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DESIGN AND CONSTRUCTION OF LARGE-AREA HEAT-FLOW SENSORS FOR MEASURING BUILDING HEAT FLOWS

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Measuring Building Heat Flows

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ABSTRACT

The problem of measuring area-averaged heat flows in room-sized spaces in the presence of solar radiation is discussed in the context of a room-sized calorimeter facility (MoWiTT). Development of a new type of heat-flow sensor suitable for making such measurements is described, and test results for moderate-sized prototypes 1 ft (0.3 m) square are reviewed. Construction of full-sized units--up to 2 ft X 4 ft (1.2 m X 0.6 m)--is described, and problems encountered during development are discussed. It is concluded that this approach represents a viable method for determining net energy balances in rooms.

INTRODUCTION

The need to measure wall heat fluxes is a recurrent one in the study of the thermal behavior of buildings and becomes acute in spaces that utilize natural energy flows. Whether the space is a daylit office or a passive solar house, in order to determine a net energy balance, one is faced with the problem of determining the amount of energy stored in, or passing through, walls of heterogeneous construction exposed to radiant fluxes that vary both temporally and spatially.

When determining the net energy flow through a fenestration system, the problem is compounded by the fact that the total fenestration area is generally much smaller than that of the other envelope elements. Errors in the determination of wall heat fluxes contribute errors in the fenestration energy flow that are amplified by the ratio of areas, generally a number between 5 and 20. In some cases this may have disastrous effects on measurement accuracy.

It is often assumed that a determination of interior surface temperatures will enable an adequate determination of wall heat fluxes. While this may be true in principle, in practice one generally cannot determine the thermal response factors of a wall with sufficient accuracy to calculate heat fluxes reliably, even in carefully constructed buildings. Alternatively, one might attempt to calculate the heat flux using the surface heat-transfer coefficient, but

this approach meets with two difficulties. First, it is difficult to predict the local convective coefficient accurately. Second, the radiative heat transfer at any point on the surface also depends on the temperatures of all other visible surfaces.

To determine the net radiative heat transfer requires, first, a network of temperature sensors with a spacing small enough to correctly detect inhomogeneities in either wall heat flow or irradiating flux. At each point in the network, the net radiative heat transfer must then be determined by summing over all the other points in the network. The labor required by this procedure, together with the difficulty of measuring surface temperatures accurately in the presence of significant radiative fluxes, makes it unattractive. One must thus consider a direct measurement of wall heat flow as the practical alternative.

HEAT-FLOW SENSORS IN THE MOBILE WINDOW THERMAL TEST (MoWITT) FACILITY

All of the aforementioned problems presented themselves during the design of a facility for accurately measuring the net energy flow through fenestration systems under realistic field conditions. The MoWITT consists of a pair of room-sized calorimeters in which an accurate dynamic net heat balance enables direct measurement of the fenestration energy flow (see Fig. 1). An early design of the facility utilizing very thick walls and requiring extreme accuracy for the heat-flow sensors proved too expensive to construct.¹ In the present design, the two calorimeters are surrounded by a guard space containing flowing, carefully conditioned air at the same temperature as the air inside the calorimeter. Details of this arrangement are shown in parts b, c, and d of Fig. 1. The first module of this facility, with one calorimeter operational, is complete (Figs. 2 and 3) and is being calibrated.

The guarded calorimeter eases the problem of wall heat flow by decoupling the flow from the outdoor temperature; however, two aspects of the problem remain. The facility is designed so that with an opaque wall as a sample, the net heat flow through the calorimeter walls is less than 3 W. Under nighttime winter conditions with a fenestration system in place, radiant heat transfer to the fenestration will cause the wall temperature to drop below the air temperature, and there will be a small heat flow from the guard into the calorimeter and out through the fenestration. Under daytime conditions, the solar flux, either direct or diffuse, will cause the wall temperature to rise above that of the air, and there will be a relatively large heat flow through the wall. Because of this, and because the calorimeter walls will seldom be in a state of thermal equilibrium, it is necessary to have accurate heat-flow sensors with a wide dynamic range.

