because there was negligible solar radiation. There are several successful runs which have different parameters. This allows some flexibility for comparison with the results of the February 18-21 period. For all runs shown in Table 13, R3 = 21 and R4 = 36.4 °F-hr/kBTU.

TABLE 13

SUCCESSFUL RUNS FOR FEBRUARY 24-26TH CONDITIONS

Run #	Parameter			
	C1	R5	R7	C2
4	18	5	4.5	5
5	18	5	5	5
6	18	5	5.5	2.5
9	18	4	4.5	3
19	20	4	4	9
21	20	5	3.5	9
16	20	7	4	9
27	20	4	4.2	6

Sensitivity of the Model to Variations in the Parameters

In the following runs, one parameter was changed, all others remained the same. Variation of Ground (V9) and Basement (V7) temperatures. The values of V9 and V7 were 41°F and 48°F for the successful runs. The storage and house temperatures showed a drop of only 0.5°C

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with respect to the base case when V9 = 30°F and V7 = 36°F. Increasing V9 to 50°F and V7 to 60°F only raised the curves by 2°C and 1°C respectively after the 60 hours of simulation. Thus, the base solution is relatively insensitive to the ground and basement temperatures.

Variation of Storage Losses

When R3 was increased from 21 to 35 °F-hr/kBTU, the change in storage temperature was less than a degree celsius different than the base case after 60 hours of simulation.

Variation of R8. When R8 was increased from 72.5 to 86 °F-hr/kBTU, the change in house temperature was less than 0.5 degree celsius.

Variation of R5. When R5 was changed from 4 to 3 °F-hr/kBTU, the house temperature increased by about 0.5 degrees.

Variation of storage and house heat capacities. When C1 and C2 were decreased to 12.6 and 2.6 from [illegible] and 5 respectively, the storage and house temperatures dropped by 5°C and 2°C from the base case by the 60th hour of simulation. The model is relatively more sensitive to the heat capacity parameters.

Computer Simulation of the House for the Period February 18-21, 1977

During February 18 through 21, the house was occupied by a bachelor. A portion of the log he kept is shown in Table 14.

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TABLE 14

PORTION OF THE HOUSE LOG

Date February '77	Time	Open/Close Gates	Comments
18	09.30	O	Sun, some cloud.
	17.30	C	Intermittent
19	10.20	O	Mostly overcast
	15.00	C	Oven on 14.00 - 15.00 hrs.
20	09.40	O	Sun almost all day
	17.40	C	
21	09.55	O	Sun
	17.40	C	
22	12.00	O	Overcast - sun sneaking out Snow
	19.20	O	Sun later aft.
23	09.00	O	Sun all day
	16.20	C	
24	07.30	O	House vacant, window open above pantry, curtains and blinds closed

The collector gates were opened and closed shortly after the fan was turned on and off by the differential thermostat, except on February 19th. On that day, the fan was on only between 10.20 and 11.00 hours, but the gates were not closed until 15.00 hours. From 11.00 to 15.00 hours, some heat from the house was lost through the collector glazing. To estimate the additional heat loss, it is assumed that the south wall was only double glazing at this time. The result is an increase of heat loss by about one-eighth. Accordingly, the parameter R7 was modified for this period of the simulation.

The measured values of average collector air temperature, average storage temperature and the temperature in one of the bedrooms are shown

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by solid lines in Figures 20 - 23.

The program was run a number of times with different values of the parameters until a reasonable agreement between the calculated and measured values was obtained. The temperatures match within 2°C. This run is called the "median case". A copy of the computer print-out is in Appendix E. The print-out indicates the values of the parameters in English units, which gave the best match. They are presented in Table 15. For purposes of comparison, the parameter values which were calculated in Section 4.3 are also given in Table 15.

TABLE 15

MODEL PARAMETERS

Name of Parameter	Calculated Value for Initial Trial Run	Value used in "Median Case"
R1	2.5	2
R2	.5	.6
R3	13	21
R4	36.4	36.4
R5	14	4
R5X	12	10
R7	5	5.4
R8	72.5	72.5
C1	18	20
C2	4.8	6
K1	.8	.8
K2	.01	.01

The value of the house heat loss parameter "R7" used in the median case is larger than the calculated value which assumed the average monthly wind speed of 12 km/hr. However, as shown in Figure 22a, the

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wind speed was substantially less than 12 km/hr for most of the period. The average speed was 8 km/hr. The infiltration of cold air into the house was less than normal. The calculated value of heat loss resistance depends on wind speed as shown in Table 16.

TABLE 16

HEAT LOSS RESISTANCE AND WIND SPEED

	Wind Speed			(km/hr)
	0	6	12	24
R7 ^{o}F-hr/kBTU	6	5.4	5	4.4

This explains why using R7 = 5.4 gave a better match than did R7 = 5.

The value of C2 in the median case is slightly larger than the calculated value, which indicates that heat storage in house components was under-valued in the calculation. In the median case, we use a smaller value of R5 than calculated with U factors to take care of the effect of convective heat exchange between storage and house.

The calculated and measured collector temperature curves have different shapes in Figure 20. In the model, there is no analogue of thermal storage in the collector. The 3/16 inch thick sheet of pressed wood behind the absorber provides some thermal inertia in the collector. Also, the collector is integrated with the wall so that the 5 x 5 studs provide some additional storage. The sheet metal absorber also provides some thermal inertia.

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Sensitivity of Results to Variation of Parameters

To test the convergence of the results, each parameter was varied from the value used in the "median case" with the other parameters held constant. The calculated values of the collector, storage and house temperatures were compared with those of the median case for variation of each parameter: R1, R2, C2, R7, R5, R5X, K2, I7. The results are shown in Figures 20-23, and are described in detail for each of the parameters below.

Variation of R1: R1 represents the heat loss resistance between the collector and the exterior. R1 was changed by 10% from 2°F-hr/kBTU to 1.8 and 2.2. The changes in collector and storage temperatures for February 20 and 21 are shown in Figures 20 and 21 respectively. The maximum difference observed was 1.5°C.

Variation of R2: R2 represents the heat transfer resistance in the collector. As shown in Figures 20 and 21, the collector and storage temperatures on February 21 changed by 2°C and 0.5°C respectively as a result of a change of 0.1 °F-hr/kBTU in R2.

Variation of C2: C2 represents the heat storage capacity of the house. C2 was changed from 6 to 4 and 9 kBTU/°F for two runs of the program. The results are compared with the median case and measured values in Figure 23(b). Changing C2 varies the sensitivity of the house temperature to variations of the heat input from appliances and to variations of ambient temperature. Neither an increase nor a decrease of C2 gives a result closer to the measured values than the median case.

Variation of R7: R7 represents the heat loss resistance between the house living space and the outside air. R7 was changed from 5.4 to

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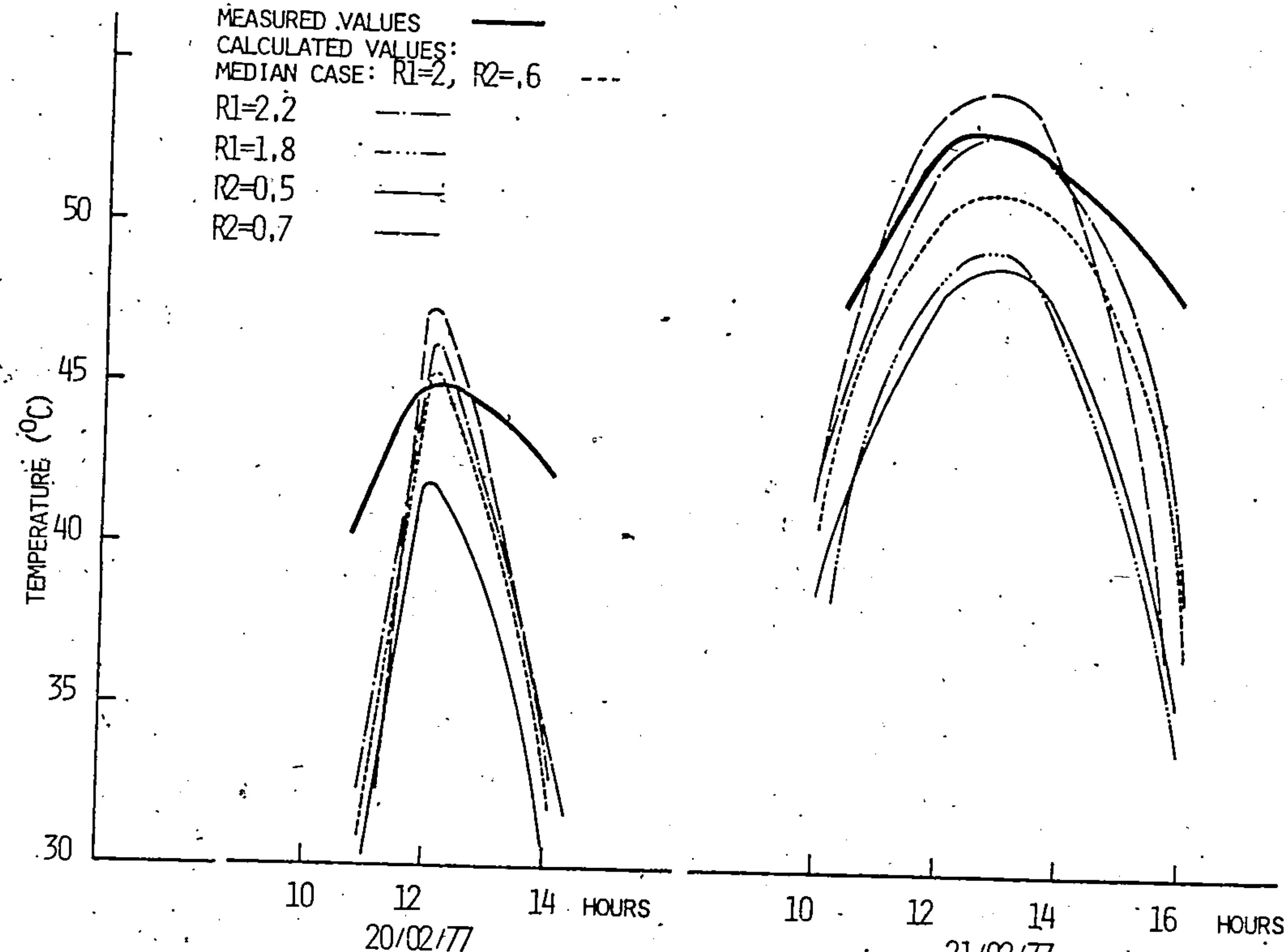

Figure 20 Measured and calculated collector average temperatures

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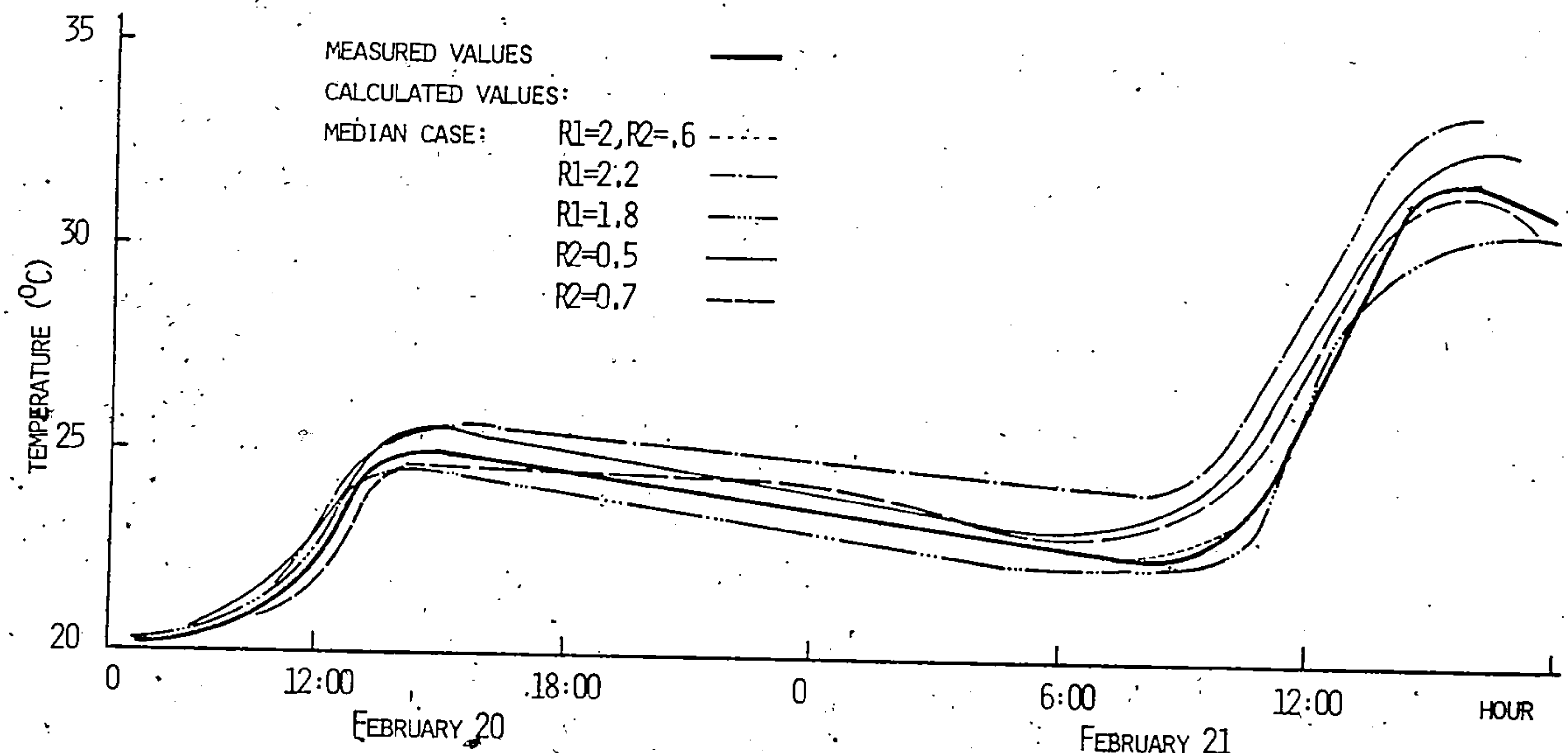

Figure 21 Measured and calculated storage temperatures

4.6 and 6 °F-hr/kBTU for two runs of the program. The effect of the changes on the calculated value of the house temperature is shown in Figure 22(b). The decrease/increase of R7 lowers/raises the calculated value of the house temperature.

