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Barakat, S. A.; Carscallen, W. E.; Sibbitt, B. E.

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S.A. Barakat, W.E. Carscallen and B.E. Sibbitt

Division of Building Research
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1. INTRODUCTION

A major objective of the solar energy program in Canada is the gathering of data on the performance of solar heating systems by monitoring solar installations. Following collection, analysis and evaluation, the data are used to determine the thermal and mechanical performance of a solar heating system and its subsystems and to formulate design guidelines. The extent of monitoring for any one installation depends primarily on the subsequent use to be made of the data.

In general, information obtained from monitoring can be used to address one or more of the following objectives:

- to describe the over-all thermal performance of a solar system in terms of its contribution to the energy needs of a specific building,

- to validate solar heating system computer simulation programs,

- to permit detailed analysis of the performance of a solar heating system, which in turn will identify shortcomings in system design (e.g., oversized storage, incorrect control operation), component weaknesses, and shortcomings in component disposition and installation in the building (subsequent analysis can also be carried out to indicate the performance improvement to be expected from modifications of the solar system; this should lead to design guidelines for solar heating systems as well as recommendations for component manufacturing, installation and maintenance).

- to validate combined solar and building heat loss computer simulation programs.

2. MONITORING PROGRAM

2.1. Performance Factors

Some of the factors used to describe the thermal performance of a solar heating system and its subsystems are defined below. Reference should be made to Figure 1, which shows a typical liquid solar heating system.*

2.1.1. Fraction solar, FS, represents the solar energy contribution to the net heating requirement (space and service water heating) of the building

$$FS = (Q_S + Q_{WS})/(Q_H + Q_{HW})$$

It can be subdivided into the fraction solar for space heating (Q_S/Q_H) and the fraction solar for service water heating (Q_{WS}/Q_{HW}). The net space heating demand of the building can be obtained in a number of ways:

- by measurement of Q_S and Q_A, ($Q_H = Q_S + Q_A$),
- by comparison with a similar non-solar building for which purchased energy is measured, i.e., for which $Q_H = Q_A$,
- by analysis, using a building heat loss model to account for L_B, Q_p and Q_{IG}, ($Q_H = L_B - (Q_p + Q_{IG})$),
- by detailed measurement where most losses and gains contributing to L_B, Q_p and Q_{IG} are measured and the remainder calculated.

2.1.2. Heating system utilization efficiency, η_{HS}, is the ratio of the solar energy utilized to the amount collected, and a measure also of the heat losses of the system

$$\eta_{HS} = (Q_S + Q_{WS})/Q_C$$

2.1.3. Collector array efficiency, η_C, is the ratio of the energy collected by the array to that incident on it. This accounts for array losses as well as variation of insolation during the measurement period. It should therefore be distinguished from the instantaneous collector efficiency reported by manufacturers and test agencies

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*Terms are defined in the Legend at the back of this Note.

$$\eta_C = \frac{Q_C}{I_C \cdot A_C}$$

2.1.4. Over-all solar system conversion efficiency, η_o, is the ratio of the solar energy utilized to the solar energy incident on the collector array

$$\eta_o = \frac{(Q_S + Q_{WS})}{I_C \cdot A_C} = \eta_C \cdot \eta_{HS}$$

This represents the efficiency with which the solar system converts solar radiation to usable energy. It can also be expressed as

$$\eta_o = (\frac{FS}{A_C}) \cdot (\frac{Q_H + Q_{HW}}{I_C})$$

The first parameter, FS/A_C, characterizes the solar system design; the second, $(Q_H + Q_{HW})/I_C$, characterizes the building heating load, hot water usage, and weather.

2.1.5. Storage subsystem efficiency, η_S

$$\eta_S = \frac{Q_S + Q_{WS} + \Delta Q_{ST}}{Q_{in}}$$

Storage efficiency is an indication of the energy loss characteristic of the storage unit.

Other performance factors may be of importance in some applications, including heat exchanger effectiveness and heat pump coefficient of performance, if applicable.

