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The Mobile Window Thermal Test Facility (MoWiTT)

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INTRODUCTION

The heat transfer characteristics of a window system are generally specified by three static laboratory tests; a hotbox measurement of nightime winter U-value, a calorimeter measurement of shading coefficient, and a static pressurization measurement of air infiltration. These tests were developed to predict worst-case or design heat transfer rates in order to properly size heating and cooling equipment, and they are well adapted to that purpose.

In the design of energy-efficient buildings, however, one is interested in average energy performance and annual energy consumption in addition to performance under design conditions and one wishes to know the relative performance of alternative systems rather accurately in order to make rational economic choices. Determining average performance is particularly complicated in the case of window systems, where the dynamic effects introduced by solar gain and building thermal mass are extremely important. Two examples[1] of serious errors which result from improperly treating solar gain will serve to emphasize this point:

1. Inappropriate use of fixed solar control devices in a small building to reduce summer cooling loads may result in an increased winter heating load which more than offsets the cooling season savings.
2. Overemphasis of nighttime U value as a determinant of net annual energy consumption may lead one to conclude that reducing window area saves energy, whereas inclusion of proper credit for solar gain may show that the reverse is true.

Two generic approaches have been used to determine net annual energy performance. The first approach uses the static laboratory performance measurements in conjunction with a computer model of the building which includes the effect of weather. This approach has the advantage that it is flexible and uses standarized measurements. However, it is then necessary to verify that the computer model adequately simulates the performance of the window system under study and that the basic weather data is sufficiently representative. One must also consider whether the laboratory measurements accurately represent the behavior of the device under field conditions - a questionable assumption, especially in the case of air infiltration.[2,3]

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The second approach uses an existing building and measures the change in building energy consumption as alternative window systems are installed. This approach has the advantages that it uses actual rather than simulated weather conditions and tests the behavior of the fenestration systems under field conditions of solar gain, internal natural convection, wind and occupant usage. On the other hand, it is difficult to measure a building's energy consumption with sufficient accuracy to extract quantitatively the effect of fenestration, and it is difficult to control extraneous variables sufficiently to do good comparative measurements. An excellent study of this type has been done at Twin Rivers, N.J.[4] and a thorough discussion of the methodological problems will be found in that study. However, even if one is able to solve the problems of measurement one is still left with results dependent on the idiosyncrasies of a particular building in a specific climate, and generalization of the results is difficult.

A number of compromises between these two generic approaches have been used. At the National Bureau of Standards whole test houses were built inside a large environmental chamber which simulated winter temperatures in order to validate the NBSLD computer program.[5,6] While this approach has the significant advantages of combining full-scale real-building performance with in-laboratory standardization and reproducability, to extend it to window system measurements would require a very large movable solar simulator and some means of simulating sky diffuse and ground reflected radiation. This would result in an extremely expensive apparatus; moreover, the resulting average energy performance is only as accurate as the simulation of weather conditions. This again raises the issue of validation.

The approach of using small test rooms has been taken in a number of places, primarily for testing solar collectors and passive solar components. This compromise combines economy with treatment of real weather conditions and full scale rooms. Existing units have been typically limited by fixed siting and orientation (generally south-facing), inflexible and unrepresentative room environments, or both.

MoWiTT CONCEPT

In designing the Mobile Window Thermal Test Facility we have extended the small test cell approach to provide the following capabilities:

- Full scale testing of window and skylight units of variable size and type
- Accurate side by side, simultaneous comparative testing of different window systems and window management strategies
- Dynamic performance measurement using real weather conditions
- Flexibility in simulating interior building environments ranging from light weight to thermally massive structures, from poorly to well insulated, and from leaky to air tight
- Variable orientation

- Variable location and climate

The MoWiTT is a portable test building which is rotatable about a central pivot point to provide variable orientation. Taking advantage of the fact that extreme climate conditions are available within reasonable driving distance of the San Francisco Bay Area, the MoWiTT was designed to be truck-transportable. It will normally alternate between a summer site in the Central Valley and a winter site in the mountains, with periodic visits to LBL for maintenance. Other locations are also possible if testing under some specific set of climatic conditions should prove to be of interest.

The facility is shown in Fig. 1. It consists of four test rooms (approximately 2.7m X 2.1m X 2.1m high [9′ x 7′ x 7′]) with a guard room on each end. One exterior wall of each room is removable as is the insulated partition wall between each of two pairs of chambers. This allows testing of windows of various sizes ranging from small residential windows (mounted in an appropriate test wall section) to large window walls. It also permits varying the cavity ratio of the room.