The lower value of R7 gives a run with a better match to the measured values when the wind speed is higher and infiltration greater. On the other hand, the higher value of R7 produces a good match for periods of February 18 and 19, when the wind was calm and infiltration was greatly reduced. These results can be considered verification of the value of R7 which was calculated for various wind speeds as shown in Table 16.

Variation of R5 and R5X: R5 represents the heat transmission resistance between the storage and the house. The value of R5 was increased from 4 to 7 °F-hr/kBTU. The result is shown in Figure 23(a). The house temperature was decreased slightly compared to the median case; storage temperature was increased slightly. Thus, the results are not sensitive to the variation of R5.

R5X represents the additional path of heat transmission when the fan is on. When R5X was changed from 10 to 4 °F-hr/kBTU, the effective resistance of R5 and R5X in parallel was changed from 3 to 2 °F-hr/kBTU. The result was an increase of the calculated house temperature by one degree celsius during part of the period when the fan was on.

Variation of K2: K2 represents the solar heat gain factor through the windows. A value of 0.01 was calculated in Section 4.3 and was used in the median case. When K2 was increased to 0.05, the house temperature increased by 2°C and 3.5°C during the sunny periods of February 20 and 21 respectively, as shown in Figure 23(a).

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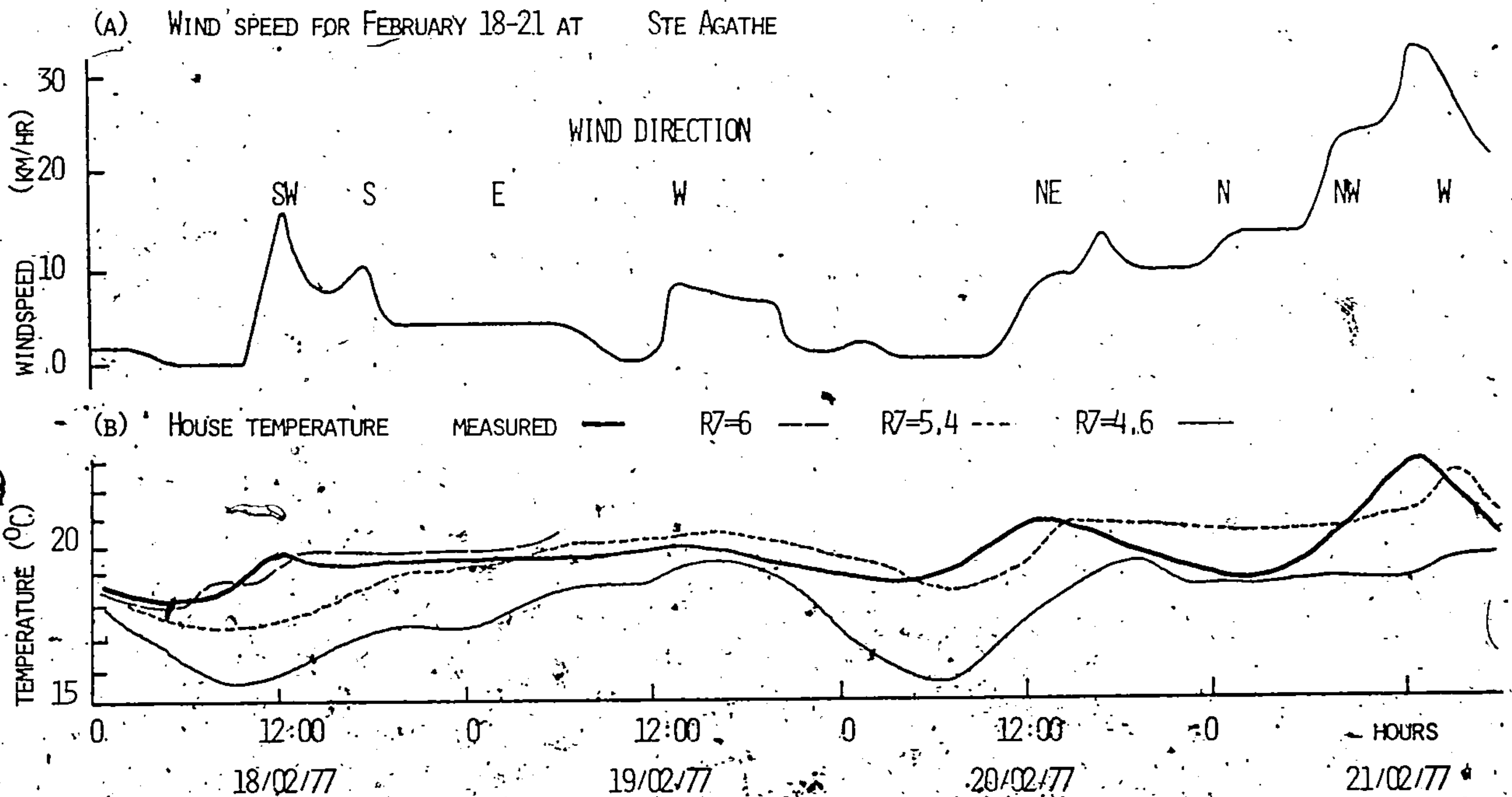

Figure 22 (a) Wind speed and direction
(b) Measured and calculated house temperatures for the Median case and Variation of House heat loss parameter R7.

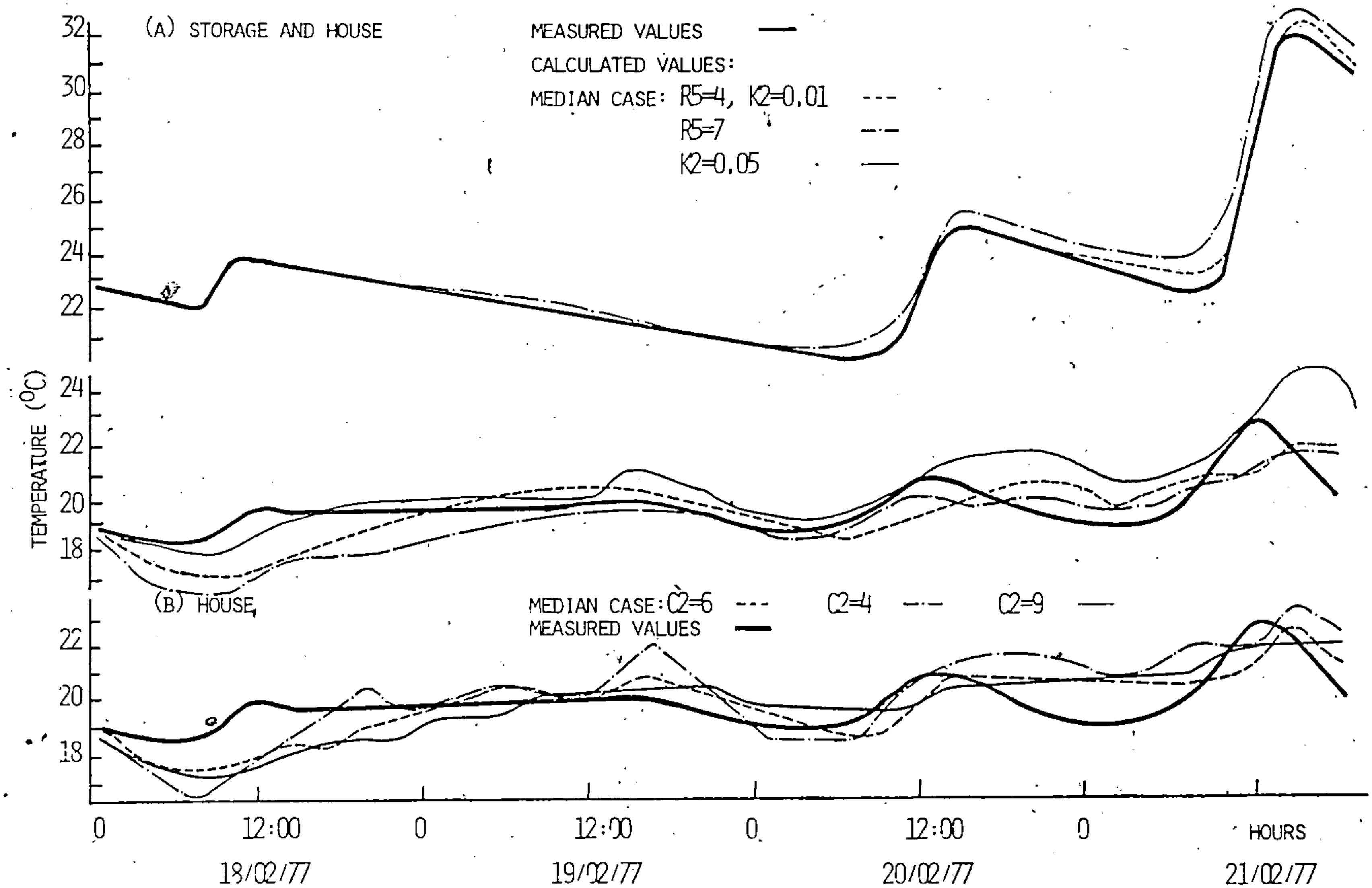

Figure 23 Measured and calculated house and storage temperatures for variation of R5, K2 in (a), and C2 in (b)

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This increase with respect to the measured values of house temperature is larger than reasonable considering also the effect on the calculated house temperature for the evening of February 20. Thus, K2 should probably be less than 0.05.

Variation of I7: I7 represents the fraction of appliance energy use which enters the house as heat. The median case used I7 = 0.8. When I7 was increased/decreased by 0.2, the calculated house temperature was increased/decreased by about 2°C or 3°C. This is a significant variation, which indicates that the value of I7 = 0.8 is a reasonable choice.

Summary of Results of the Simulation Study

A successful match to the measured values of the temperatures in the collector, storage and house was obtained with the Simulation Program. The simple analogue circuit, with careful choice of parameters, was used successfully to model the heat flows between the different parts of the house and solar heating system and between the house and the outdoor heat sink.

The match of experiment and theory was accomplished for two time periods with different heat supply situations. The results of the two periods are consistent with each other. The value of R7 was 5.4 °F-hr/kBTU for February 18-21 and 4.2 °F-hr/kBTU for February 24-26. About half of this difference was due to the difference of wind speed between the two periods: 8 km/hr for the former and 15 km/hr for the latter. The other half of the difference is due to the fact that when the house was vacant between February 24 and 26, the effective heat loss was increased slightly

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because the collector was more open to the house. The effect of wind speed on the effective heat loss resistance of the house has been studied. The results of the simulation are consistent with calculated values of the resistance for various known wind speeds which occurred during the six days of the period of simulation.

The model was tested for sensitivity to changes in the values of the parameters.

4.5 Use of the Results in a Heat Balance Calculation

In this section, an attempt is made to discover how well the results of the simulation study apply to a longer period of time.

Measured values of auxiliary electric heat consumption in the house and of the total entry of electricity to the house for the three month period of October 1 to December 31, 1976 are used to estimate the input of heat to the house. The heat collected by the solar heating system calculated in Section 3.3 and shown in Table 5 is included in the estimate.

To obtain an estimate of the heat losses from the house during the three months, some modifications are made to the results of Section 4.4 to account for the different conditions of the periods.

As described in Chapter 2, the house was designed to conserve heat by the addition of extra insulation above and below grade, a low profile for the north winds, minimal glazing on the north side and an earth berm on north, east and west sides. An estimate of the heat loss resistance of the building has been obtained in Section 4.3 for use in the simulation program. Using the value of 5.4 ^{o}F-hr/kBTU, a reasonable match of

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calculated and measured house temperatures was obtained for a four day period in February 1977. Can this value of resistance be used to represent the building during the whole heating season? No. The wind speed for the four day period averaged 8 km/hr, which is about two-thirds of the average wind speed throughout the winter. The thermal resistance can be modified to 5 ^{o}F-hr/kBTU to account for the increased infiltration losses expected from a higher average wind speed.

For the period October 1976 to December 1976, one door was not weather-stripped. The amount of heat loss through the crack is about double the value used in Section 4.3. The effect on the total resistance of the house is to decrease R to 4.6 hr-^{o}F/kBTU. Another factor in the heat load is the frequency of opening and closing of doors. This is difficult to assess, but for the period of October - December it is estimated that the doors were opened more than in most houses. The heat resistance of the house was thereby lowered to about 4.3 hr-^{o}F/kBTU. This is equivalent to a heat loss of 233 BTU/hr-^{o}F or 123 watts/^{o}C.

Having estimated the heat losses of the house and measured the energy inputs to the house, a balance of heat in and heat out is presented in Table 17.

In this Table, the term "appliance" refers to the range, dryer, water heater, electric toilet, data acquisition system, the fan, lights, etc.

In the Table, a factor of 0.8 has been used to represent the portion of the appliance energy consumption which is used as heat in the house following the results of the previous section.

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The results shown in Table 17 are sensitive to this factor. Since the value of 0.8 is only an estimate, our confidence in this balance is not great.

In Table 17, the heat gains from the windows are calculated using the K2 factor determined from the previous section. Thus window heat gain = K2 x VSOL, where VSOL is the radiation incident on the collector. The monthly totals for VSOL are used. Also in the Table, we add heat inputs due to one adult occupant, because October - December there were two adults in the house, whereas the results of the previous section are based on one adult occupancy.

In Table 17, the calculations are based on an indoor temperature of 21°C. As previously indicated, the design of the ceiling is such that heat rises and stratifies in the upper part of the house. If the heaters maintain a temperature of 21°C at the height of the thermostat, the temperature in the ceiling could be about 3°C higher. Considering that about half of the surface area is affected by the higher temperature, it can be estimated that, on the average, the temperature of the air near the inside surfaces of the house is about $\frac{20 + 24}{2} = 22$°C.

Thus:

	October	November	December
Degree Days Re 18°C	458	646	1020
Re 22°C	581	766	1114
Degree Hours	13944	18384	26736
House - outside Heat Loss (kwhr)	1715	2261	3288

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Once the interior of the house has reached a stable temperature and is maintained there by thermostats, the heat balance equation applies: Heat into the house = Heat out of the house.

There is a difference in the calculated values of Heat In and Heat Out shown in Table 17. The difference is about 10% to 37%, depending on the month. This difference is reasonable, considering the assumptions that have been made to make up for insufficient information.