2.2 Levels of Monitoring

A number of solar heated buildings were equipped with monitoring systems, the level of monitoring dictated by the type of building and type of solar heating system as well as by the use to be made of the data. It must be recognized that refined data can only be obtained by means of an increase in the cost of instrumentation, maintenance, and subsequent data monitoring and processing. Monitoring levels are summarized as follows:

2.2.1. Level 1

The consumption of conventional or purchased energy only (i.e., electricity, gas or oil) is measured. The net heating requirement is inferred by analysis or comparison with a similar non-solar-heated building. This level will provide a rough estimate of fraction solar and is suitable for privately-funded solar-heated installations for which costly monitoring instrumentation cannot be justified. It is also the appropriate level of monitoring for funded projects that are duplicates of others monitored in more detail and at a higher level (e.g., a row-housing group containing a number of individual solar systems).

2.2.2. Level 2

This level of monitoring addresses the first objective of monitoring, as well as the second and third objectives (see Section 1.), to a degree that depends on the monitoring instrumentation and data acquisition equipment used. It can be divided into two categories according to the data output device and frequency of measurement and recording of data; the first uses integrating heat meters, the second, an automatic data acquisition system.

(a) An integrating heat meter is a device that receives analogue signals from two temperature sensors (temperature difference) and a flow sensor, and is calibrated to measure the integrated heat flow past a point in the system. (More details of the meter and associated instruments are presented in Section 3.1). Integrating heat meters are used at different points in the solar system to measure the amounts of solar energy collected (Q_C), solar energy delivered to space (Q_S), and solar energy used for hot water preheating (Q_{WS}) as well as any other heat flow quantities required for the analysis of a particular subsystem. In addition, integrating meters are used to measure purchased energy (Q_A and Q_{WA}), and an integrating pyranometer is used to measure solar energy incident on the collectors (I_C).

Integrated energy values are generally recorded on a weekly or monthly basis; more frequent reading is impractical. Integrated data are suitable for gross analysis of system and component performance (weekly and monthly values of FS, η_{HS}, η_o, η_C...) and for validating seasonal solar system simulation programs such as FCHART and SolCost.

(b) Experimental solar systems and systems with novel features of components require detailed data for dynamic system and component performance analysis. Detailed performance data are also required for validation of solar system simulation programs such as WATSUN and TRNSYS. For such detailed data gathering (that is, data collected on an hourly or quarter-hourly basis) an automatic data acquisition and logging system is required. A similar data system can be used in (a) above if the number of integrating meters becomes prohibitive and data handling becomes unmanageable.

This monitoring system also utilizes temperature and flow sensors, but all readings are recorded by a data logger or a minicomputer, both of which are capable of recording a large number of readings in very short time intervals. A data logger performs a minimum of processing on the data prior to storing in a way suitable for future computer processing (e.g., on magnetic tape). A minicomputer, on the other hand, has the additional capability of on-site processing and reducing data to final form (i.e., energy quantities and performance factors).

2.2.3 Level 3

This level constitutes measurement of the elements of the building energy requirement as well as those of the solar system. The measured quantities are the same as those in Level 2 (I_C, Q_C, Q_A, Q_S, Q_{WS}...) plus the building-related energy values (L_B, Q_P, and Q_{IG}). An automatic data acquisition and logging system is used. This level of monitoring is required for validation of combined solar-system and building heat loss simulation programs. There are currently no solar-heated buildings with this level of monitoring.

It should be noted that because of the close-coupling of the solar system and the building in a passive solar heating application the monitoring of such installations is extremely difficult. Full monitoring can only be achieved with Level 3. The alternative is to rely on Level 1 monitoring. A summary of solar-heated buildings now being monitored by DBR or undergoing installation of a monitoring system is given in Table I. The level of monitoring of each of the projects is also given.