COMPUTER SIMULATION OF ALTERNATIVE HEAT-FLOW SENSOR SCHEMES

An obvious possibility was to utilize commercially available heat-flow sensors, which consist of a thermopile deposited across a known thermal resistance. These are quite expensive per unit of area, and continuous coverage of the walls was not economically possible; it remained to determine whether an affordable network of heat-flow sensors could provide sufficiently accurate measurement under the expected conditions.

A computer simulation was performed, comparing the accuracy obtainable from a network of commercial heat-flow sensors (one for each 8 ft² (0.74 m²) of surface area) with a hypothetical continuous envelope of heat-flow sensors having the same intrinsic accuracy (5%). A winter day at a cold test site (Donner Summit, CA) was assumed, and the building simulation program BLAST² was used to calculate interior wall heat fluxes. The effects of the moving spot of direct solar radiation, which were not treated adequately by BLAST, were calculated by hand.

The details of this calculation have been published elsewhere;³ here, only the result is discussed (see Fig. 4). Two comparisons are made in this figure, one between the discrete and the continuous network of heat-flow sensors, and one between the guarded MoWITT calorimeter and a passive cell; the latter comparison is not a concern here. From the assumed temperature and solar flux, shown in Fig. 4a, BLAST performs an hourly net heat balance on the space and calculates the space load on the HVAC equipment, together with the total heat flow through the envelope (excluding the window), for each of the alternative room configurations. These are shown in Fig. 4b. For each configuration, the difference between the space load and the envelope heat flow yields the net heat flow through the fenestration, which is shown in Fig. 4d. The important result, shown in Fig. 4c, is the discrepancy between the actual heat flow through the envelope of the passive cell, as calculated by BLAST (curve), and the heat flow that would be measured by the network of commercial heat-flow sensors (points). This discrepancy is caused by the fact that each heat-flow sensor represents a wall area much larger than its actual dimension; as the sunlight moves across this area, the sensor measurement is not equal to the average flux so long as the area is partially illuminated. As shown in Fig. 4d, this may result in an inferred net energy flow for the fenestration that is incorrect by as much as 50%. Because the simulated network represents the finest mesh that was economically feasible, it was concluded that a discrete network of commercial heat-flow sensors was impracticable.

DESIGN CONSIDERATIONS FOR LARGE-AREA HEAT-FLOW SENSORS

Therefore, methods of constructing large-area heat-flow sensors economical enough to continuously cover the calorimeter walls must be considered. This would simultaneously solve the problem both of the moving spot of solar radiation and that of inhomogeneities in wall construction, which are exceedingly difficult to avoid in constructing a room-sized enclosure on a finite budget.

The conceptual framework for these heat-flow sensors was identical to that of the commercial sensors: a known, planar thermal resistance together with some means of measuring the average temperature across it. Preliminary theoretical studies revealed that such a device would correctly measure the spatially averaged heat flow for a time-varying radiant flux of arbitrary spatial dependence, provided that (1) the temperature measurements were made on a scale small enough so that the spatial averaging of temperatures was correct, and (2) the scale of time variation was slow compared to the time constant of the device. Although it is difficult to predict these scale dimensions precisely, 10 cm and 10 min were estimated to be sufficiently small space and time scales, respectively.

Selection of the thermal insulator was strongly limited by requirements for low thermal conductivity, uniformity of properties, and stability. Two materials were found to be adequate: fiberglass-filled phenolic honeycomb, and rigid fiberglass board. The former, with a cell size of about 10 mm, had a spatial inhomogeneity just small enough to be neglected, and it had excellent dimensional stability. Testing indicated that both materials were adequate; fiberglass board was chosen on the basis of cost. A thickness of 1 in. (2.54 cm) was chosen as a compromise between the need to have a large temperature difference for a fixed heat flow, which argues for a high thermal resistance, and the need to have the heat-flow sensor be a small part of the wall thermal resistance and heat capacity, which argues for small thickness. This value results in a time constant of approximately 2 min and an R-value of $44 \text{ hr}\cdot\text{ft}^2\text{F}/\text{Btu}$ ($0.77 \text{ m}^2\text{K}/\text{W}$). (The calorimeter walls have an R-value of approximately $30 \text{ hr}\cdot\text{ft}^2\text{F}/\text{Btu}$ ($5.3 \text{ m}^2\text{K}/\text{W}$).