TABLE 17

HEAT BALANCE FOR OCTOBER - DECEMBER, 1976

	October	November	December
Heat Inputs (kwhr)			
Collector	913	511	1074
Auxiliary	662	1254	1490
Appliances x 0.8	996	1157	1417
Window	35	13	27
One adult body heat	80	80	80
Total input:	2686	3015	4088
Heat Outputs (kwhr)			
House - outside heat loss	1715	2261	3288
House - ground through basement heat loss	108	126	153
Storage - ground heat loss	135	150	188
Total output:	1958	2537	3629
Difference Input - Output	728	478	459
Percentage of output	37%	18%	13%

By splitting the difference between the Heat In and Heat Out, a value of 3800 kwhrs of total heat flow for December is taken. The heating degree days relative to 18^oC are 1020^oC days for December. Effectively, the heat loss coefficient for December is:

$$\frac{3800 \text{ kwhr}}{1020^oC \text{ days} \times 24 \text{ hr}} = 155 \text{ w}/^oC$$

Assuming a constant value over the whole heating season means that the total heat requirement of the house is about 18000 kwhrs in a region which has 4852 degree Celsius days per year. During the 6 month period of October 1976 to March 1977, there were 4563 degree days at Ste. Agathe, as shown in Table 4. For this period, 17000 kwhrs of heat were required. From Table 8, the estimated heat supplied by the solar heating system and baseboard heater were 5690 kwhrs and 5605 kwhrs respectively. These values are 33% and 33% respectively of the total. Thus, the appliances must have contributed 34% of total.

This result does not conflict with the solar fraction estimate of Section 3.3 because the two results are based on different totals. The solar fraction indicated that the solar heating system contributed 50% of the 11300 kwhr requirement for heat above that supplied by the occupancy of the house.

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CHAPTER 5

DISCUSSION OF RESULTS

House Design

Some comments on the design and construction of the house and the solar heating system have been presented in Section 2.4. On the whole, the occupants have been satisfied with the house. However, some improvements could be made in future houses of similar design. The collector wall is a plane surface with no openings to the interior of the house. The collector wall could be broken up into sections with recessed surfaces and windows which would both interrupt the uniformity of the wall and provide some light and view on the south side of the house.

The interior pane of ordinary glass in the collector cover has cracked in a number of units. Inadequate venting of the collector during a power failure, insufficient rigidity of the wood frame and the cantilever of the frame from the house wall are possible causes of the cracking.

The cracking could have been avoided by the use of tempered glass for the interior pane, or emergency vents which open before the collector reaches a temperature that might result in damage, or by a different frame design.

Monitoring

The information collected from the monitoring of the house has been discussed in 3.2. Further research must be based on more complete

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information about the house and heating system, such as:

i) Air flow studies in various locations in the collector, storage and living spaces;

ii) Air and surface temperatures in various locations in the living space to improve knowledge of the heat losses;

iii) Infra-red thermography to determine any unevenness of heat flows from the collector and through the building shell;

iv) More detailed records of the use of appliances and living habits of the inhabitant of the house;

v) On-site wind speed measurements;

vi) Measurement of the solar radiation on the collector contributed by the snow foreground. It is surmised that the vertical collector with snow foreground receives as much radiation as one tilted at latitude + 15°, the "optimal" tilt for winter space heating.

Collector

The heat output and efficiency curve of the collector have been presented in Sections 3.3 and 3.4. The collector efficiency curve is similar to the curve for a "Solaron" flat black absorber air heating collector. The collector parameters, $F_R \tau\alpha = 0.51$ and $F_R U_L = 2.6$ w/m^2 °C are calculated from Figure 12. If the metal screen between the glazing and the absorber had been inclined to increase heat transfer in the collector, the efficiency would have been closer to that of the collector built and tested by Gupta and Garg.

Thermal inertia in the collector was not large enough to delay the collection of heat in the morning. On a sunny day, the fan was turned on around 9.00 a.m. in February and around 8.30 a.m. in March.

Storage

Some observations about the rock storage have been presented in Section 3.5. Each section of storage appears to be nearly isothermal. The section which has a smaller volume of rock has a higher average temperature. The balance of the system would be improved by making the storage sections equal. The isothermal storage is due to the direction of air flow during heat input. There are two main disadvantages to this type of storage. The air which flows from storage to the collector is hotter than desirable, and the air which can be blown from the storage into the house is at a lower temperature than desirable. Both of these disadvantages can be corrected by reversing the direction of air flow into the storage so that the top of the storage becomes hotter than the bottom. This effect is called stratification of heat. In addition, reversing the air flow will reduce the turbulence in the plenum and storage.

The insulation between the storage chamber and the house could be improved to allow the storage to reach a higher temperature without overheating the house. During April, when there was a long series of sunny days, the house was overheated. The volume of storage that is most appropriate for the climactic region of the house could be studied by consideration of the frequency patterns of cloudy and sunny days relative to the pattern of cold nights for the region.

Heat Distribution

The existing system of convective heating is not adequate because the temperature of the storage was rarely high enough to drive a

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significant heating cycle. It is possible that a stratified storage will be a sufficient improvement by itself; however, it is likely that an additional small fan would be a cost effective improvement. The fan could be automatically controlled by a differential thermostat between the storage and the living space.

The manually operated gates were not an inconvenience to most of the occupants of the house and no significant heat losses resulted when the gates were left open occasionally on partly cloudy days. If, however, the house were occupied by someone who was less diligent or who was absent more often, the losses would be greater. If such a heating system is widely adopted, the use of automated dampers which operate synchronously with the fan is recommended.

The air distribution in the plenum could be improved by baffles and a damper could be used to isolate the storage from the cold basement.

The fan that is used could be replaced in future similar heating systems with a variable speed fan which could circulate air at a rate dependent on the temperature of the collector. This would decrease the front losses of the collector both when the storage is hot and when it is cool.

The electricity consumption pattern was discussed in Section 3.7. The house heating demand maxima do not coincide with the network-wide peak demands on Hydro-Quebec. Occasionally the peak heating demands are coincident with the heating peaks of total electric homes.

The use of appliances by the occupants provides a significant amount of heat to the living space. It was estimated in Section 4.5

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that the average contribution was about 34% of the total heat required to maintain the house at 21°C between October 1, 1976 and March 31, 1977. This percentage is probably higher than other houses because the extra insulation of the house results in a smaller total heat requirement.

Simulation Study

A simple electrical circuit was used successfully as a model for the thermal networks in the house. Agreement was obtained between measured and model-calculated temperatures of collector, storage and house for two four-day periods of different weather and occupant conditions. The calculated solutions were not unique since there were many interactions between components. Different combinations of parameter values were able to give similar results. A sensitivity study was made to see how much the calculated temperatures changed for a change in the value or each parameter. The parameters used for the successful solution were consistent with the calculations of heat loss resistance by the methods of Ashrae, including the effects of wind on the infiltration losses.

The model could be further refined to include such effects as the thermal storage in the collector. The parameters were used in a heat balance calculation in Section 4.5. This calculation was possible only for October, November and December.

Solar Heating System

The heat collected by the solar heating system has been calculated in Section 3.3. The daily and monthly average efficiencies of the

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system have been presented. The solar fraction achieved during the period of October 1, 1976 to March 31, 1977 was estimated to be 50%. It was shown that this period was more adverse for a solar heating system than normal because the degree days were about 3% higher than the ten year average, and the number of hours of bright sunshine was about 12% less than the twelve year average. Everything else being equal, one would expect that the solar fraction for the normal six month period would be about 55%. Based on observations of the house during the other months of the year, it can be assumed that the system could provide 90% of the other 1000 kwhr of heat required for a normal heating season. The annual solar fraction is estimated to be 56%. The collector design is quite good, but the heat output was degraded by faults in the rest of the system.

The potential solar fraction of the system, when the storage is stratified and other improvements are made, is estimated by use of the Relative Area Method[25] design procedure. The Method of Relative Areas is based on the f-chart[6] design procedure which is, in turn, based on the TRNSYS[5] simulation program. TRNSYS can simulate an air heating collector and solar heating system which includes a stratified pebble bed storage. The Method of Relative Areas provides a number of coefficients which correlate its results with the results of the f-chart method for many locations in the U.S.A. and Canada.

The result of measurements of the solar radiation on the vertical collector of the solar house is similar to the solar radiation on a vertical surface for Montreal used by f-chart. However, as shown in Table 4, the heating degree days for Ste. Agathe are 15% larger than for

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Montreal. Consequently, the UA factor of the house is increased by 15% for use in the equation below.

From the table of parameters from Reference 25:

Parameters for Montreal are: A_S = 21.54 m^2 °C hr/MJ

Z = 0.05744 m^2 °C/W

C_1' = .516

C_2 = .268

From Figure 12
Parameters for the collector are: $F_R\tau\alpha$ = 0.51

F_RU_L = 2.6 W/m^2 °C

The adjusted UA factor for the house is:

$$\frac{11000\text{kwhr}}{24\text{ hr/day}} \times 3842 = 115\ \text{W/}^{\circ}\text{C}$$

The area of collector that will provide a solar fraction of 50% is:

$$A_o = (A_s \times UA)/(F_R\tau\alpha - F_RU_LZ) = 24.72\ m^2$$

The collector area of the house A = 42.5 m^2. The annual solar fraction expected for the house is $f = C_1 + C_2 \ln(A/A_o) = 66\%$.

This is an improvement of about 10% over the 56% estimated for the existing system.

The relative area method is based on a collector tilt of latitude + 15°, or 60° from the horizontal, so that the above comparison is as good as the assumption that the vertical collector, with snow foreground, receives as much radiation during the heating season as does the tilted one.

Economics

A study of some of the economics of this particular system, as built, is shown in Appendix F. It seems likely that an improved version of the solar heater, built today, would be cost effective, on a life cycle

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basis, compared to either oil or electric heating. The contrast between the economics of this system and that of most other cold region solar heaters occurs because the site-built collector costs about one half as much as present factory-built collectors, but operates with a comparable efficiency. This type of system, which can be constructed as part of the building with readily available materials and tools, is well suited to owner builders, contractors and the building trades. Compared to heaters with factory-built collectors, the site-built system has the potential for faster market penetration, lower costs to the owner and, therefore, more employment in the near future.

The experience documented in this thesis will also aid future designers to minimize the cost and maximize the output of their solar heating systems. As with any prototype, some mistakes were made, which need not be repeated. The simulation program can be used as a design tool for future projects. The most common mistake made in solar heater designs is the failure to match the components of the system to each other and to the specific weather patterns of the location of the building. With the simulation program and weather data from Environment Canada, the designer can vary parameters in the program, such as the size of the storage or the transmission of the collector glazing or the insulation of the shell of the building to arrive at the most cost effective solution. In particular, the evidence presented here that a site-built vertical collector with a foreground snow reflector can perform as well as a factory-built roof collector should influence builders to choose the less expensive vertical design.

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SUMMARY

The house was a success from the point of view of the occupants. The solar radiation, electricity use and temperatures in the house, collector and storage have been measured during part of the 1976-77 heating season. This site-built collector performed well, with an efficiency similar to that of a prefabricated collector of twice the cost. Daily and monthly heat collected and efficiencies have been calculated during October 1, 1977 to March 31, 1977. The system provided about one half of the house heat requirement that was not met by heat from the appliances in the house. The portion provided during a season of normal weather is estimated to be 56%. The portion provided by a modified system is estimated to be about 66%. Modifications to this system could include: stratification of the storage, more insulation above storage and a small fan for heat distribution from the storage to the house. Additional changes in design for other houses with this type of system could include: installation of the collector screen with a slope to increase heat transfer, windows in the south wall to provide more light, alternate collector glazing to reduce cost, and automatic dampers.

A simple electrical circuit was used successfully as a model for the thermal networks in the house. The heat loss parameters of the model are consistent with the results of calculations based on the heat loss coefficients of the building materials.

The cost of the site-built collector was about $6/sq. ft. The breakeven costs of the system with all oil and all electric heating systems

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have been calculated. The annual cash flow, which is the most significant measure for the owner, shows a net saving after the thirteenth year of operation based on a $0.05/gal/year increase in the cost of oil.