Each test room is designed to function as a calibrated hotbox. The interior air temperature may be accurately controlled by heating or cooling the chamber, and the amount of heat added or removed is carefully monitored. Heat loss or gain through the chamber walls is also measured, and the net gain or loss through the window can then be inferred. We term this mode of operation the metering mode.

The test chambers are also designed to operate in the simulation mode. In this mode, the heat loss rate (excluding the window) and the heat capacity of the chamber are adjusted to simulate a selected type of structure and the response of the chamber to the diurnal weather cycle is studied, either by recording the chamber temperature or by recording the heating or cooling power necessary to keep the temperature within a specified comfort zone.

MoWiTT TECHNICAL DESIGN GOALS

The flexibility and accuracy necessary to measure window performance in a realistic fashion while distinguishing between alternative designs for achieving low thermal transmission produce a set of requirements for the MoWiTT quite unique even among thermal test facilities. For a high performance window system a nighttime R value of 2 m^2K/W (10 $BTU^{-1}ft^2$ hr F) is reasonable; indeed, a few blind and shutter systems with larger R values are already commercially available. In order to distinguish between alternative systems one needs resolution at least as good as 10%, or 0.05 $W\ m^{-2}\ K^{-1}$ (0.01 $BTU\ hr^{-1}\ ft^{-2}\ F^{-1}$). For a common residential-sized window (approximately 1 m^2 [10 ft^2]) this becomes 0.05 W/K (0.1 $BTU\ hr^{-1}\ F^{-1}$).

The test chamber (which is close to the minimum size necessary to provide a realistic, room-like interior environment for the window) has an exterior shell area of about 21 m^2 (230 ft^2) In order to achieve a resolution of 0.05 W/K (.1 $BTU\ hr^{-1}\ F^{-1}$) on the sample the uncertainity in heat transfer through the walls must be small by comparison; this requires that the average wall heat conductance be known to better than $2 \times 10^{-3}\ Wm^{-2}K^{-1}$ ($4 \times 10^{-4}\ BTU\ hr^{-1}\ ft^{-2}\ F^{-1}$). It is clearly not feasible to make the absolute wall conductance this small. If each chamber were made a guarded hotbox one would need to control the guard temperature to a few hundreths of a degree K both spatially and in time, an impractical requirement in a facility this size. On the other hand, to obtain this small a conductance using insulation would require a wall consisting of 8 m of polyurethane. Given the diurnal thermal cycle such a wall would never come to equilibrium.

Fortunately it is not necessary to reduce the skin conductance to this low value. The crucial requirement is to be able to measure the heat flow to this accuracy. We have chosen the following approach. We first insulate the walls as heavily as practical in order to reduce the magnitude of the heat loss to be measured; we have chosen a nominal wall R value of 14 m^2K/W (80 $ft^2hr\ F\ BTU^{-1}$). The resulting test chamber is shown in Fig. 2. The conductance of the insulation is then 0.07 W/m^2K (0.01 $BTU\ hr^{-1}\ ft^{-2}F$) and we estimate that there will be an equal conductance through framing and detailing. If we measure the skin heat loss with a fractional accuracy ϵ, then the minimum sample thermal transmission which can be measured is

$$U\ A = (2.9\ W/K) \times \epsilon$$

where

U = sample thermal transmittance

A = sample area.

Without any provision for measuring heat losses through the walls ($\epsilon = 1$), therefore, for a small residential window ($1m^2$) one could just distinguish single ($6W/M^2K$) from double glazing ($3W/m^2K$). The MoWiTT design goals call for $\epsilon = .01$. We discuss the critical question of how we plan to achieve this goal in a later section.

Although the design accuracy will be necessary to study (for example) the actual nighttime performance of an insulated shutter system as compared with that predicted from its laboratory-measured U value, investigation of other issues will require much less accuracy. For example, $\epsilon = 1$ already provides sufficient resolution to study the extent to which solar gain provides usable heat as opposed to overheating, to check the calculations of ref. 1, and to study window management strategies. Running the test chambers in the simulation mode will typically not require high accuracy and will yield data useful in better understanding the role of windows in building energy performance. This means that the MoWiTT can accumulate useful data without continuously being maintained at the level of fine-tuning necessary for highly accurate measurements.