3. MONITORING OF NRC SINGLE-FAMILY SOLAR DEMONSTRATION HOUSES

3.1. Equipment

Monitoring systems corresponding to Level 2(a) were installed in the summer and fall of 1977 in twelve of the fourteen NRC solar demonstration houses across Canada (1). They incorporate a variety of liquid and air solar systems, some with heat-pump assistance. A typical monitoring arrangement is shown in Figure 2. For subsystems in which energy is transferred by a heat transfer medium (air or liquid), an integrating heat meter was used to measure the integrated values of heat flow and fluid flow to or from the subsystem. It accepts analogue signals from two temperature sensors and a flow sensor, and displays integrated energy value in MWh and integrated fluid flow in m^3. A factor proportional to the product of density and specific heat of water is built into the electronics of the meter. It is, therefore, necessary to calibrate the meter if it is to be used with fluids other than water.

Precision platinum resistance thermometers (RTD's) were used for temperature measurement. They have a nominal resistance of 100 Ω at $0^\circ C$

and a thermal coefficient of resistance of 0.00385 $\Omega/\Omega/°C$. The RTD's were interchangeable within 0.05°C over the range 20 to 90°C.

As both liquid and air systems were monitored, two types of flow meter were selected. Liquid flows were measured with a positive-displacement nutating disc flow meter equipped with an impulse head to yield one pulse (switch closure) for every 10 L of liquid passing through the meter. This pulse output was fed into the integrating heat meter. The integrated flow could also be read off a digital counter. Air flows were measured with a propeller-type vane anemometer. The output of the vane anemometer was in the form of an a-c signal of variable frequency that depended on the rotational speed of the vane and hence on the air velocity or air flow rate. An electronic interface was provided between the anemometer and the integrating heat meter to provide the meter with the proper pulse input.

For subsystems having energy inputs in the form of a conventional energy source (i.e., oil, gas or electricity) alternate measuring schemes were utilized. The auxiliary energy contribution of an oil or gas furnace was estimated from the measured fuel consumption and an assumed furnace efficiency. Gas consumption was measured with a displacement gas meter. Oil consumption was calculated using the furnace nozzle size and the measured elapsed on-time of the furnace. The latter was measured with a totalizing clock. The electric energy consumption was measured with kWh meters with the output displayed on five dials, but these were later changed to a digital output because many of the monitoring agents experienced difficulty in reading the dial combinations.

For measurement of energy flows in circuits where the temperature levels remained relatively constant between measurements (one week), only the fluid flow was integrated and the temperature difference measured along with the other parameters on a weekly basis. Energy flow was calculated using the average temperature difference and the integrated fluid flow. The energy demand for domestic hot water heating systems was determined in this way because the water mains temperature and the hot water supply temperature (set to a fixed value) could be assumed constant in the interval between readings. A commercial electronic thermometer was used, consisting of three thermistors connected to a readout through a three-channel selector.

Solar radiation incident on the collector array was normally estimated using values obtained from the nearest radiation measuring station. If there was no station nearby, a pyranometer was mounted at the site at the same slope as the collectors and was connected to an integrator to give a continuous digital readout of the integrated solar radiation.

3.2. Calibration and Installation

Calibration and installation of the monitoring equipment were carried out by NRC staff; on-site plumbing and electrical modifications of the solar system to prepare it to accept the equipment were performed by the local plumbers and electricians originally involved in its installation. All equipment was calibrated individually in the laboratory prior to installation to check accuracy or determine calibration factors. An exception was vane anemometers, which were calibrated after installation because of the dependence of air flow on actual operating temperature and pressure. In-situ calibration of the vane anemometer was accomplished by correlating its output (pulses/min) with a direct flow rate measurement using a pitot tube traverse. A summary of the instruments used, their range, and accuracy is given in Table II.

3.3. Comments

Two factors common to all the demonstration monitoring resulted in distortion or disruption of the monitoring process. The first was related to monitoring equipment failure and the other to human error. Most equipment failure was associated with the vane anemometers and the integrating heat meters. The vane anemometers suffered from bearing failures after a relatively short operating period (the brass bushings failed after one or two months of operation), and this led to erroneous air flow (and hence heat flow) readings.

Malfunction of the integrating heat meters ranged from a drift from calibration condition to complete failure. Failure rate of the vane anemometers was as high as 50 per cent; for the heat meters it was 20 per cent. Other factors that disrupted the monitoring process were related to the solar system itself (1). Another source of error was the inability of some monitoring agents to read meters correctly (such as the dial readouts of kWh and gas meters). This indicated the need for well prepared data sheets to minimize any possibility of error in recording dial readings and locating decimal points.