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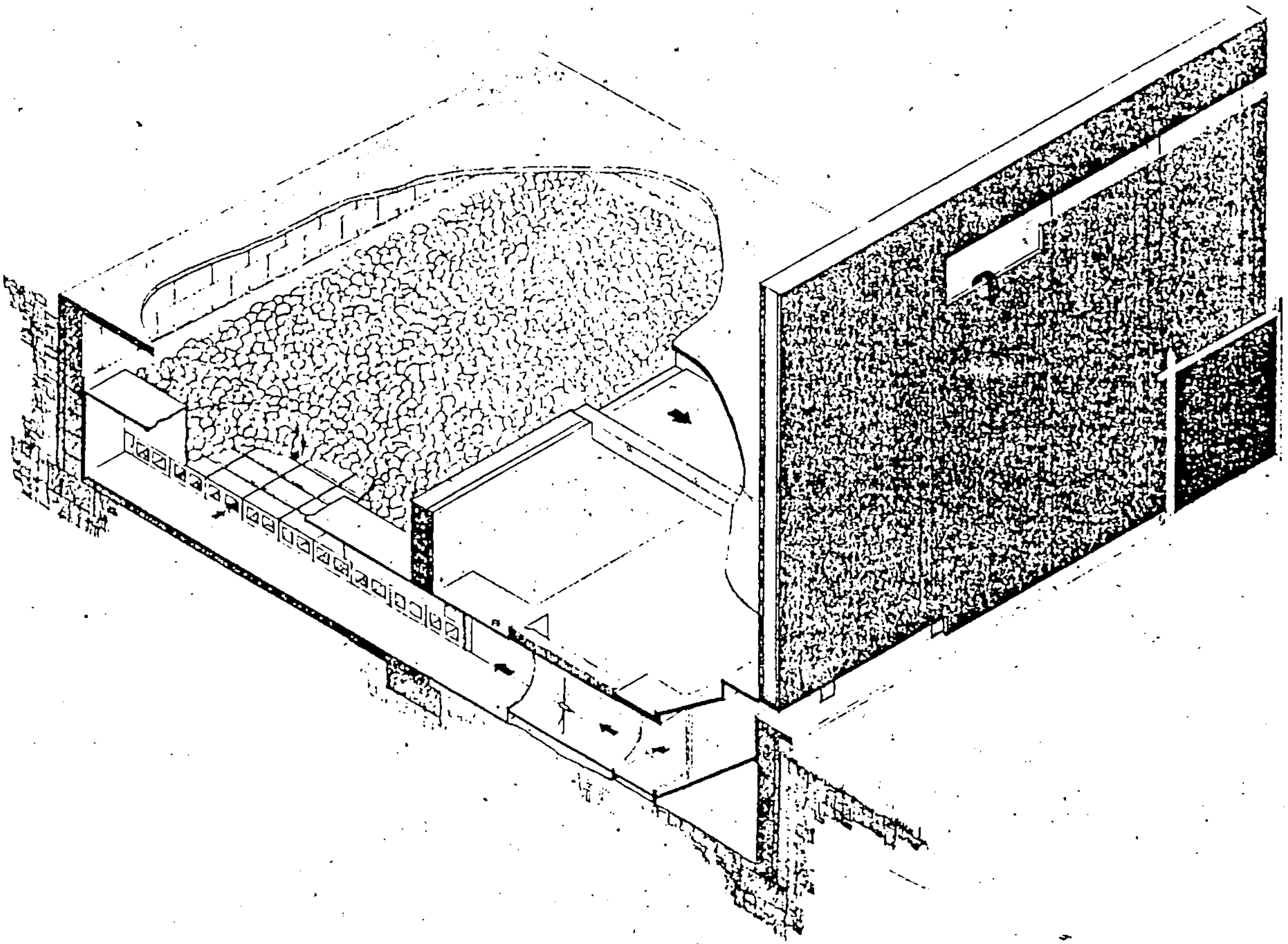
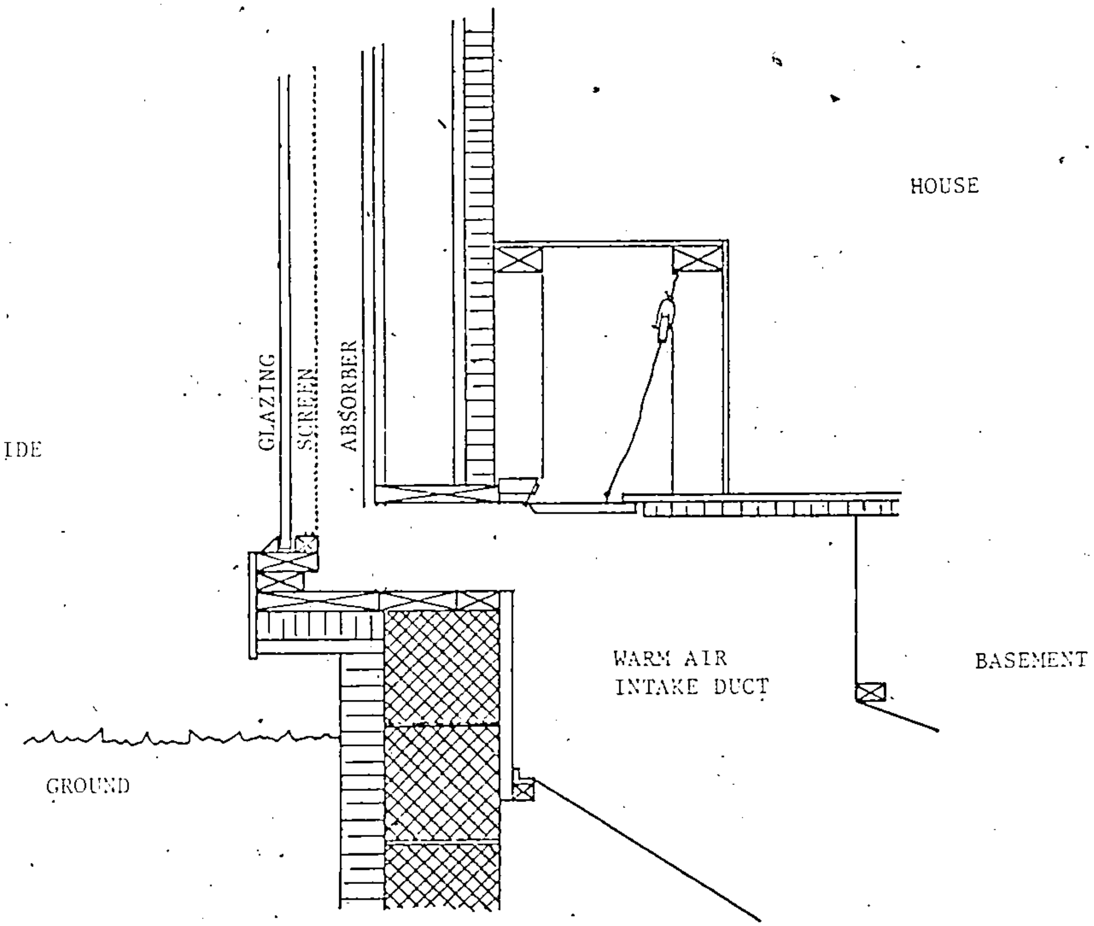
APPENDIX A



SECTION PERSPECTIVE OF THE SOLAR HEATING SYSTEM

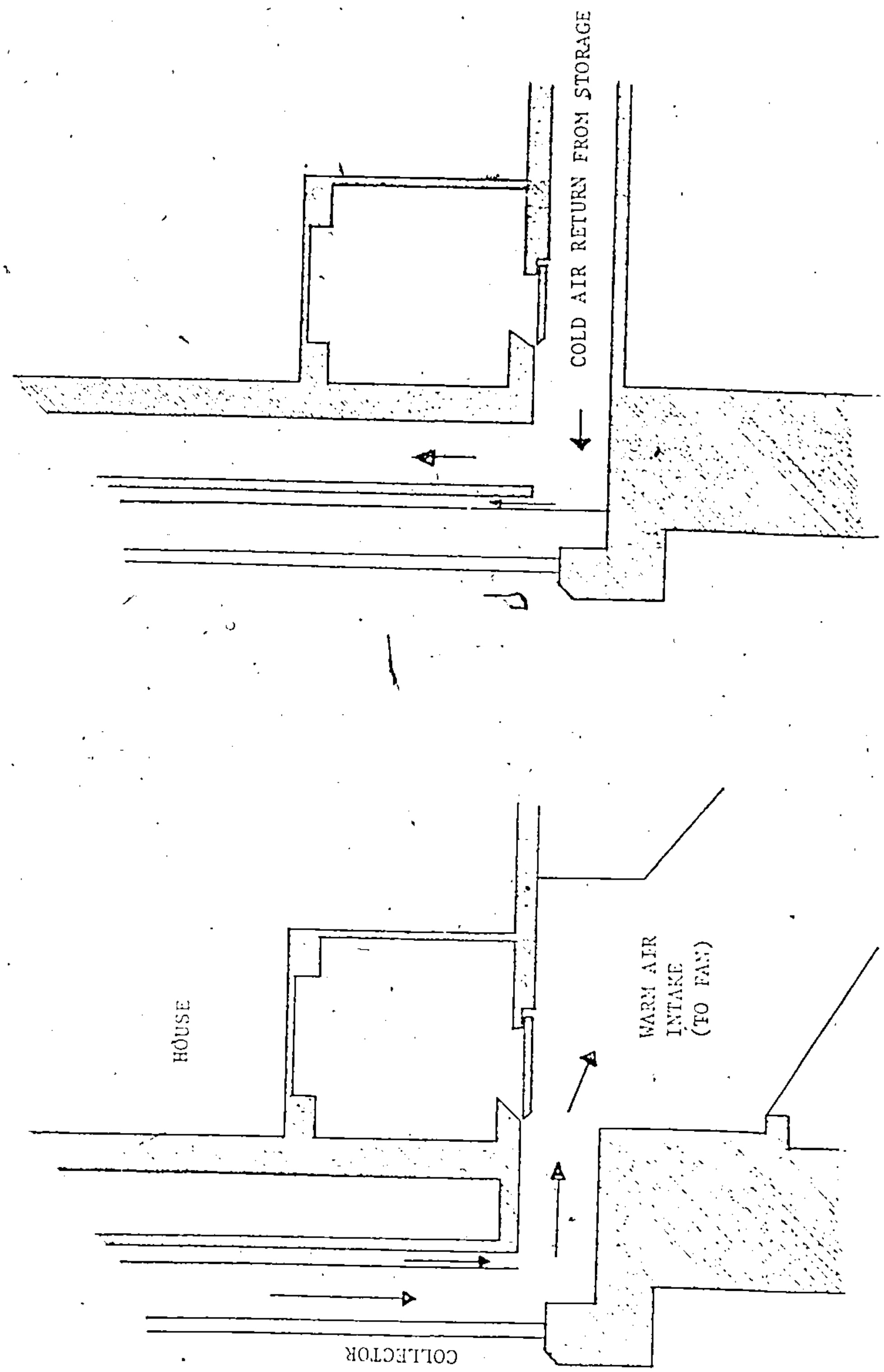
POOR PRINT

POOR PRINT



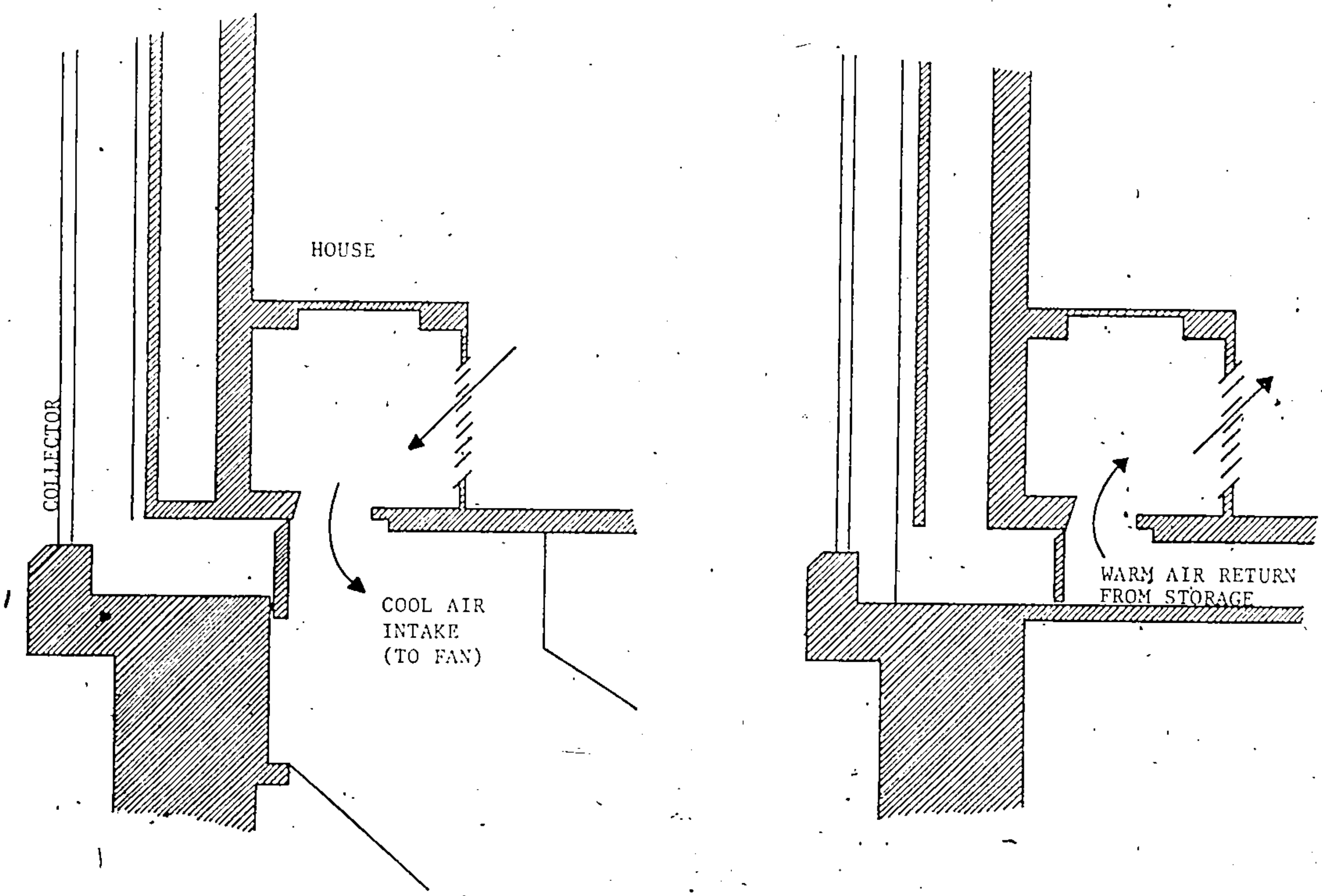
Section at bottom in centre of collector.