The standard method^{4,5} of measuring the temperature difference across the thermal resistance by means of a thermopile was considered but rejected for several reasons, including inconvenience of construction, potential for noise, and insufficient sensitivity.

A NEW TYPE OF HEAT-FLOW SENSOR

Instead, a method was used that utilizes detection of resistance temperature coupled with synchronous AC detection of the temperature-induced resistance difference. While this method has been commonly used to measure heat flows in low-temperature physics, its application to large-scale heat-flow measurements in buildings appears to be novel. Large-signal results on a first crude prototype were presented in Ref 1; subsequently, results on a similarly constructed heat-flow sensor but without synchronous AC detection also appeared in the literature.⁶

A schematic diagram of the method is shown in Fig. 5. Nickel resistance wires laid on either side of the thermal resistance were connected to opposite sides of a Wheatstone bridge, which was driven by an AC signal. After amplification, the bridge output was put through a synchronous detector that accepted only that part of the input having exactly the same frequency and phase as the driving signal. This feature, which provided superior noise rejection, allowed much higher amplification and therefore greater sensitivity than would otherwise be possible.

The inherent sensitivity of this method is demonstrated by the following: In one arrangement, the sensitivity of the bridge output before amplification was $145 \mu\text{V} (\text{W}/\text{m}^2)^{-1}$. For a copper-constantan thermocouple pair, the corresponding figure was $30 \mu\text{V} (\text{W}/\text{m}^2)^{-1}$. A detailed discussion of the construction and expected performance of the heat-flow sensors has been published elsewhere.⁷

PERFORMANCE OF PROTOTYPES

To check the suitability of this type of heat-flow sensor to the intended application, a guarded hot-plate was constructed and a series of prototype heat-flow sensors 1 ft (0.305 m) square were tested. Details of the hot-plate and the calibration procedure are given in Ref 7.

Because of the very different demands placed on the heat-flow sensors under daytime and nighttime conditions, the behavior of the prototypes was of interest in both the large-signal and the small-signal regions. Calculation indicated that even under direct solar illumination, the local heat flow was unlikely to exceed 30-60 Btu/ft²hr (100 - 200 W/m²); this was taken to be the definition of large signals. Because of the limitations of the hot-plate, the calibration data just reached this region. Under nighttime winter conditions, the design criteria for the MoWiTT called for the ability to distinguish between an R-10 and an R-12 window system. For a moderately cold night and a residential-size window, this implies that the heat-flow sensors must be able to reliably measure an average heat flow of 0.03 Btu/ft² hr (.08 W/m²).

Typical results for a prototype are shown in Fig. 6. It has a linear response over the entire range of interest and a temperature coefficient on the order of 0.5%/°F (1%/°C). Although the smallest heat flow reliably achievable with the guarded hot-plate was 3 W/m², it was also possible to measure the zero-heat-flow output voltage accurately and thereby to verify that the output continues to follow the straight line for very small signals. It is estimated that the limit of measurability is 0.08 W/m² or less. This prototype used filled honeycomb as the thermal resistance; results for prototypes using fiberglass board show little difference. Details of prototype construction are shown in Fig. 7.

The response of the heat-flow sensor to inhomogeneous heat fluxes is clearly crucial. Our tests on small prototypes indicate that the sensors accurately measure inhomogeneous fluxes of the magnitude anticipated in building measurements. One can show theoretically that a heat-flow sensor will accurately measure the spatial average of an arbitrary incident flux provided that it can accurately measure the mean temperature on each face of the thermal insulator. Numerical modeling of the sensors indicates that good accuracy can be expected, as long as radiant fluxes are not strongly concentrated in regions that are small compared to the wire spacing, a condition which should hold in building applications.

CONSTRUCTION OF FULL-SIZED UNITS

While the successful construction and testing of 1 ft x 1 ft (0.3 m x 0.3 m) units at a reasonable cost represented a significant advance, it remained to construct units of a size [4 ft x 2 ft (1.2 m x 0.6 m)] convenient for installing in the MoWiTT and to construct many of them economically. It was necessary to simplify the design, to choose appropriate bonding agents, and to work out an economical fabrication method. With the assistance of highly competent engineering and shop personnel, these tasks were accomplished (see Fig. 8). An impression of the magnitude of the construction project is conveyed in Fig. 9, which shows most of the completed heat-flow sensors for the first calorimeter chamber.