As a result of these problems there is not a complete set of monitored data for the 1977/78 heating season for the demonstration houses. In many instances even the collected data were so distorted that meaningful conclusions could not be drawn regarding the performance of the solar systems. A summary of the thermal performance of a number of the monitored solar systems has been presented in Reference (1). Work is now under way to rectify the sources of error. A new bearing for the vane anemometers is being designed and new integrating heat meters are being tested and calibrated to replace faulty ones. It is expected that a complete evaluation of the solar systems' performance will be possible following the 1978/79 season.

4. MONITORING OF AYLMER SENIOR CITIZENS APARTMENT BUILDING SOLAR SYSTEM

A senior citizens residence located in Aylmer, Ontario, incorporates a solar heating system with a seasonal storage unit and 219 m^2 of liquid-heating collectors. A monitoring system of Level 2(b) category, with a minicomputer-based data acquisition system, is being installed by NRC. It is based on a Digital Equipment Corporation LSI-11 minicomputer with 28 K memory equipped with a dual floppy disk unit (250 K) and a Texas Instruments model 700 keyboard printer. Analogue channels are input through a Monitor Labs reed scanner and a Fluke 8500 multimeter with binary output. Period, rate and logic channels are connected to the LSI-11 through an ADAC optical isolator interface.

For each of the 200 channels the system calculates a running integral based on 30-sec scans. At each scan the measured value is compared with its previous value; if these differ by more than a preset amount and if a preset "minimum time" has elapsed, a new block of data consisting of all the channels identified as "quickly varying" is written on the floppy disk. Data from "slowly varying" channels are written on the disk at pre-specified time intervals. On-line fortran routines will perform running integrations of key performance measurements and drive a display panel to be located in the lobby of the building.

Liquid flow and electrical energy sensors are essentially the same as those described earlier. The kWh meters are equipped with a photo-electric pulse generator to interface with the minicomputer. Yellow Springs Instrument Company precision thermistors matched to within ±0.1 C deg are used for temperature measurement, and a Weathertronics thin-film capacitive sensor is used to measure relative humidity. Solar radiation is measured with an Eppley 848 pyranometer. A Weathertronics three-cup anemometer with a d-c generator and a vane with a potentiometer will be used to measure wind speed and direction, respectively. Air flow in the mechanical ventilation system will be determined with Validyne pressure transducers measuring the pressure drop across a heat wheel and the pressure differentials from averaging pitot tubes. For comparison, air flow will also be measured with a vane anemometer with a pulsed output.

Some features are included in this monitoring system that were not included in previous systems of the same level: an automatic power-failure restart system, and a data reduction program to analyse recorded data as they become available. The monitoring system is expected to be operational early in 1979.

5. CONCLUSIONS

- Monitoring systems have been installed by NRC in several solar heated buildings representing a variety of solar system designs and applications.

- The level of the monitoring system installed in each building depended on the type of building, the solar system, and the end use of the monitoring data produced. Monitoring ranged from measurement of conventional fuel consumption only to use of minicomputer data acquisition systems.

- Valuable experience was gained in designing, calibrating and installing monitoring equipment in various buildings. More effort is needed in the development or improvement of some of the measuring equipment, for example, the vane anemometer and the integrating heat meter.
- Cooperation of the monitoring agent and his full understanding of the solar system and the monitoring system operation are vital factors in collecting reliable data.

REFERENCES

1. Carscallen, W.E. and B.E. Sibbitt. Summary of the 1976/1977 Solar Demonstration Houses. Presented at 1978 SESCI Conference 'Renewable Alternatives,' London, Ontario, August 1978.