POOR PRINT



DAYTIME: HEAT COLLECTION CIRCUIT

POOR PRINT



NIGHTIME: HEAT DISTRIBUTION CIRCUIT

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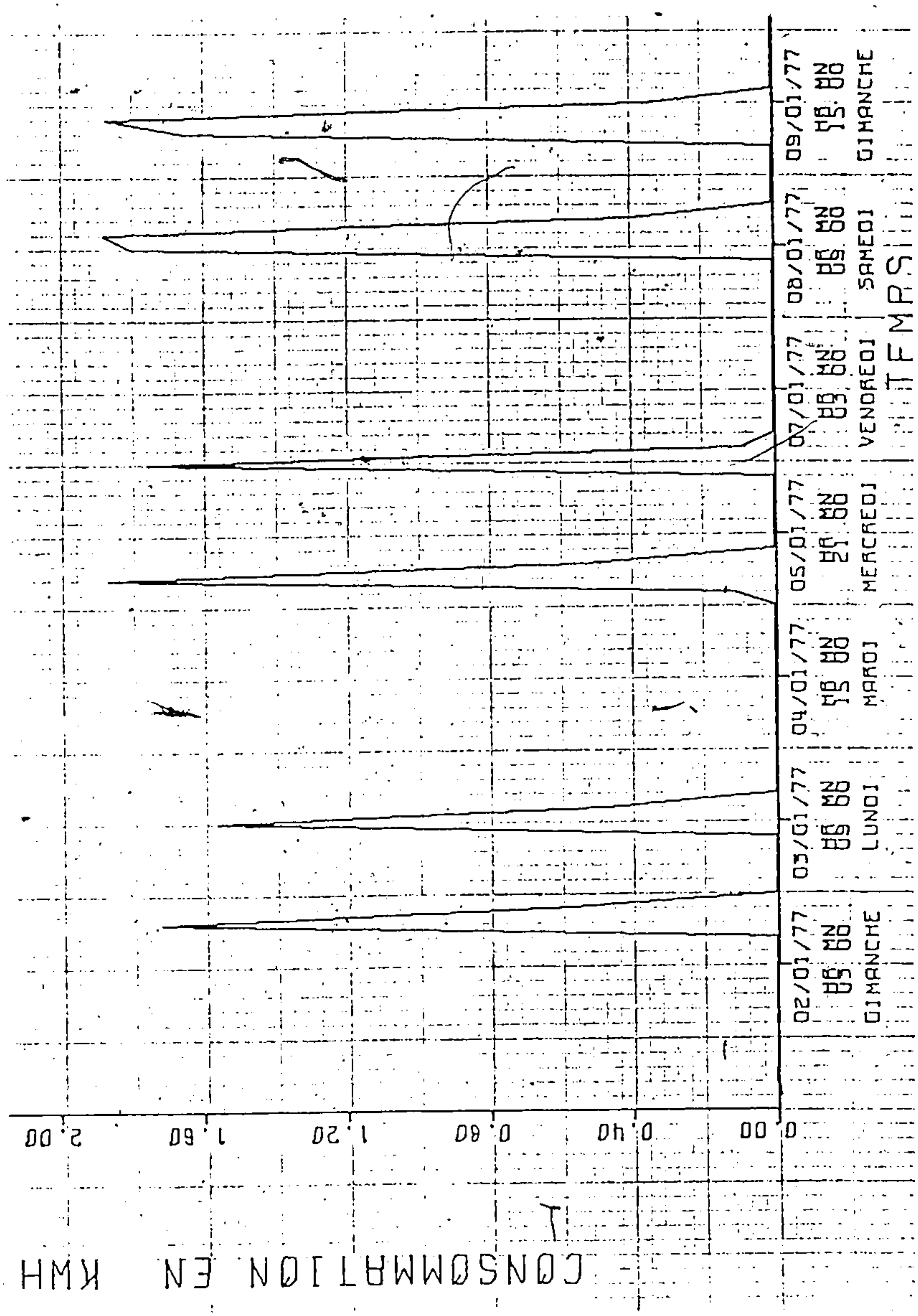
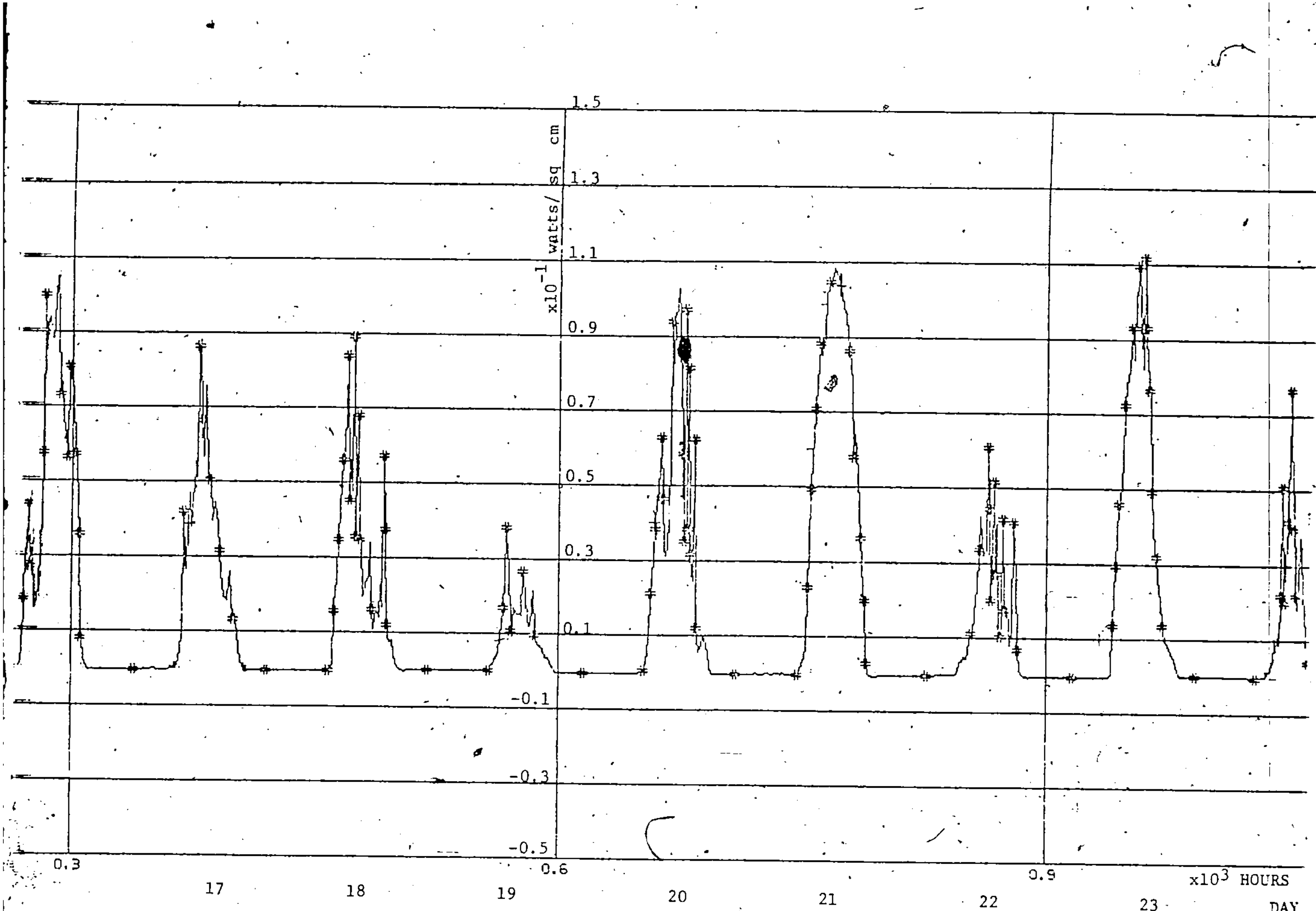
APPENDIX B

POOR PRINT

B1



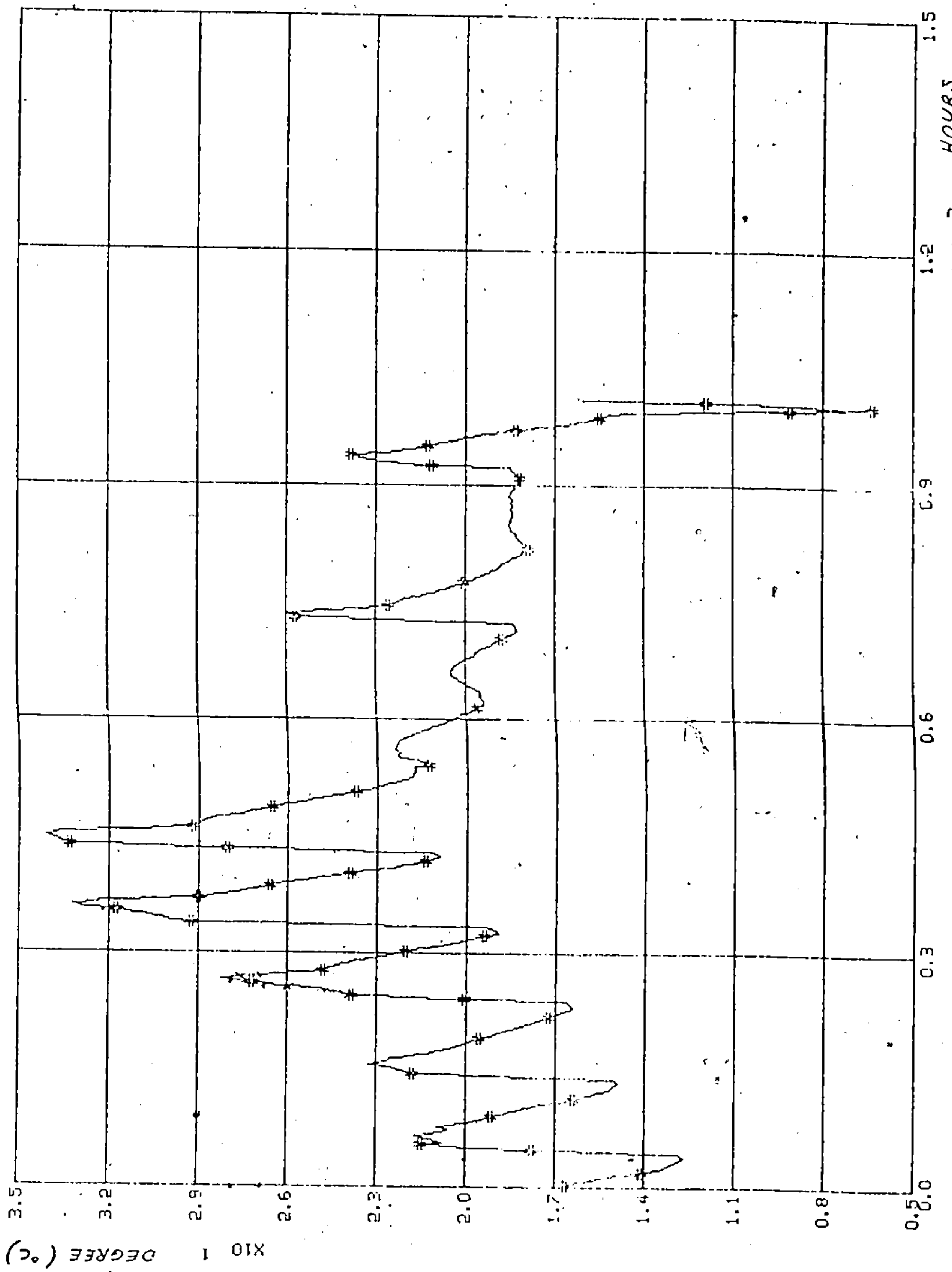
Fan Consumption



FEBRUARY 1977 Vertical Solarimeter each 15 min.

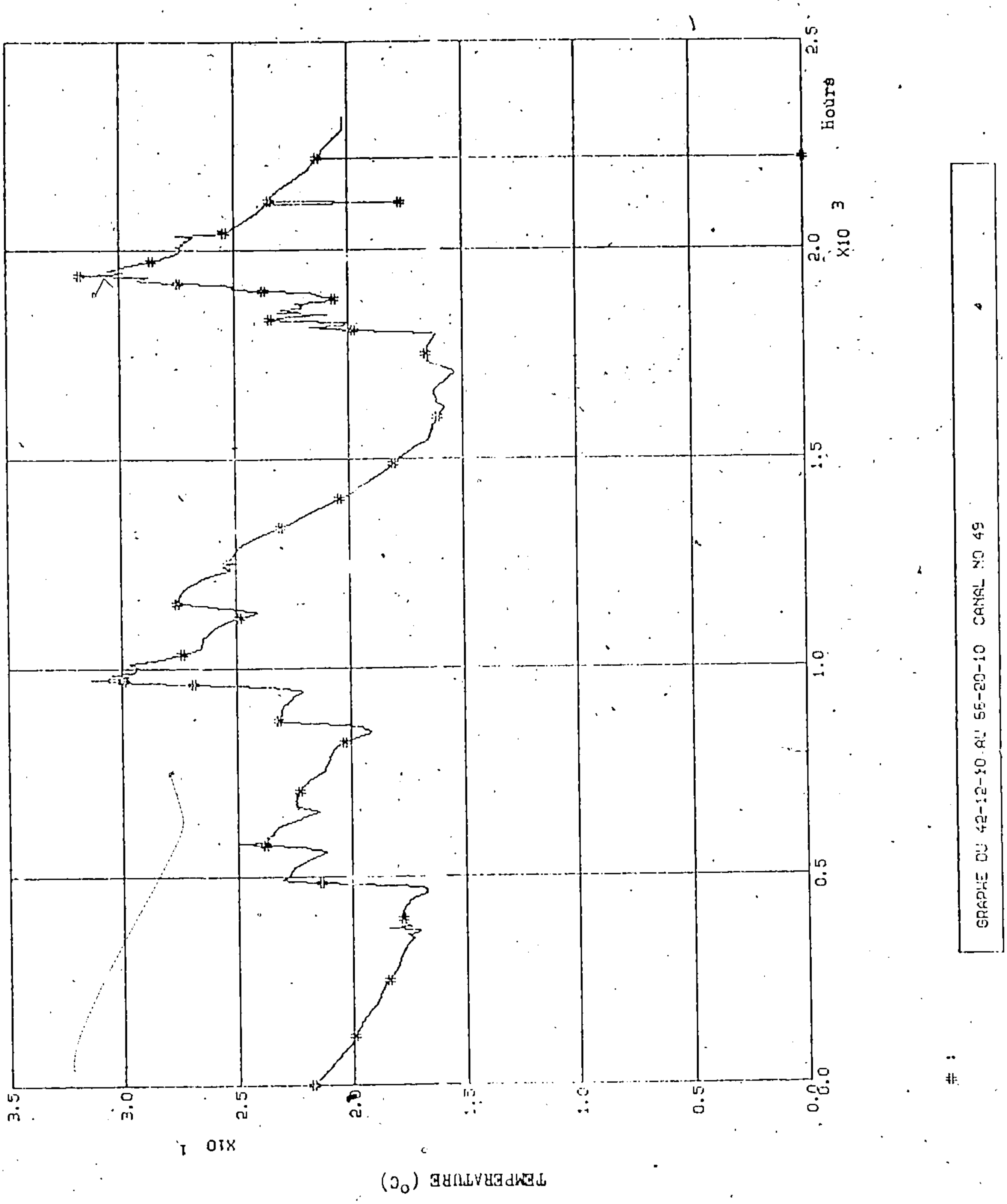
POOR PRINT

B3



du 66/21/10 au 77/9/55 Graphe du canal no 41 avec un intervalle d'une hre.

POOR PRINT



TEMPERATURE (oC)
X10 1
Hours
X10 3
GRAPHE DU 42-12-10 AU 56-20-10 CANAL NO 49

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APPENDIX C

POOR PRINT

APPENDIX C

HEAT LOSS RESISTANCE AND CAPACITANCE CALCULATIONS

(See Figure 17 for Locations of Surfaces)

Surface #	Construction	Resistance (°F-hr-ft²/BTU)	U-Value (BTU/hr-°F-ft²)	UA (BTU/hr-°F)
R3 Storage-basement				
Wall between storage and basement:	Inside air film	.68		
	K&B sheathing	1.33		
	8" concrete block	1.11		
	2" styrene insulation	10.00		
	Outside air film	.68		
	TOTAL	13.80	.073	13.2
A = 36 x 5 sq. ft.				
Ceiling of storage:	Air film	.61		
	Sheathing	1.33		
	1" styrene	5.00		
	Air film	.61		
	TOTAL	7.55	.132	61.8
A = 36 x 13 sq. ft.				75.0

$$R3 = \frac{1}{UA} = 13 \frac{^oF\text{-hr}}{kBTU}$$

Surface #	Construction	Resistance (°F-hr-ft²/BTU)	U-Value (BTU/hr-°F-ft²)	UA (BTU/hr-°F)
R4 Storage-ground				
Storage walls:	Inside air film	.68		
	K&B sheathing	1.33		
	8" concrete block	1.11		
	3" styrene insulation	15.00		
	TOTAL	R = 18.12	.055	15.1
A = (37' + 24') x 4.5 = 274 sq. ft.				