PROBLEMS ENCOUNTERED DURING DEVELOPMENT

In the course of development, a number of problems, some anticipated and some unanticipated, were encountered and solved. Because the full-sized units have not yet been tested, it remains to be seen whether all of the solutions were successful. A recounting of these problems may be of interest.

A crucial issue, which permeated the development of the heat-flow sensors, was the need to protect the nickel wires from strain. As is well known, nickel has a large strain-gauge coefficient that gives a signal indistinguishable from a thermal resistance change. A particularly unpleasant form of this effect occurs when the strain results from differential thermal expansion. This was observed in the earliest prototype and produced behavior that would be puzzling if one were not aware of the effect. This problem was solved in the prototypes by bonding the nickel wire to a material having a very similar coefficient of expansion and by using spacers. In the production model, the spacers were replaced with an alternate method of insuring that the wires were not subjected to a stress large enough to cause appreciable strain.

To make matters worse, the program of complete coverage for the calorimeter surfaces called for heat-flow sensors to be installed in the floor, where they must bear a load. In fact, this is one of the most crucial locations for the sensors. This meant that, not only must the wires be protected from strain, but the thermal resistance must be protected from compression, which would change its calibration. By inserting thin plastic supports in the heat-flow sensors, it proved possible to construct units insensitive to compression; in the end, however, it proved more economical to provide external supports, which protected the sensors without providing a significant shunting conductive path.

The pattern in which the nickel wire was laid on the thermal resistance provided a nonuniform weighting of the surface. Over the body of a heat-flow sensor, this did not result in a measurement bias, provided that the heat flux did not vary appreciably over the dimension of a wire spacing and that the heat-flow sensor dimension was a multiple of the wire spacing. However, at the edges of the meter, where the wire turned around, it was more difficult to achieve the correct weighting. The solution to this difficulty is only approximate; it will be interesting to ascertain the magnitude of this effect.

A related difficulty arose when connecting the heat-flow sensors together on a single surface to form a single large sensor, done in order to reduce the complication of handling large amounts of data. Because the sensitivity of the sensor was inversely proportional to wire spacing, it followed that all of the meters to be connected together must have the same wire spacing. Since at least one dimension of the heat-flow sensor must be a multiple of the wire spacing, it also followed that the sizes of all sensors to be connected together must have a common multiple. It was not a trivial undertaking to find a modular size that best suited the calorimeter chamber. A consequence of this is that, unless heat-flow sensors are

to be specifically designed for a given space as built, one must be content with less than complete coverage. In the MoWiTT, between 88% and 89% coverage was achieved, depending on the size of the window sample.

Modular sizes were further necessitated by the need to match the heat-flow sensors to a calibration apparatus. In order to achieve the most complete coverage possible, together with sufficient flexibility to enable testing windows of varying sizes, four different sizes of sensor were used. To calibrate these, a large calibrated hot-plate that has a segmented metering section is currently being completed (see Fig. 10).

One final problem resulted from the desire to connect the individual heat-flow sensors in series to form a few wall-size sensors. Because a heat-flow sensor forms two sides of a Wheatstone bridge, with reference resistors forming the other two sides, the sensor has an undetermined constant, namely the balance point of the bridge. For the prototypes, this point was set with the heat-flow sensor in an isothermal cavity that insured zero heat flow; but with a large number of sensors connected in series before connection in the bridge, this is no longer possible. It will, instead, be necessary to determine the zero-point voltage for the assembled heat-flow sensors from a long-term average of the calorimeter conditions. The accuracy with which this can be done will determine the ultimate sensitivity of the sensors to small heat flows.

CONCLUSIONS

It is possible to make large, durable heat-flow sensors economically in sizes up to 4 ft x 2 ft (1.2 m x 0.6 m) using a novel design. Prototypes 1 ft (0.3 m) square have been tested and show good results; there is no reason to expect different performance from larger models, although final tests have not been conducted. The small-signal accuracy achievable when a number of units are connected in series depends on the accuracy with which the zero-point voltage of the ensemble can be determined. This point is more uncertain than the performance of the individual units.