INSTRUMENTATION SYSTEM

A schematic of the instrumentation system is shown in Fig. 3. Data will be collected with a microcomputer and recorded on a floppy disc for later processing at LBL. A telephone link to LBL will allow remote monitoring of the instrumentation and diagnosis of troubles. A total of 96 channels of analog information will be available for monitoring variables in the test chamber. A multiplexing arrangement allows switching these channels from one test chamber to another for monitoring temperatures, etc. The microcomputer will also control operable devices such as shades and shutters for the study of window management strategies. Local weather conditions will be recorded using a dedicated weather station.

All energy inputs to the test chambers will pass through the instrumentation room where they will be monitored and recorded by the microcomputer. Heat will be provided by electric heaters and the input power measured. Cooling will be provided by a variable-flow chilled water system; flow rates, input and output temperatures will be measured for each chamber. Similarly humidity will be controlled and monitored. Power provided to auxiliary and test devices within the chamber will also be monitored.

The flexibility required of the test chamber gives rise to a very large range of loads. In the metering mode a representative heating load for a high-performance window (assuming 294K (70 F) inside and 266 K (20^{o}F) outside temperature) is about 50W (170 BTU hr^{-1}). During the daytime solar gain may result in a cooling load of up to 2 KW (7000 BTU hr^{-1}) for large test windows--in the metering mode the MoWiTT must be cooled even in wintertime. On the other hand, when a chamber is used with an artificial heat leak to simulate a poorly insulated building the heating load may go as high as 1 KW (3400 BTU hr^{-1}).

The temperature and humidity control systems providing this large dynamic range are shown in Fig. 4. Fig. 4(a) shows the metered cool and reheat arrangement by which accurate temperature control will be maintained. Accurate flow control of water from the chiller over the large range necessary will be achieved by pulsing the indicated gate valve on and off at variable frequency. The logic of the temperature controller (Fig. 4(b)) is arranged to minimize the amount of reheating for an accurate net energy determination. The flow limits f_{MIN} and f_{MAX} are calculated dynamically by the computer depending on the need for dehumidification.

Humidity does not need to be measured with great accuracy but must be maintained at reasonalbe comfort levels to provide a meaningful test situation. As shown in Fig. 4(c) condensation from the cooling coil is collected in two reservoirs located in the test chamber. Each sets on a strain guage calibrated to read the weight of the water in the reservoir. From this information the computer can calculate the net latent heat balance. It will also signal the operator when water needs to be added to or subtracted from the system and determine the amount.

The air infiltration rate will be continuously measured by injecting a tracer gas and monitoring its concentration. Exterior pressure sensors near the test windows will aid in correlating air infiltration rates with wind and weather conditions.

The above instrumentation is necessary when running in the metering mode, i.e, using the test chamber as a calibrated hotbox. In order to simulate a building two additional devices will be necessary. A variable heat leak will be provided using an air-to air heat exchanger. Running at a constant flow rate this will provide a heat loss which follows the outdoor air temperature, simulating building envelope loss. More complicated heat loss mechanisms can of course be simulated by using the microprocessor to control the cooling system. In addition, a ventilator and flow meter system will provide a controllable and monitored air exchange for simulating envelope leakage.

MEASUREMENT OF SKIN HEAT FLOW

Two methods of measuring the heat flow through the chamber walls suggest themselves. The first is to operate each chamber as a calibrated hotbox, calculating the heat flow through the skin from the temperature difference across it. However, this is no longer a static problem; the heat storage time of the walls is not negligible compared with the diurnal outdoor thermal cycle. Therefore a dynamic modeling of the chamber walls would be necessary, including measurement of the wall response factors. The heat flow could then be deduced from the interior and exterior surface temperature history of the walls.

This approach will undoubtedly be tried. It is difficult to estimate a priori the accuracy attainable by this method. It has many drawbacks, not the least of which is the difficulty of initially calibrating the chambers and the necessity of frequent recalibration to guard against degradation of the insulation due to outgassing or other effects.

For these reasons we favor the second approach, that of covering the interior walls of each chamber with heat flow meters and continuously monitoring the heat flow into and out of the insulation. There is however, a considerable difficulty associated with this approach. Commercial heat flow meters typically have a sensitivity on the order of 0.3 mV/W, which implies signals of the order of 10^{-2}mV for the expected heat flows - an inconveniently small value. Moreover, they are typically available in small sizes (e.g, 5 cm X 5cm) at a cost on the order 10 \$/cm^2. At this cost one can clearly not cover the walls of a room. On the other hand, thermal shunts through the skin may be quite localized and extrapolating small-area measurements of heat flow to the entire wall is a questionable procedure, particularly after the facility has been moved several times.