POOR PRINT

Surface	Construction	Resistance (^oF-hr-ft^2/BTU)	U-Value (BTU/hr-^oF-ft^2)	UA (BTU/hr-^oF)
Storage floor:	Under storage is 1" of styrene insulation. The storage floor is 7' below the surface of soil on account of the earth berm. Take a U value from Table 2, Chapter 24, Ref. 13 and modify it to account for insulation.			
A = 36 x 14 sq. ft.			.024	12.3 / 27.4
	R4 = 36.4 ^oF-hr/kBTU			
R5 Storage-bedrooms				
	Still air film	.62		
	1" styrene insulation	5.00		
	3/4" flooring wood	.93		
	vinyl tile	.05		
	Still air film	.62		
A = 36 x 14 sq. ft.	R =	7.22	.14	70.6
	R5 = 14 ^oF-hr/kBTU			
R5X Additional path for heat flow from ducts to living space				
	½" styrene insulation	2.5		
	3/4" wood flooring	.93		
	vinyl tile	.05		
	Still air film	.62		
A = 24 x 14 sq. ft.	R =	4.10	.25	84
	R5X = 12 ^oF-hr/kBTU			

POOR PRINT

Surface	Construction	Resistance (^oF-hr-ft^2/BTU)	U-Value (BTU/hr-^oF-ft^2)	UA (BTU/hr-^oF)
R7 House-ambient resistance is composed of transmission pathways through walls, roofs, windows and doors and infiltration through cracks.				
North Wall:	Outside air film	.17		
	5" wood	6.25		
	4" peat moss panel (tested value 3.7/inch)	14.80		
	3/4" air space	.97		
	3/16" panel finish	.30		
	Inside air film	.68		
	TOTAL	23.17	.043	
East and West Walls - lower part:	Outside air film	.17		
	5" wood	6.25		
	2" styrene	10.00		
	3/4" air	.97		
	Finish panel	.30		
	Inside air film	.68		
	TOTAL	18.37	.054	
East and West Walls - upper part:	Outside air film	.17		
	Sheathing	.90		
	6" fiberglass	20.00		
	Finish panel	.30		
	Inside air film	.68		
	TOTAL	22.05	.045	

POOR PRINT

Surface	Construction	Resistance (°F-hr-ft²/BTU)	U-Value (BTU/hr-°F-ft²)	UA (BTU/hr-°F)
Roof over bedrooms:	Outside air film	.17		
	Built up roofing	.33		
	5/8" plywood deck	.78		
	Air space	.90		
	5" styrofoam	18.00		
	Air space	.97		
	Acoustic tile	1.25		
	Inside air film	.61		
	TOTAL	23.01	.043	
Roof over living space:	Outside air film	.17		
	Deck	.78		
	2" air space	.85		
	4" styrene	20.00		
	3/4" air space	.97		
	Acoustic tile	1.25		
	Inside air film	.61		
	TOTAL	24.63	.041	
Collector Wall:	Outside air film	.17		
	Double glazed sealed unit	1.72		
	4" air space	.97		
	3/4" reflective air space	2.00		
	3/4" sheathing	.80		
	5" air space	.97		
	3/4" sheathing	.80		
	2" styrene	10.00		
	3/4" air space	.97		
	Panel	.30		
	Inside air film	.61		
	TOTAL	19.31	.06	
Windows:	Well-fitting sliding type		.56	
Doors:	Single 2" thick solid wood doors		.49	

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Summary for R7 - Transmission Heat Losses

Surface	Area $(ft)^2$	U $(BTU/hr-^oFt^2)$	UA $(BTU/hr-^oF)$
North wall:	196	.043	8.43
East and West walls -			
lower:	186	.054	10.04
upper:	65	.045	2.90
Roof -			
flat:	574	.043	24.70
sloping:	444	.041	18.20
Collector wall	520	.060	31.20
and windows:	16	.190	3.00
Windows:	95	.560	53.20
Doors	35	.490	17.20
		TOTAL	168.87

$$R7 = \frac{1}{UA} = 5.9\ ^oF\text{-}hr/kBTU$$

Infiltration

The average wind speed for February at Ste. Agathe-des-Monts is 12 km/hr = 7.5 miles/hr. Using Chapter 21, Ref. 13, the infiltration load is calculated. For windows of average fit and weatherstripped, infiltration air is about 6 ft^3/hr-ft of crack. For a door weatherstripped but loose fitting, infiltration is about 40 ft^3/hr-ft of crack for a wind speed of 7.5 miles/hr.

Infiltration - through windows and door:	125 ft x 6 ft^3/hr-ft	750 ft^3/hr
through 1 door:	19 ft x 48 ft^3/hr-ft	760 ft^3/hr
TOTAL		1510 ft^3/hr

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Specific heat of air: .24 BTU/lb°F

Density of air: .081 lb/ft^3

Heat loss = .24 BTU/lb (°F) x .081 lb/ft^3 x 1510 ft^3/hr = 29.3 BTU/hr°F

Adding transmission and infiltration heat losses for a total:

$$168.6 + 29.3 = 198 \text{ BW/hr-}^\circ\text{F}$$

Thus the value of R7 = $\frac{1}{198}$ = 5.0 hr-°F/kBTU

R8 - House-soil berm

The wall construction is similar to case of R7

	U Value	Area $(ft)^2$	UA
North wall:	.043	111	4.77
East and West:	.054	168	9.07
		TOTAL	13.84

R8 = 72.5 °F-hr/kBTU

where area is the wall surface covered by the soil berm.

C1 - Heat capacity of Rock Storage

C1 = R + C R = Volume of rock x specific heat x density x rock fraction

C = Volume of concrete container x specific heat x density

R = 776 x .2 x 140 x .58 = 12.6 kBTU/°F

C = 247 x .15 x 144 = 5.3 kBTU/°F

TOTAL heat capacity C1 = 17.9 kBTU/°F

C2 - Heat Capacity of House

The heat capacity is estimated from the volume of wood in the house. The walls are 5" thick softwood. The volume of the walls is about 250 ft^3. The volume of wood in the interior of the house is about 200 ft^3.

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Total 450 ft^3. Taking the density and specific heat of softwood 32 lb/ft^3 and 0.33 BTU/lb °F from Ref. 13: C2 = 32 lb/ft^3 x .33 BTU/lb °F x 450 ft^3 = 4.75 kBTU/°F.

K2

K2 represents the solar heat gain factor through the windows of the house. K2 x I1 is calculated, where I1 is the radiation incident on the south facing wall. For the south wall, the total radiation for the day is about 1020 BTU on February 21. From Reference 13, Chapter 26, Table 22, an estimate of the solar heat gain on the east and west windows is (733 + 600)/2 = 665 BTU/ft^2. The area of the windows is about 100 ft^2. Therefore total heat gain is 66.5 kBTU. However, all the windows are equipped with roller shades and drapes which were closed most of the time. From Table 34 of Chapter 26 of Reference 13, the roller shades have a shading coefficient of .25. Thus, the expected total heat gain through the east and west windows for February 21 is 66.5 x .25 = 16.6 kBTU. Estimated value of K2 = 16.6/1020 = .016.

POOR PRINT

APPENDIX D

POOR PRINT

PROGRAM SOLHETX

```
00100  REM     ******************************************************
00110  REM     *          TITLE:  SOLAR HEATING HOME SIMULATION
00120  REM     *          AUTHOR: MIT EE DEPT / R KERR
00130  REM     *          DATE  :  JULY 1977 & MARCH 1978 REVISION
00140  REM     *          LANGUAGE  :  BASIC VERSION 3
00150  REM     *          COMPUTER  : CDC 6400
00160  REM     *          FILE NUMBER  :  003
00170  REM     ******************************************************
00240  REM
00250  REM
00260  REM     **********  GET INPUT VALUES  **********
00270  GOSUB 00500
00280  REM     **********  ASSUME INITIAL CONDITIONS  **********
00290  GOSUB 00820
00320  REM     **********  CONVERT RESISTANCES TO CONDUCTANCES  ****
00330  GOSUB 01020
00340  REM     **********  UTILITY ROUTINE  **********
00350  GOSUB 01140
00360  REM     **********  CONTROLLER ROUTINE  **********
00370  GOSUB 01230
00380  REM     **********  SOLVE THE CIRCUIT PROBLEM  **********
00390  GOSUB 01390
00440  REM     **********  OUTPUT ROUTINE  **********
441  IF S1=1 GO TO 450
442  IF H1=L1 GO TO 450
443  GO TO 460
00450  GOSUB 02460
00460  REM     **********  STEP TIME  **********
00470  GOSUB 02520
00480  IF H1<M3 THEN 00350
00490  REM     **********  THIS IS THE END OF THE MAIN PROGRAM  *****
00491  GO TO 03050
```

POOR PRINT


```
00500  REM
00510  REM          **********  GET INPUT VALUES  **********
00530  PRINT "INPUT COLLECTOR R, R1";
00540  INPUT R1
00550  PRINT "INPUT R BETWEEN COLLECTOR AND TANK, R2";
00560   INPUT R2
00570  PRINT "INPUT TANK TO BASEMENT R,R3";
00580  INPUT R3
00590  PRINT "INPUT TANK TO GROUND R,R4";
00600  INPUT R4
00610  PRINT "INPUT TANK TO HOUSE R, R5";
00620  INPUT R5
621  PRINT "R5X MODIFIES R5 WHEN FAN IS ON, INPUT R5X";
622  INPUT E5
00650  PRINT "INPUT HOUSE TO AMBIENT R, R7";
00660  INPUT R7
00670  PRINT "INPUT HOUSE TO GROUND R, R8";
00680  INPUT R8
00690  PRINT "INPUT K FACTOR FOR COLLECTOR, K1";
00700  INPUT K1
00710  PRINT "INPUT K FACTOR FOR HOUSE, K2";
00720  INPUT K2
741  PRINT "INPUT APPLIANCE HEAT GENERATION FACTOR,I7";
742  INPUT I7
00750  PRINT "INPUT GROUND TEMP VOLTAGE, V9";
00760  INPUT V9
761  PRINT "BASEMENT TEMPERATURE, V7";
762  INPUT V7
00770  PRINT "INPUT TANK CAPACITANCE, C1";
00780  INPUT C1
00790  PRINT "INPUT HOUSE CAPACITANCE, C2";
00800  INPUT C2
00810  RETURN
00820  REM
00830  REM      **********  ASSUME INITIAL CONDITIONS  **********
841  PRINT "TIME      IS    V8    I3    I4     S1    V1    V3    V5 "
842  H1=0
843  L1=0
00850  V1=V8 'COLLECTOR TEMP = AMBIENT
00860  H=.25 'TIME INCREMENT = .25 HR
00880 V3=74'INITIAL TANK TEMP=74
00885  FILE #2 ="LARG"
00890  INPUT #2,I1 'GET IST VALUES OF INSOL,
00891  I1=I1*128.3
892  FILE #3 ="LARGT" 'INITIAL AMBIENT TEMP
893  INPUT #3,V8
894  FILE #4 ="LARGA"  'INITIAL APPLIANCE
895  INPUT #4,I5
896  I4=I5*I7*3.41    'CONVERT TO BTU
897   FILE #5="LARGH"  'INITIAL AUXILARY
898  INPUT #5,I6
899  I3=I6*3.41
00910  V5=65 'INITIAL HOUSE TEMP
00990  H1=0 'INITIALIZE TIME
01000  M3=350 'MAX NO OF ITERATIONS
01010 RETURN
```

POOR PRINT

D3

```
01020  REM
01030  REM        **********  CONVERT RESISTANCES TO CONDUCTANCES  *****
01050  G1=1/R1
01060  G2=1/R2
01070  G3=1/R3
01080  G4=1/R4
01090  G5=1/R5
1091  E6=1/E5  'R5 AND R5X IN PARALLEL
1092  G9=G5+E6
01110  G7=1/R7
1111  B7=G7
01120  G8=1/R8
1121  S1=0
1122  S3=1
01130  RETURN
01140  REM
01150  REM        **********  UTILITY FUNCTIONS FOR ALL ROUTINES  ******
1170  J1=V7*G3+V9*G4+V3*C1/H
01180  J2=V8*G7+V9*G8+K2*I1+C2*V5/H
01190  J3=K1*I1+V8*G1
01200  W1=G3+G4+C1/H
01210  W2=G7+G8+C2/H
01220  RETURN
01230  REM
01240  REM        **********  CONTROLLER ROUTINE  **********
1281  IF S1=1 THEN 1315
01290 IF V1>V3+20 THEN 01320  'TURN FAN ON
01300  RETURN
1315  IF V1>V3+3 THEN 1320
1316  S1=0   'TURN FAN OFF
1317  GO TO 1300
01320  S1=1
01330 GO TO 01300
01390  REM
01400  REM        **********  SOLVE THE CIRCUIT PROBLEM  **********
01420  IF S1=1 THEN 01450
1421  GOSUB 01520
1422  RETURN
1450  GOSUB 01780
1451  RETURN
01520  REM
01530  REM        **********. S1 OPEN  **********
01550  I2=I3*S3+I4
01560  D1=(W1+G5)*(G5+W2)-G5*G5
01570 N1=J1*(G5+W2)+G5*(J2+I2)
01580  N2=(W1+G5)*(J2+I2)+J1*G5
01590  V3=N1/D1
01600  V5=N2/D1
01620  V1=V8+K1*I1*R1
01640  RETURN
```

POOR PRINT


```
01780  REM
01790  REM       **********  S1 CLOSED   **********
01800  I2=I3*S3+I4
01810  D1=(G1+G2)*((G2+G9+W1)*(G9+W2)-G9*G9)-G2*G2*(G9+W2)
01820  N1=J3*((G2+G9+W1)*(G9+W2)-G9*G9)+G2*((J1*(G9+W2))+G9*(J2+I2))
01830  N2=(G1+G2)*(J1*(G9+W2)+G9*(J2+I2))+G2*J3*(G9+W2)
01840  N3=(G1+G2)*((G2+G9+W1)*(J2+I2)+J1*G9)+G2*(-G2*(J2+I2)+J3*G9)
01850  V1=N1/D1
01870  V5=N3/D1
01880  V3=N2/D1
01900  RETURN
02460 REM
02470 REM       **********  OUTPUT ROUTINE  **********
2481   B3=(V3-32)/1.8  'CONVERT OF TO OC
2482   B8=(V8-32)/1.8
2483   I1=I1/3.41  'CONVERT RADIATION INTO KILOWATTS
2486   I1 =INT(I1)
2487   B1=(V1-32)/1.8
2489   B5=(V5-32)/1.8
2490   B1=INT(B1)
2493   B5=INT(B5)
2494   B3=INT(B3)
2495   B8=INT(B8)
02504  PRINT H1;TAB(8);I1;TAB(13);B8;TAB(18);I6;I5;TAB(32);S1;TAB(36);
02505  PRINT B1;TAB(42);B3;TAB(48);B5
02510 RETURN
02520 REM
02530 REM       ********** STEP AHEAD IN TIME  **********
02550 H1=H1+H 'GET NEW INSOL,TEMP
02555  INPUT #2,I1 'GET NEW INSOL
2556   I1=I1*128.3
2557   L1=INT(H1)
2558   IF H1=L1 THEN 02561
02560 RETURN
02561  INPUT #3,V8 'GET NEW TEMP
2562   INPUT #4,I5
2563   I4=I5*I7*3.41
2564   INPUT #5,I6 'GET AUXILARY HEAT
2565   I3=I6*3.41
2566   IF H1>34 THEN 2568  'FOR 34<H1<42  MODIFY G7
2567   RETURN
2568   IF H1<42 THEN 2571
2569   G7=B7
2570   RETURN
2571   G7=B7*1.13
2572   RETURN
```