LEGEND

A_C = Net collector array aperture area

I_C = Incident solar energy

L_B = Building heat loss

Q_p = Solar heat gain

Q_C = Collected solar energy

Q_{in} = Solar energy input to storage

Q_S = Solar energy delivered to space

Q_{WS} = Solar energy to domestic hot water heating

Q_A = Auxiliary energy to space

Q_{WA} = Auxiliary energy to domestic hot water heating

Q_H = Space heating requirement

Q_{HW} = Domestic hot water (DHW) heating requirement

L = Heat loss

Q_{IG} = Building internal heat gain

ΔQ_{ST} = Net change in amount of stored energy

TABLE I SUMMARY OF NRC MONITORED SOLAR BUILDINGS

PROJECT NAME	LOCATION	SOLAR SYSTEM	SOLAR SYSTEM FUNDING	MONITORING LEVEL	MONITORING STARTING DATE
Provident House	Kettleby, Ont.	Space and DHW seasonal storage	Federal/Ont.	Level 2(b) Data Logger	September 1976
Mississauga House	Mississauga, Ont.	Space and DHW, water/air heat pump	Federal	Level 2(b) Data Logger	September 1976
Aylmer Sr. Citizens Home	Aylmer, Ont.	Space and DHW, seasonal storage	Ont./NRC	Level 2(b) minicomputer	Winter 1978/79
Applewood School	St. Catharines, Ont.	Space and DHW heating	Ontario	Level 2(b) minicomputer	Winter 1978/79
Humber Collegiate	Rexdale, Ont.	DHW preheating	Ontario	Level 2(b) minicomputer	Winter 1978/79
Shediac, Office Building	Shediac, N.B.	Space heating	N.B. Elec. Power Com.	Level 2(a)	January 1978
Nepean Police Headquarters	Ottawa, Ont.	Space and DHW heating	Township of Nepean	Level 2(b) Data Logger	Winter 1978/79
13 Demonstration Single-family Houses*	Across Canada	Space and DHW heating	NRC	Level 2(a)	Fall/Winter 1977
Wisniki House	Naramata, B.C.	Passive solar wall	Private	Level 1	February 15 to April 30, 1977
Domshy House	Regina, Sask.	Space heating, Solar Furnace	Private	Level 1	Jan.-May 1977

*For more information on these buildings, see Ref. [1].

TABLE II SUMMARY OF MONITORING EQUIPMENT

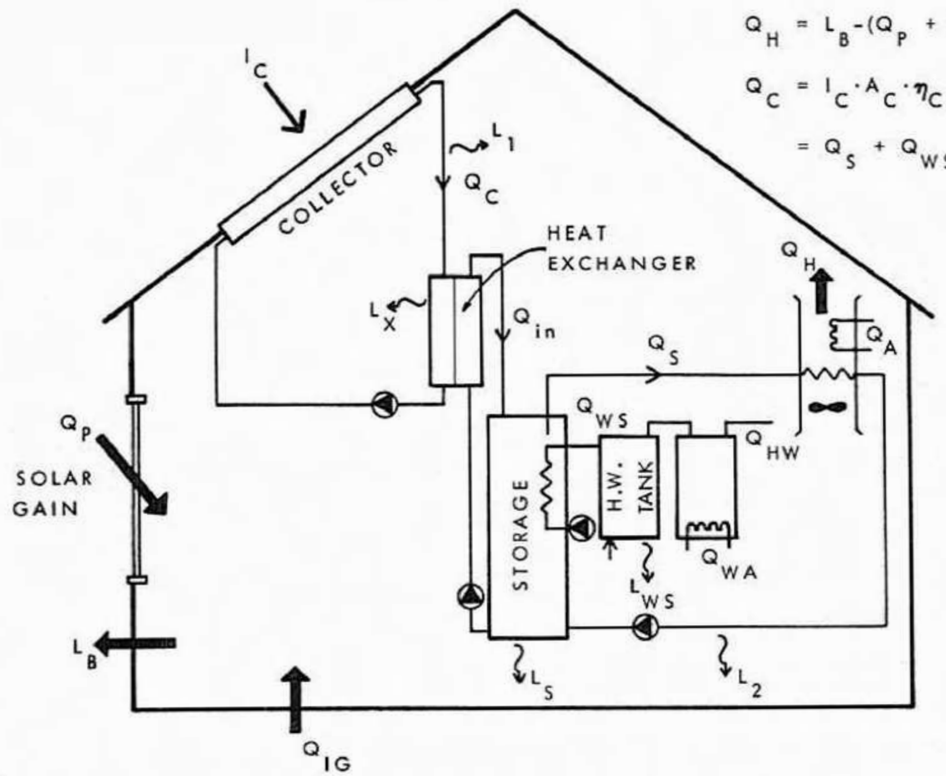
PARAMETER	SENSOR	MAKE	ACCURACY
Temperature	1. Platinum RTD 2. Electronic thermometer (thermistors)	RDF Cole Parmer	0.05°C (from 20 - 90°C) 0.5°C (from 0 - 100°C)
Liquid flow	Positive displacement meter	Neptune	1.5% of measured value
Air flow	Vane anemometer	Weather-measure	2% of measured value
Heat flow	Integrating heat meter	Siemens	2% of measured value
Electric energy	kWh meters	General Electric	0.4% of measured value
Solar radiation	Pyranometer Integrator	Rho-Sigma Acromag	5%* of daily integrated value of a first class instrument