For all of these reasons we are attempting to develop economical large-area heat flow meters. Although still in its early stages, progress in this direction is encouraging and will be summarized in the following section.

HEAT FLOW METER DEVELOPMENT

Our initial attempts involved straightforward application of the standard technique of measuring the temperature difference across a piece of insulation using a hand-made thermopile. This type of heat flow meter is quite tedious to make, however, and suffers from the same low sensitivity as the commercial variety (which is not surprising, since both use thermopiles).

We report here results using a new type of heat flow meter[7] originated at Lawrence Berkeley Laboratory. This heat flow meter is theoretically capable of extremely high accuracy and should be economical to make in large sizes ($\simeq 1\text{m}^2$). One of our early small prototypes is shown in Fig. 5. It is .3m square.

This prototype has been tested for stability and linearity. In order to study it under conditions of zero heat flow it was enclosed in a copper box and placed in the calibrated hot box at the LBL Building Technology Laboratory. The results of this test are shown in Fig. 6. As can be seen, the device exhibits excellent short-term stability, with a noise level less than 0.1mV.

Next, the heat flow meter was placed in a test frame and mounted as a sample between the hotbox and cold box. A commercial heat flow meter (5cm X 5 cm) was mounted on the center of the prototype. The transmittance of the heat flow meter was measured keeping the hot box temperature (T_H) near room temperature and with a coldbox temperature (T_C) 23 K lower. The hotbox temperature was then raised and the coldbox temperature lowered, keeping (T_H + T_C) constant while varying (T_H - T_C). The result of these measurements is shown in Fig. 7. Since the hotbox skin losses at the elevated temperatures prevented an accurate determination of the heat flow, this was calculated from the measured transmittance and (T_H - T_C).

This measurement yielded a sensitivity of (6.4 ± .2) mV W^{-1} m^2 for the prototype. From the noise level of 0.1mV found in the previous test we deduce a limiting sensitivity of 0.02 W/m^2. This is about 10 times higher than our design goal and prototypes of greater sensitivity are planned.

As can be seen from Fig.7. both the prototype and commercial heat flow meters show comparable performance. Both show a linear response but with a considerable zero offset. The reason for this offset in our prototype is currently being investigated.

CONCLUSIONS

A Mobile Window Thermal Test Facility (MoWiTT) is currently being designed as part of the LBL Energy Efficient Windows Program. Sufficient accuracy for measurement of seasonal average net energy performance and study of issues related to solar gain is expected.

Assessment of differential thermal performance of small, high performance windows necessitates very accurate determination of the losses through the test chamber shell. This is best measured directly rather than calculated from wall surface temperatures because of heat storage effects in the walls and the diurnal cycle of exterior temperature.

A promising method for constructing large, economical, highly accurate heat flow meters to make this measurement has been developed. An early prototype yields performance equivalent to a commercial heat flow meter but has 30 times the area.

Construction of the MoWiTT facility is planned for late 1980 with initial operation in early 1981.