POOR PRINT


```
2573   REM
02580  REM    ********** LIST OF PROGRAM VARIABLES**********
02590  REM    ********** FOR THE CIRCUIT MODEL **********
02600  REM    *    NAME OF VARIABLE              DESCRIPTION
02605  REM    *
02610  REM    *    K1       COLLECTOR COVER TRANSMISSION FACTOR
02620  REM    *    K2         HOUSE SOLAR HEAT GAIN FACTOR
02625  REM    *    I1            SOLAR POWER ON COLLECTOR
2626   REM    *   IS
02628  REM    *    I3        AUXILARY HEAT POWER
02630  REM    *    R1       COLLECTOR COVER HEAT LOSS RESISTANCE
02640  REM    *    R2       COLLECTOR HEAT TRANSFER RESISTANCE
02650  REM    *    R3         STORAGE TANK-BASEMENT RESISTOR
02670  REM    *    R4     TANK-GROUND RESISTOR
02680  REM    *    R5                 TANK-HOUSE RESISTOR
2681   REM   *    R5X         TANK-HOUSE RESISTOR WHEN FAN ON
02700  REM    *    R7     HOUSE-AMBIENT RESISTOR
02710  REM    *    R8                 HOUSE-GROUND RESISTOR
02720  REM    *    V1      AVERAGE COLLECTOR TEMPERATURE
02740  REM    *    V3  AVERAGE STORAGE TEMP
02760  REM    *    V5       HOUSE TEMP
2761   REM    *      V7         UNHEATED BASEMENT TEMP
02780  REM    *    V8     AMBIENT TEMP
02790  REM    *    V9     GROUND TEMP
03000  REM    *    C1     STORAGE CAPACITANCE
03010  REM    *    C2      HOUSE CAPACITANCE
03020  REM    *****************************************
03040  REM
03050  END
```

POOR PRINT

APPENDIX E

POOR PRINT

```
basic
OLD, NEW, OR LIB FILE: old
FILE NAME: solhetx

READY.
set,larg,largt,larga,largh

READY.
run

 78/03/27. 10.49.26.
PROGRAM   SOLHETX

INPUT COLLECTOR R, R1 ? 2
INPUT R BETWEEN COLLECTOR AND TANK, R2? .6
INPUT TANK TO BASEMENT R,R3 ? 21
INPUT TANK TO GROUND R,R4 ? 36.4
INPUT TANK TO HOUSE R, R5 ? 4
R5X MODIFIES R5 WHEN FAN IS ON, INPUT R5X ? 10
INPUT HOUSE TO AMBIENT R, R7? 5.4
INPUT HOUSE TO GROUND R, R8 ? 72,5
 TOO MUCH DATA, RETYPE INPUT  AT  680
? 72.5
INPUT K FACTOR FOR COLLECTOR, K1? .8
INPUT K FACTOR FOR HOUSE, K2? .01
INPUT APPLIANCE HEAT GENERATION FACTOR,I7 ? .8
INPUT GROUND TEMP VOLTAGE, V9 ? 41
BASEMENT TEMPERATURE, V7? 48
INPUT TANK CAPACITANCE, C1? 20
INPUT HOUSE CAPACITANCE, C2 ? 6
```

POOR PRINT

E2

TIME	IS	V8	I3	I4	S1	V1	V3	V5
0	0	-26	2.2	1.5	0	-26	23	18
1	0	-27	2.2	1.5	0	-27	23	18
2	0	-27	2.2	1.5	0	-27	23	18
3	0	-28	2.2	1.5	0	-28	22	17
4	0	-29	2.2	1.5	0	-29	22	17
5	0	-30	2.2	1.5	0	-30	22	17
6	0	-30	1.9	1.9	0	-30	22	17
7	0	-30	1.9	1.9	0	-30	22	17
8	14	-27	1.9	1.9	0	18	22	17
8.75	23	-27	1.9	1.9	1	27	22	17
9	25	-21	1.9	1.9	1	30	22	17
9.25	29	-21	1.9	1.9	1	32	22	17
9.5	35	-21	1.9	1.9	1	37	22	17
9.75	19	-21	1.9	1.9	1	26	22	17
10	23	-15	.85	2.6	1	31	23	17
10.25	20	-15	.85	2.6	1	28	23	17
10.5	38	-15	.85	2.6	1	41	23	17
10.75	15	-15	.85	2.6	1	25	23	17
11	28	-8	.25	2.6	1	36	23	17
11.25	14	-8	.25	2.6	1	26	23	17
11.5	14	-8	.25	2.6	1	26	23	17
11.75	8	-8	.25	2.6	1	22	23	18
12	8	-8	.15	2.6	0	18	23	18
13	14	-7	.4	2.6	0	37	23	18
13.25	6	-7	.4	2.6	1	21	23	18
14	6	-7	1.1	1.5	0	13	23	18
15	24	-6	.6	1.4	0	68	23	18
15.25	16	-6	.6	1.4	1	27	23	18
15.5	5	-6	.6	1.4	1	20	23	18
16	3	-6	1	2.2	0	4	23	18
17	0	-7	1.2	2.2	0	-4	23	18
18	0	-7	1.2	2.3	0	-7	22	19
19	0	-7	.9	2.3	0	-7	22	19
20	0	-8	.6	1.6	0	-8	22	19
21	0	-8	.6	1.6	0	-8	22	19
22	0	-8	.6	1.7	0	-8	22	19
23	0	-8	1.2	1.6	0	-8	22	19
24	0	-8	1.6	1.6	0	-8	22	19
25	0	-8	1.5	1.7	0	-8	22	19
26	0	-8	1.7	1.6	0	-8	22	19
27	0	-8	1.7	1.7	0	-8	22	19
28	0	-7	1.7	1.6	0	-7	21	20
29	0	-7	1.8	1.6	0	-7	21	20
30	0	-8	1.8	1.6	0	-8	21	20
31	0	-8	1.7	1.6	0	-8	21	20
32	0	-7	1.7	1	0	-5	21	20
33	4	-5	1.7	1	0	7	21	20
34	16	-2	1.1	1	0	48	21	20
34.25	12	-2	1.1	1	1	25	21	20
34.5	12	-2	1.1	1	1	25	21	20
34.75	4	-2	1.1	1	1	19	21	20
35	5	-2	1	1	0	16	21	20

POOR PRINT

E3

36	6	0	1	3.4	0	20	21	20
36.75	11	0	1	3.4	1	24	21	20
37	8	0	.9	3.4	1	22	21	20
38	7	-1	.3	3.4	0	21	21	21
39	2	-3	.1	3.4	0	6	21	21
40	1	-4	.3	2.1	0	1	21	21
41	0	-5	.6	2.1	0	-3	21	21
42	0	-10	.6	2.1	0	-10	21	20
43	0	-13	.7	2.1	0	-13	21	20
44	0	-16	1.4	2.6	0	-16	21	20
45	0	-18	1.5	2.6	0	-18	21	20
46	0	-20	1	2.6	0	-20	21	20
47	0	-21	.8	2.6	0	-21	20	20
48	0	-22	1.6	1.9	0	-22	20	19
49	0	-23	2	1.9	0	-23	20	19
50	0	-24	1.7	1.9	0	-24	20	19
51	0	-25	2.4	1.9	0	-25	20	19
52	0	-26	2.1	2	0	-26	20	19
53	0	-26	2.3	1.7	0	-26	20	18
54	0	-27	2.5	2	0	-27	20	18
55	0	-26	2.2	2.8	0	-26	20	18
56	4	-23	2.5	2.2	0	-10	20	18
57	16	-17	1.6	2	0	33	20	18
57.25	20	-17	1.6	2	1	25	20	18
57.5	19	-17	1.6	2	1	25	20	18
57.75	26	-17	1.6	2	1	30	20	18
58	19	-11	1.7	2.6	1	27	20	18
58.25	14	-11	1.7	2.6	1	23	20	19
58.5	13	-11	1.7	2.6	1	22	20	19
58.75	14	-11	1.7	2.6	1	23	20	19
59	17	-4	1.2	1.8	1	27	21	19
59.25	25	-4	1.2	1.8	1	33	21	19
59.5	40	-4	1.2	1.8	1	43	21	19
59.75	35	-4	1.2	1.8	1	40	22	19
60	40	-2	1	3	1	45	22	19
60.25	41	-2	1	3	1	46	22	19
60.5	43	-2	1	3	1	48	23	20
60.75	40	-2	1	3	1	46	23	20
61	24	-2	.9	1.9	1	35	24	20
61.25	15	-2	.9	1.9	1	28	24	20
61.5	41	-2	.9	1.9	1	47	24	20
61.75	16	-2	.9	1.9	1	30	24	20
62	34	-2	0	1.9	1	43	25	20
62.25	13	-2	0	1.9	1	28	25	20
62.5	11	-2	0	1.9	1	26	25	20
62.75	10	-2	0	1.9	1	26	25	20
63	26	-2	0	1.2	0	78	25	20
63.25	5	-2	0	1.2	1	22	24	20
64	3	-4	.1	2.4	0	7	24	20
65	2	-6	.4	4	0	1	24	20
66	0	-9	.9	4	0	-9	24	21
67	0	-11	.5	4	0	-11	24	21
68	0	-11	.3	1.4	0	-11	24	21

POOR PRINT

69	0	-11	.1	2.2	0	-11	24	21
70	0	-14	.5	4	0	-14	24	21
71	0	-16	1.6	1.2	0	-16	24	21
72	0	-14	1	1.9	0	-14	23	20
73	0	-13	1	1.3	0	-13	23	20
74	0	-11	1.5	1.5	0	-11	23	20
75	0	-11	1.3	1.8	0	-11	23	20
76	0	-11	2	1.9	0	-11	23	20
77	0	-13	1.7	1.6	0	-13	23	20
78	0	-16	1.9	1.9	0	-16	23	20
79	0	-17	2.1	2.3	0	-17	23	20
80	3	-17	1.5	3	0	-7	23	20
81	24	-12	1.1	3.7	1	32	23	21
81.25	26	-12	1.1	3.7	1	34	23	21
81.5	30	-12	1.1	3.7	1	36	23	21
81.75	33	-12	1.1	3.7	1	38	24	21
82	35	-11	.6	2.4	1	40	24	21
82.25	37	-11	.6	2.4	1	42	24	21
82.5	36	-11	.6	2.4	1	42	25	21
82.75	38	-11	.6	2.4	1	44	25	21
83	43	-9	0	2.5	1	48	25	21
83.25	44	-9	0	2.5	1	48	26	21
83.5	44	-9	0	2.5	1	49	26	21
83.75	45	-9	0	2.5	1	50	27	21
84	45	-10	0	.6	1	50	27	21
84.25	46	-10	0	.6	1	51	28	21
84.5	45	-10	0	.6	1	51	28	21
84.75	45	-10	0	.6	1	51	28	21
85	44	-9	0	2.2	1	51	29	21
85.25	44	-9	0	2.2	1	51	29	21
85.5	43	-9	0	2.2	1	51	30	21
85.75	41	-9	0	2.2	1	50	30	21
86	40	-8	0	1.7	1	50	30	21
86.25	39	-8	0	1.7	1	49	31	21
86.5	36	-8	0	1.7	1	48	31	21
86.75	35	-8	0	1.7	1	47	31	21
87	33	-10	0	2.2	1	45	31	[illegible]
87.25	24	-10	0	2.2	1	39	31	[illegible]
87.5	27	-10	0	2.2	1	41	32	21
87.75	25	-10	0	2.2	1	40	32	21
88	22	-10	0	2.2	1	38	32	22
88.25	19	-10	0	2.2	1	35	32	22
88.5	15	-10	0	2.2	1	33	32	22
89	8	-9	0	2.9	0	17	32	22
90	0	-12	0	1.4	0	-12	31	22
91	0	-17	0	2.1	0	-17	31	21
92	0	-19	0	1.6	0	-19	31	21
93	0	-21	0	1.8	0	-21	31	21
94	0	-23	0	2.5	0	-23	31	20
95	0	-24	.4	1.4	0	-24	30	20
96	0	-25	.5	1.4	0	-25	30	19
97	0	-26	.7	1.7	0	-26	30	19
98	0	-25	1.3	1.8	0	-25	30	19

POOR PRINT

APPENDIX F

POOR PRINT

APPENDIX F

ECONOMICS OF THE LA MACAZA SOLAR HEATING SYSTEM

The construction costs of the solar heating system, the breakeven costs of the system with electric heat and oil heat, and annual cash flows are presented in this Appendix.

TABLE 1

COSTS IN 1975 DOLLARS (INCLUDES 12% + 8% SALES TAXES)

Components	Material	Labour	Total
Collector			
Wood frame	95	260	355
Sheet metal absorber	60	25	85
Screen absorber	180	100	280
Double glazed sealed units	1720	325	2045
Paint	75	150	225
Total Collector:			2990
Storage			
Extra insulation	165	75	240
Concrete blocks for channels	185	110	295
Rocks	300	120	420
Plenum duct	90	70	160
Total Storage:			1115
Distribution			
Fan and controls	720	35	755
Ducts	110	220	330
Dampers and grills	175	290	465
TOTAL	3875	1780	5655

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The cost of the site-built collector is about \$3,000, or about \$6/sq. ft., which is about one half the price of an equivalent performance collector purchased from a manufacturer, transported and installed in 1975.*

In order to find the net cost of the solar heating system, we must subtract the cost of the exterior wall which was replaced by the collector.

Assume:	Cladding of cedar 1" x 8"	\$20.50/sq. m.[1]
	Sheathing of ½" plywood	3.80
	Additional equivalent insulation of glass fibre 1"	7.10
		\$31.40/sq. m.
	TOTAL WALL COST	= \$1,570.00

Net additional cost of solar heating system 5655 - 1570 = \$4085. Note that the capacity of the auxiliary heating system is not changed. Suppose that the solar heating system were financed by a mortgage at the May, 1975 rate of 10% for a period of 25 years for 90% of the cost, i.e., .9 x 4085 = \$3676 is financed.