*for clear day data

$$Q_H = L_B - (Q_P + Q_{IG}) = Q_S + Q_A$$

$$Q_C = I_C \cdot A_C \cdot \eta_C$$

$$= Q_S + Q_{WS} + \text{(LOSSES)}$$



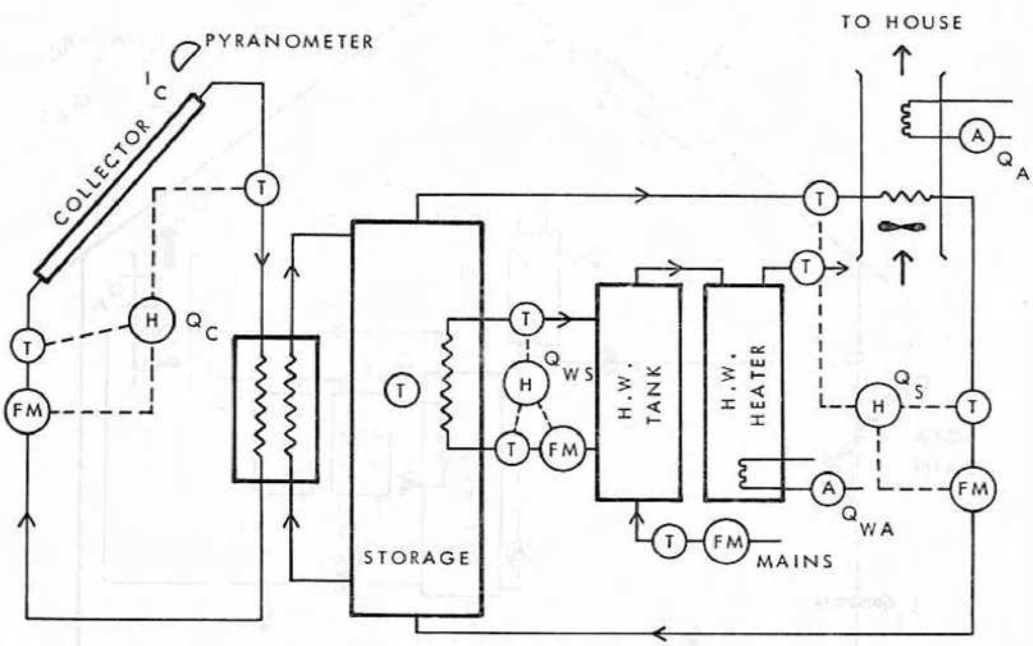
BUILDING HEAT LOSS, L_B

- WALLS/CEILING
- WINDOWS
- BASEMENT
- AIR LEAKAGE (VENTILATION)

INTERNAL GAINS, Q_{IG}

- LIGHTS
- APPLIANCES
- PEOPLE

FIGURE 1 BUILDING ENERGY BALANCE



(T) TEMPERATURE SENSOR
(FM) FLOW METER
(H) INTEGRATING HEAT METER
(A) FUEL CONSUMPTION (e.g., KWh meter)

FIGURE 2 TYPICAL MONITORING EQUIPMENT LAYOUT