ACKNOWLEDGEMENT

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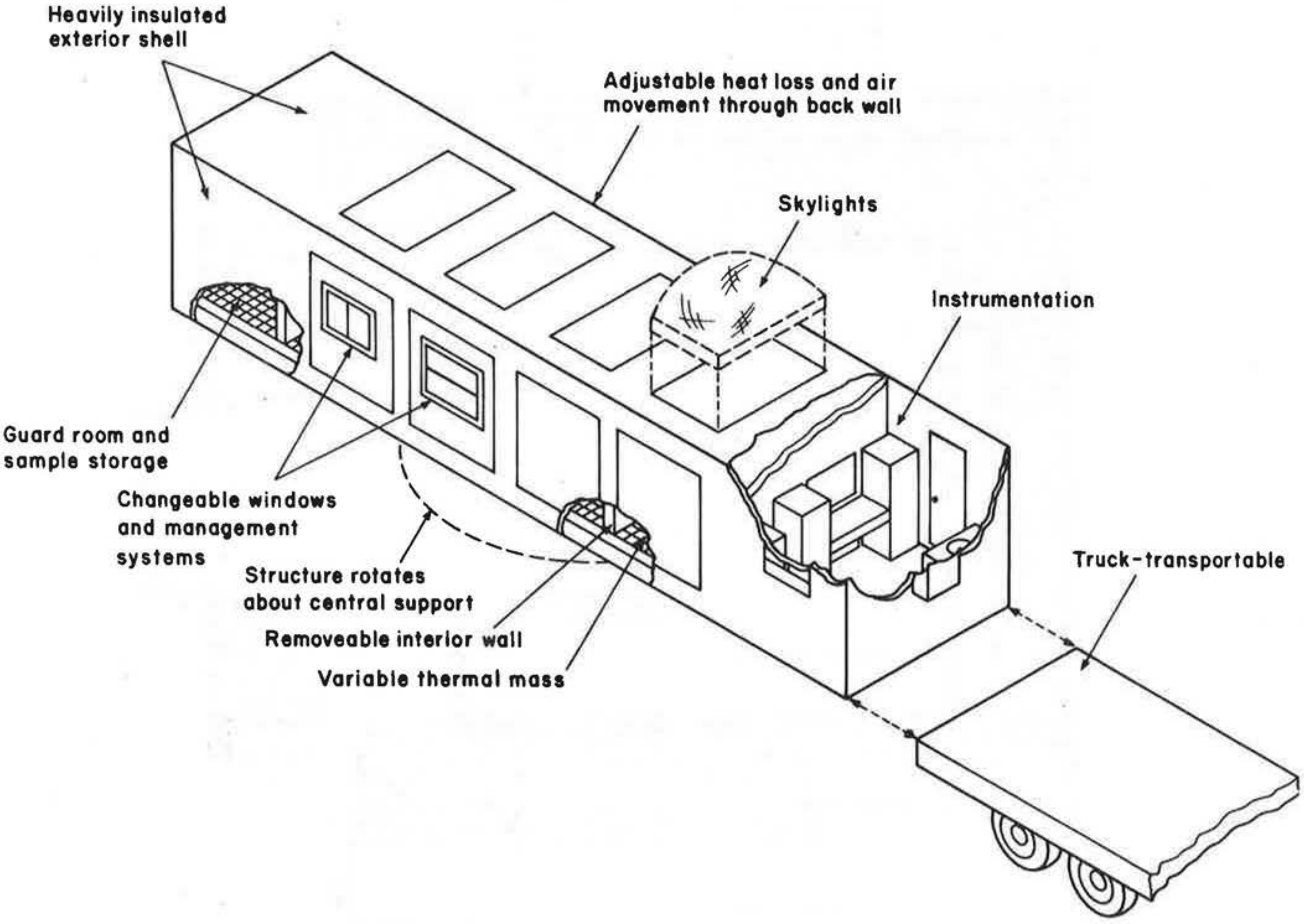

Fig. 1. The Mobile Window Thermal Test Facility.