The annual mortgage payment is equal to $\frac{\$3676}{P/A,\ 10\%,\ 25} = \$400$.

Consider the <u>Breakeven Cost</u> of the partially solar heated system with electricity.

Let X be the cost of electricity (\$/kwhr)

Let f be the fraction of heat supplied by the solar heating system

Let H be the heat load of the house (kwhr)

Then the annual cost with solar is:

---

* "Solaron" collector costs a customer \$15-\$20/sq. ft. in 1977.

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\$400 for mortgage + (1 - f)HX for auxiliary heating

+ 300 kwhr x X\$/kwhr for the electric consumption of fan

+ \$30 for maintenance of the fan and replacement of filters

$= \$430 + X\,[300 + (1-f)H]$

Annual cost for all-electric heating is HX

The breakeven cost of electricity is the value of X which makes the above annual costs equal. Thus:

$$HX = \$430 + X\,[300 + (1-f)H]$$

$$X = \frac{\$430}{(fH-300)\text{kwhr}}$$

In Section 3.3, we found that the solar heating system supplied 50% of the 11000 kwhr heat requirement of the house for the six month period of October 1976 - March 1977. Assuming that 90% of the 1000 kwhrs of heat required during the other months of the year can be supplied by the solar heater, the annual solar fraction is 55%. If f = .55 and H = 12000kwhr by substitution in the above equation, the breakeven cost of electricity is 0.068 dollars per kilowatthour.

If the changes suggested in Chapter 5 were made for a cost of about \$500, the performance of the system could be improved to give about 70% of the heat requirements. The mortgage would be about \$420 and the breakeven cost would be $\frac{450}{(.7 \times 12000-300)}$ = 0.055 dollars per kilowatthour.

The 1976 cost of electricity in Montreal was \$0.038/kwhr for the first 200 kwhr; \$0.017/kwhr for the next 400 kwhr, and \$0.155 for the remaining consumption.

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The case of oil heating

A heating value of 140,000 BTU/U.S. gal., with combustion efficiency of 60%, gives 84,000 BTU/gallon. Of this, 50% is wasted by increased infiltration (2), which leaves 42000 BTU/gallon useful, or $42000 \times 1.055 \text{ kw/BTU} \times \frac{1}{3600 \text{ sec/hr}} = 12$ kwhr/gal., or 14.4 kwhr/gal (Can).

The cost of home heating oil in Montreal is now more than $.50/gal. and will likely rise to $.75/gal. in five years. In such a case, $\frac{\$.75}{14.4} = .052$ $/kwhr. If the solar heating system provided 70% of the heat required by the Macaza house, the breakeven cost was 0.055 $/kwhr. The system would compare favourably with 100% oil heating.

Table 2 shows cash flows for the case of 60% solar and 40% oil heating, and a demand of 12000 kwhr/yr. The solar heating system begins to have less annual cost than the all-oil system after the sixth year. After the thirteenth year, there is a positive return on the investment in that savings make up for the extra cash outflows of the first six years.

TABLE 2

ANNUAL CASH FLOWS FOR HEATING

Solar and Oil Auxiliary

Year		(1) Mortgage	(2) Heating Cost 60% solar and 40% oil	(3) Fan Cost	(4) =(1)+(2)+(3) Total Cost	(5) Conventional Heating cost 100% oil	(5)-(4) Incremental Cash flow
1975	1	420	168	5.5	594	420	-174
1976	2	420	188	6.0	615	470	-145
1977	3	420	208	6.5	635	520	-115

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TABLE 2 (Cont'd)

Year		(1) Mortgage	(2) Heating Cost 60% solar and 40% oil	(3) Fan Cost	(4) =(1)+(2)+(3) Total Cost	(5) Conventional Heating cost 100% oil	(5)-(4) Incremental Cash flow
1978	4	420	228	7.0	656	570	-86
1979	5	420	248	8.0	677	620	-57
1980	6	420	288	9.0	698	670	-28
1981	7	420	308	10.0	719	720	+ 1
1982	8	420	328	10.5	739	770	+31

Assumptions:

(1) Cost of oil in La Macaza in October 1975 was .50/gal (Can)

(2) Cost of oil increases at $.05/gal/yr.

(3) Heating demand is 12000 kwhr/yr.

(4) f of solar system 60%.

(5) Electricity for fan costs doubles in price each 8 years.

In conclusion, the economics of the existing La Macaza solar heating system are suitable for an owner/investor who is prepared to wait more than ten years for a return on his investment, based on the Assumptions of Table 2. An improved version could be much more cost effective. Other economic factors such as taxes, resale value, interest rates, security of energy supply and inflation will all affect the investment situation. However, these considerations are beyond the scope of this work. There is a computer program which takes account of such factors.

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Table 3 shows a sample economic analysis which is performed by the f-chart interactive program (3) for a different solar heating system whose thermal analysis is also given in Table 3.

Table 4 shows the system and economic parameters that were specified to the program. It is worth noting that this particular system includes part of the hot water heating load, which is a year round load and thus improves the economic picture.

The f-chart program calculates present worth of costs with and without the solar heating system and can immediately show the owner/investor how he stands. It also includes parameters for property and income taxes.

References

1. "Yardsticks for Costing", 1977, published by the Canadian Architect.

2. McGrue, Jay, "Heat Loss and Found", Applied Science and Engineering, Littleton, Colorado.

3. Beckman, W.A., "f-chart Interactive Program", University of Wisconsin-Madison.

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TABLE 3
THERMAL AND ECONOMIC ANALYSIS OF A SOLAR HEATING SYSTEM BY
f-CHART PROGRAM

OTTAWA OT 45.27

****THERMAL ANALYSIS****

TIME	PERCENT SOLAR	INCIDENT SOLAR (MMBTU)	HEATING LOAD (MMBTU)	WATER LOAD (MMBTU)	DEGREE DAYS (F-DAY)	AMBIENT TEMP (F)
JAN	24.2	32.99	46.46	0.58	1624.	14.
FEB	32.2	37.31	41.22	0.53	1441.	14.
MAR	46.1	46.10	35.14	0.58	1231.	27.
APR	64.0	40.72	20.09	0.56	708.	41.
MAY	99.7	40.31	9.51	0.58	341.	54.
JUN	100.0	37.76	2.29	0.56	90.	61.
JUL	100.0	39.72	0.41	0.58	25.	63.
AUG	100.0	40.01	2.02	0.58	81.	61.
SEP	100.0	37.78	6.09	0.56	222.	57.
OCT	61.8	32.19	16.02	0.58	567.	46.
NOV	24.4	21.96	26.66	0.56	936.	32.
DEC	18.8	25.43	42.00	0.58	1469.	18.
YR	40.3	432.27	247.92	6.86	8735.	

****ECONOMIC ANALYSIS****

SPECIFIED COLLECTOR AREA = 840. FT2
INITIAL COST OF SOLAR SYSTEM = $ 7905.
THE ANNUAL MORTGAGE PAYMENT FOR 20 YEARS = $ 725.

YR	INTRST PAID	END OF YR PRINC	DEPRC DEDUCT	PROP TAX PAID	INC TAX SAVED	BACKUP FUEL COST	INSUR, MAINT COST	COST WITH SOLAR	SAVNGS WITH SOLAR	PW OF SOLAR SAVNGS
1	569	6959	0	158	0	963	79	2715	-1102	-1090
2	556	6791	0	167	0	1059	83	2035	-261	-241
3	543	6609	0	177	0	1165	88	2156	-205	-182
4	528	6413	0	188	0	1282	94	2289	-142	-121
5	513	6202	0	199	0	1410	99	2434	-73	-60
6	496	5973	0	211	0	1551	105	2593	3.	3
7	477	5727	0	224	0	1706	112	2767	89	68
8	458	5460	0	237	0	1877	118	2958	184	134
9	436	5173	0	251	0	2064	125	3167	289	203
10	413	4862	0	267	0	2271	133	3396	406	274
11	388	4526	0	283	0	2498	141	3647	535	347
12	362	4164	0	300	0	2748	150	3923	678	423
13	333	3772	0	318	0	3023	159	4225	836	502
14	301	3349	0	337	0	3325	168	4555	1011	584
15	267	2893	0	357	0	3658	178	4918	1205	669
16	231	2400	0	378	0	4023	189	5316	1419	758
17	192	1867	0	401	0	4426	200	5753	1657	850
18	149	1292	0	425	0	4869	212	6232	1919	947
19	103	670	0	451	0	5355	225	6757	2209	1048
20	53	0	0	478	0	5891	239	7333	2529	1154

THE DISCOUNTED PAYBACK PERIOD IS(YR) 13.
YRS UNTIL CUMULATIVE SAVINGS=MORTGAGE PRINCIPLE 15.
PRESENT WORTH OF YEARLY TOTAL COSTS WITH SOLAR = $ 49376.
PRESENT WORTH OF YEARLY TOTAL COSTS W/O SOLAR = $ 55648.
PRESENT WORTH OF CUMULATIVE SOLAR SAVINGS = $ 6273.

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TABLE 4

VARIABLES FOR f-CHART THERMAL AND ECONOMIC ANALYSIS OF A SOLAR HEATING SYSTEM

CODE	VARIABLE DESCRIPTION	VALUE	UNITS
1	AIR SYSTEM=1,LIQUID SYSTEM=2.................	1.00	
2	COLLECTOR AREA..............................	840.00	FT2
3	FRPRIME-TAU-ALPHA PRODUCT(NORMAL INCIDENCE)..	0.50	
4	FRPRIME-UL PRODUCT..........................	0.80	BTU/H-F-F2
5	NUMBER OF TRANSPARENT COVERS................	1.00	
6	COLLECTOR SLOPE.............................	60.00	DEGREES
7	AZIMUTH ANGLE (E.G. SOUTH=0, WEST=90)........	0.00	DEGREES
8	STORAGE CAPACITY............................	60.00	BTU/F-FT2
9	EFFECTIVE BUILDING UA.......................	1200.00	BTU/HR-F
10	CONSTANT DAILY BLDG HEAT GENERATION..........	10000.00	BTU/DAY
11	(EPSILON)(CMIN)/(EFFECTIVE BUILDING UA)......	2.00	
12	HOT WATER USAGE.............................	30.00	GAL/DAY
13	WATER SET TEMPERATURE.......................	120.00	F
14	WATER MAIN TEMPERATURE......................	45.00	F
15	CITY CALL NUMBER............................	168.00	
16	THERMAL PRINT OUT BY MONTH=1, BY YEAR=2......	1.00	
17	ECONOMIC ANALYSIS (YES=1, NO=2..............	1.00	
18	USE OPTMZD. COLLECTOR AREA=1, SPECFD. AREA=2.	2.00	
19	SOLAR SYSTEM THERMAL PERFORMANCE DEGRADATION.	0.0	_/YR
20	PERIOD OF THE ECONOMIC ANALYSIS..............	20.00	YEARS
21	COLLECTOR AREA DEPENDENT SYSTEM COSTS........	6.00	$/FT2 COLL
22	CONSTANT SOLAR COSTS........................	2865.00	$
23	DOWN PAYMENT(_ OF ORIGINAL INVESTMENT).......	10.00	_
24	ANNUAL INTEREST RATE ON MORTGAGE............	9.00	_
25	TERM OF MORTGAGE............................	20.00	YEARS
26	ANNUAL NOMINAL(MARKET) DISCOUNT RATE.........	4.00	_
27	EXTRA INSUR.,MAINT. IN YEAR 1(_ OF ORIG.INV.)	1.00	_
28	ANNUAL _ INCREASE IN ABOVE EXPENSES..........	6.00	_
29	PRESENT COST OF SOLAR BACKUP FUEL (BF).......	6.33	$/MMBTU
30	BF RISE' _/YR=1,SEQUENCE OF VALUES=2.........	1.00	
31	IF 1, WHAT IS THE ANNUAL RATE OF BF RISE.....	10.00	_
32	PRESENT COST OF CONVENTIONAL FUEL (CF).......	6.33	$/MMBTU
33	CF RISE' _/YR=1,SEQUENCE OF VALUES=2.........	1.00	
34	IF 1, WHAT IS THE ANNUAL RATE OF CF RISE.....	10.00	_
35	ECONOMIC PRINT OUT BY YEAR=1, CUMULATIVE=2...	1.00	
36	EFFECTIVE FEDERAL-STATE INCOME TAX RATE......	0.0	_
37	TRUE PROP. TAX RATE PER $ OF ORIGINAL INVEST.	2.00	_
38	ANNUAL _ INCREASE IN PROPERTY TAX RATE.......	6.00	_
39	CALC.RT. OF RETURN ON SOLAR INVTMT(YES=1,NO=2	2.00	
40	SALVAGE VALUE (_ OF ORIGINAL INVESTMENT).....	0.0	_
41	INCOME PRODUCING BUILDING(YES=1,NO=2........	2.00	

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APPENDIX G

ERROR ESTIMATION

The estimates of the probable errors in monthly values of solar heat collected, incident solar radiation and solar fraction were based on the following considerations.

Completely random errors are assumed. Errors which result from computations are determined by standard statistical methods[32,33].

The probable error in air flow measurement of 20% is discussed in Section 3.6 of the text. The error in temperature measurement of 1% can be neglected by comparison. Thus, the error in the heat collected, QU, which is the product of air flow and temperature difference is 20%. After integration, (by Simpson's rule), of the QU values for a day, the error in the daily total heat collected, Q, is found by the root-sum-square method[33]. Again, the error of 1% in the time coordinate due to manual integration was neglected in comparison to the air flow error. For three trial days of different weather conditions, the probable error in Q's computed in this way were 6.5%, 7.2% and 7.5%. Thus, it can be assumed that an error of 7% in daily Q values can be used for all the days of the month.

For those days when interpolation was used to obtain a Q value the error in the least squares regression of Figure 8 was 1.3% which can be neglected relative to 7%.

The probable error in the monthly total heat collected was obtained by the root-sum-square combination of daily errors[33] in Q.

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The value obtained was about 2% for each month. Using the same method, the probable error in the heat collected during the 6 month period is 0.8%.

The baseboard heater measurement is accurate to 1%, which can be neglected in comparison to the error in Q in the calculation of solar fraction in Table 8. As discussed in Section 3.6, we can assume errors in the solarimeter readings of 5%.

After integration of the readings for the same three trial days, the probable error in the daily total vertical incident radiation is 1.75%.

The values of monthly probable errors shown in Table 7 were calculated on the assumption that the error in every daily VSOL was 1.75%.