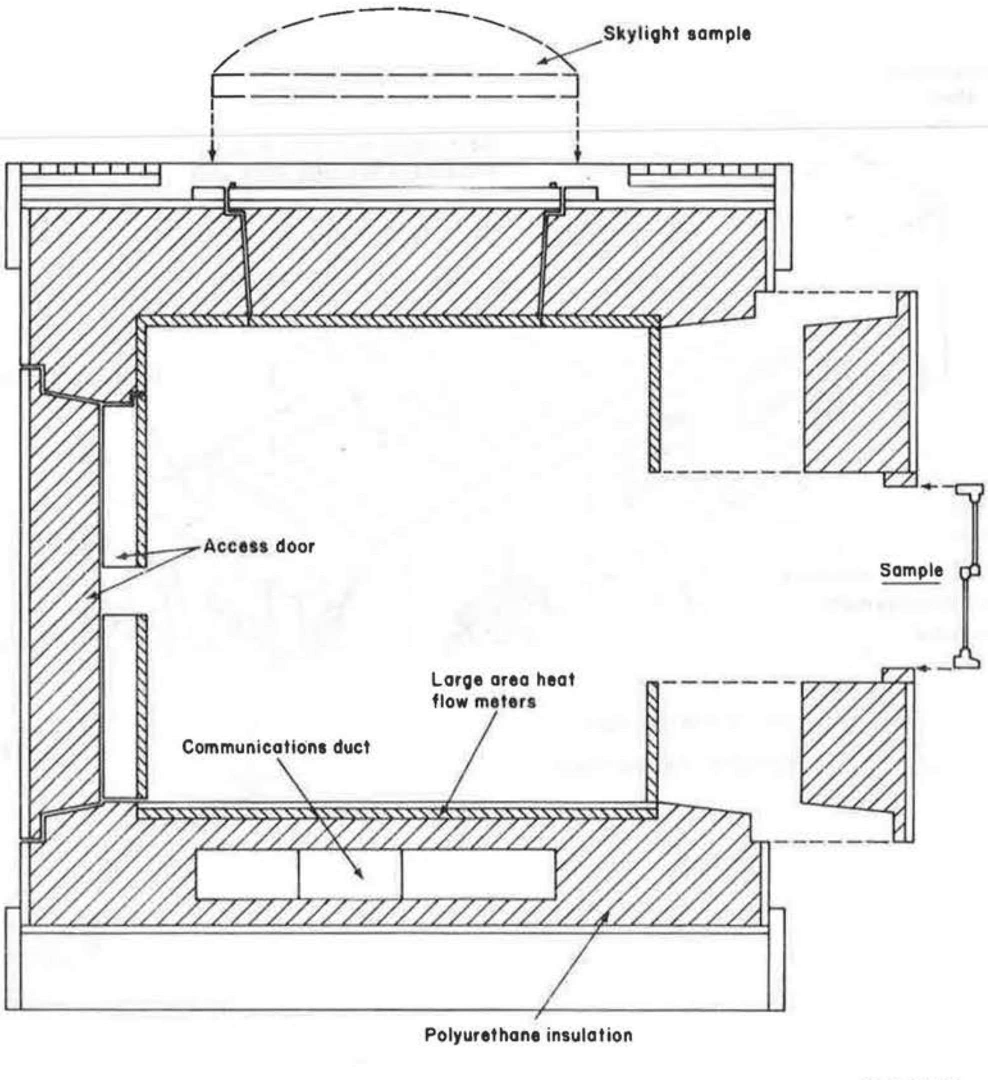

Fig. 2. A Cross Section of one of the Test Chambers. Typical mounting of a residential-sized window in a heavily insulated, removable test wall section (withdrawn) is shown. A second removable insulating plug (top) allows optional testing of skylights. The large-area heat flow meters covering the test wall are movable and may be modified to fit differing wall sections. All electrical and plumbing communications with the chamber are routed to the instrumentation room through a communications duct to prevent uncontrolled heat transfer through cable penetrations in the chamber walls.

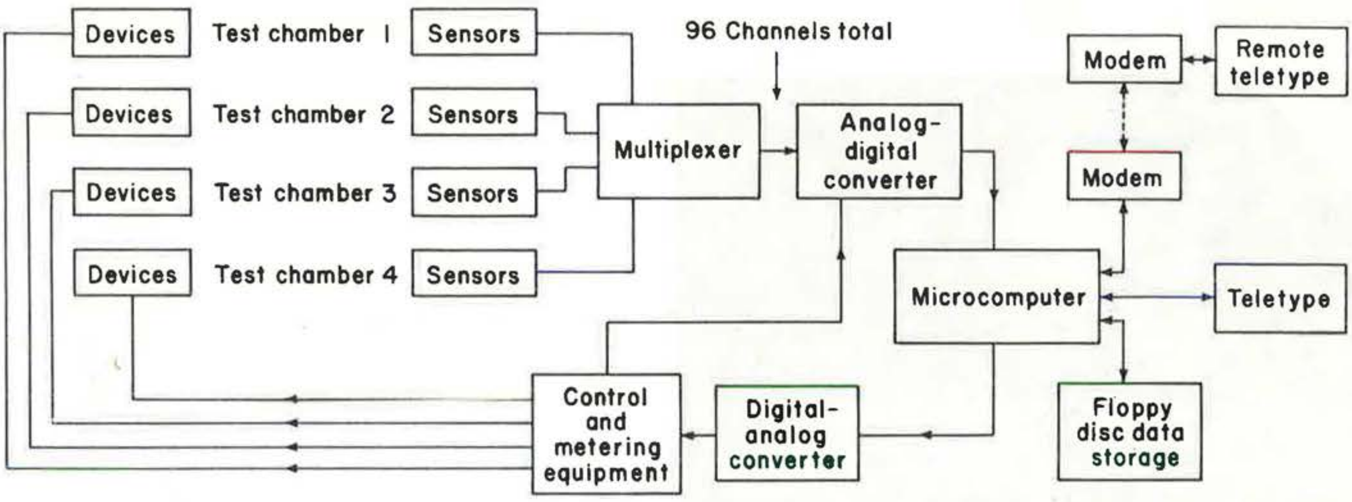

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Fig. 3. Mobile Window Thermal Test Facility Instrumentation.

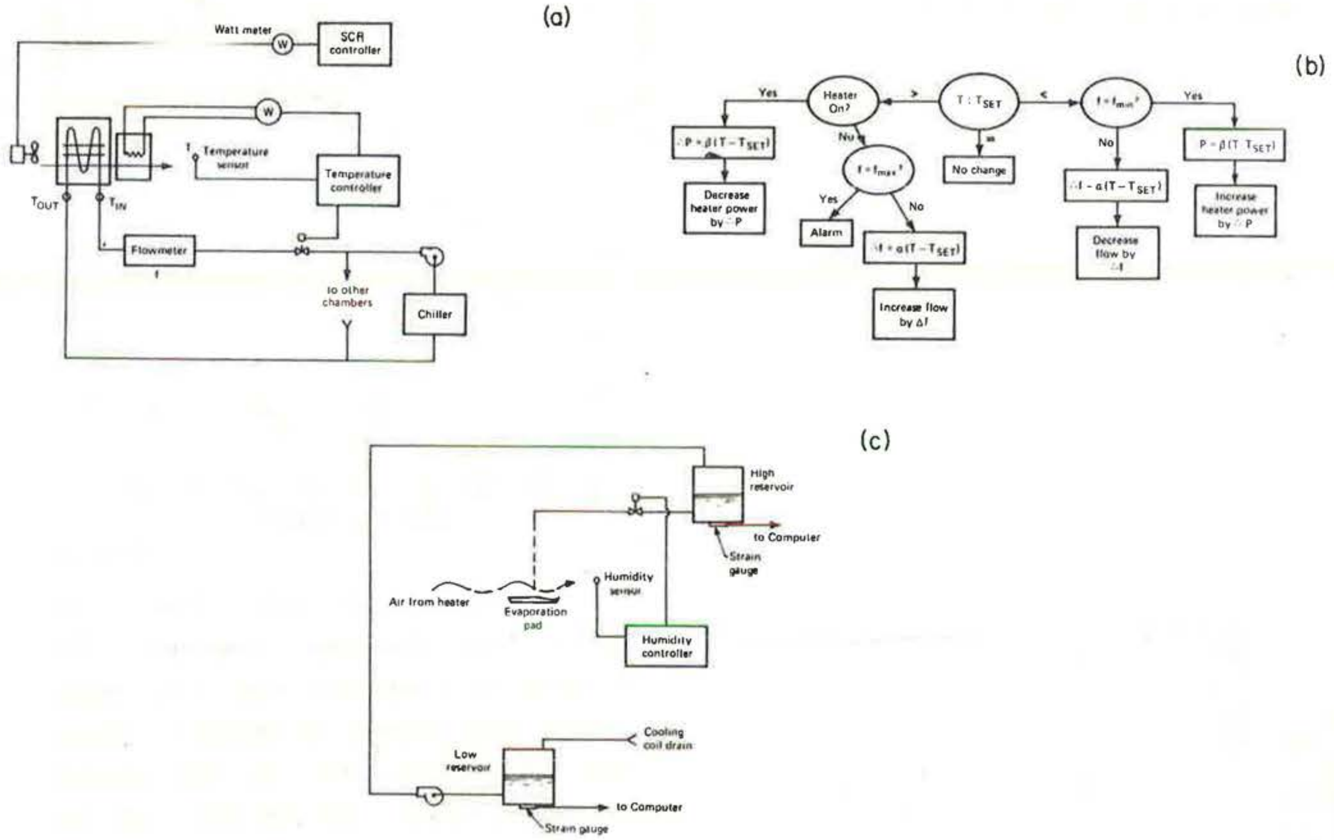

Fig. 4. Temperature and Humidity Control Systems. (a) Schematic of the temperature control system. (b) Logical diagram of the temperature controller. Ovals indicate decision points. The symbols α and β denote system gain constants; f_{MIN} and f_{MAX} are externally set values. (c) Humidity control system.

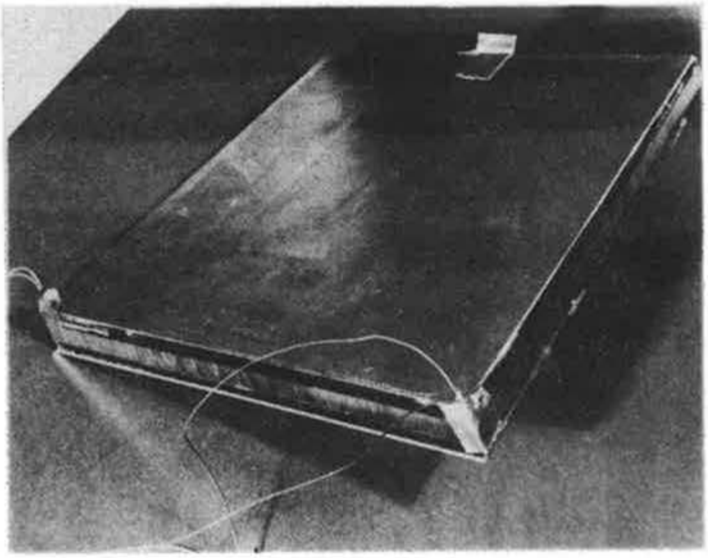

Fig. 5. Prototype Heat Flow Meter. Overall size is 30cm X 30cm (1 ft X 1 ft).

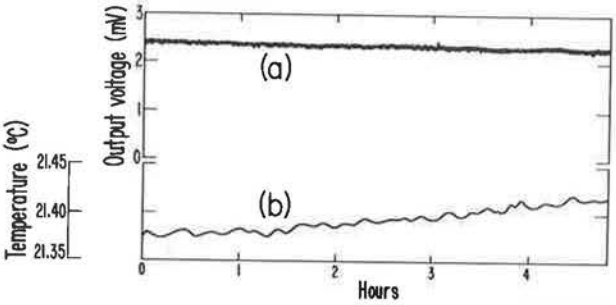

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Fig. 6. Short Term Stability Test of Prototype Heat Flow Meter. (a) Heat flow meter output. (b) Enclosure temperature.

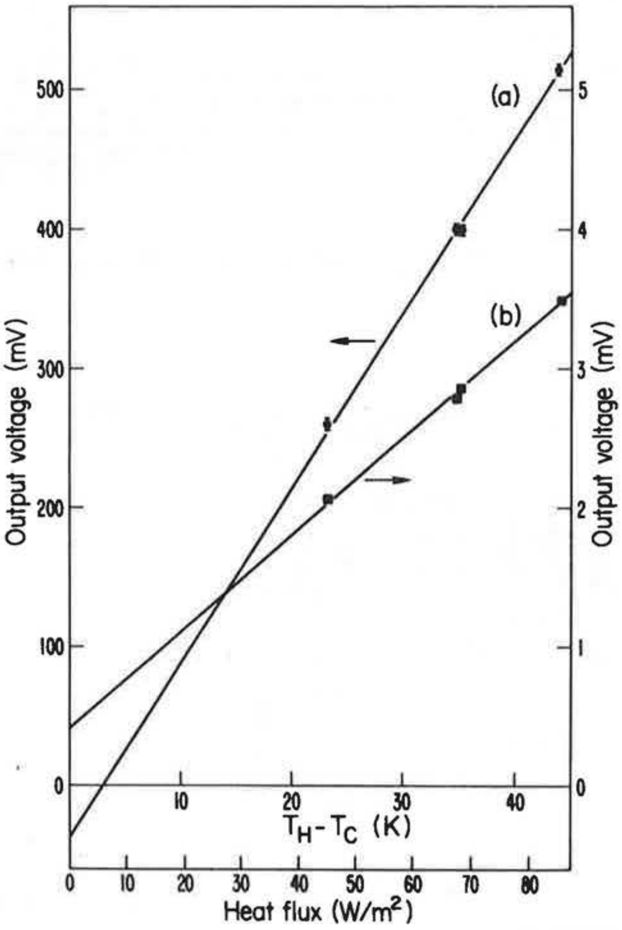

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Fig. 7. Response of Prototype Heat Flow Meter. (a) Prototype response. (b) Response of commercial heat flow meter (5cm X 5cm) mounted on center of prototype (cold side). The heat flux (second horizontal scale) was derived from the temperature difference.