Large-scale spatial average heat-flow measurements in building spaces thus appear feasible. The units are producible at tolerable cost, and their properties, e.g., time constant, thermal capacity, and thermal resistance, can be adjusted to meet the demands of particular applications.

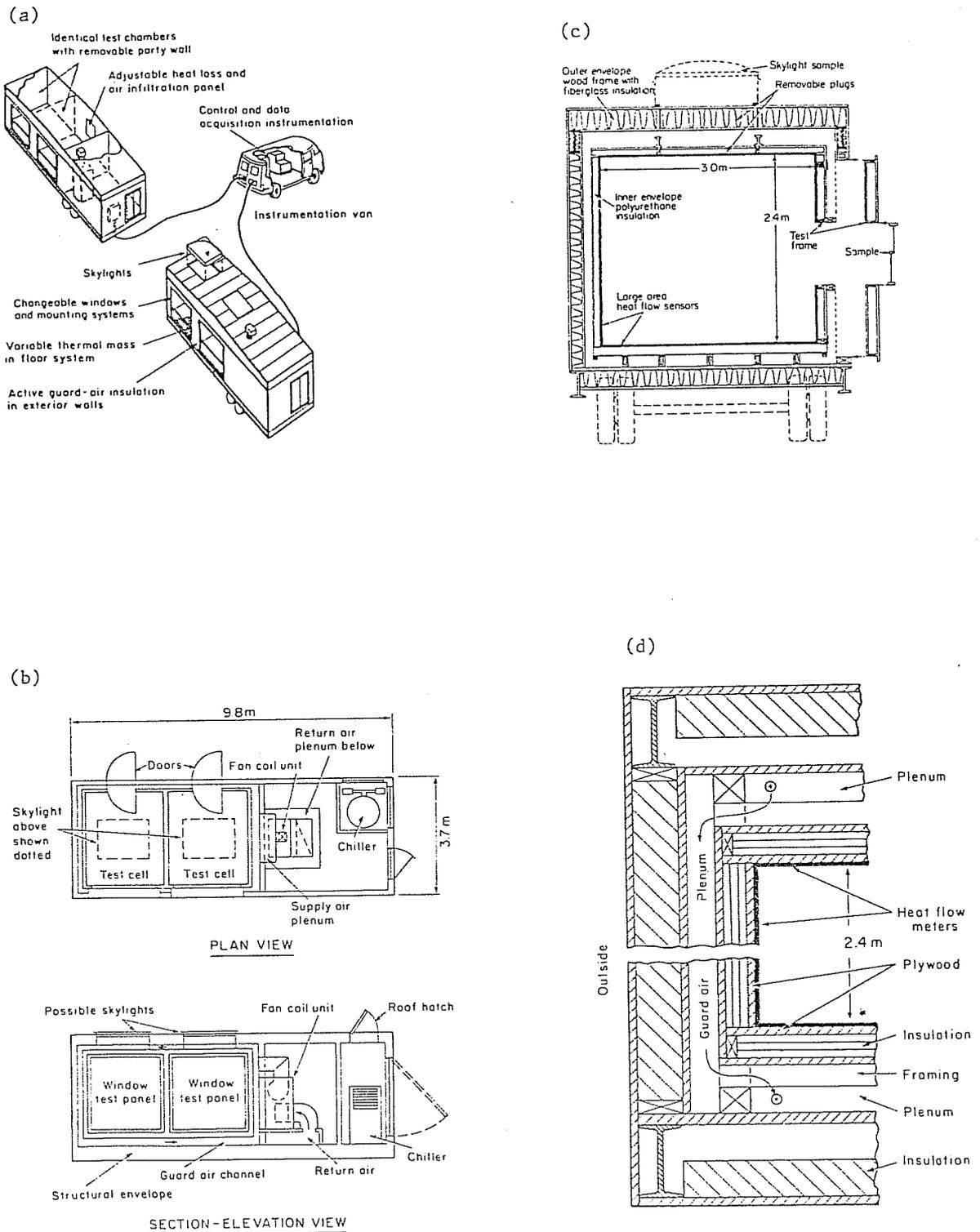
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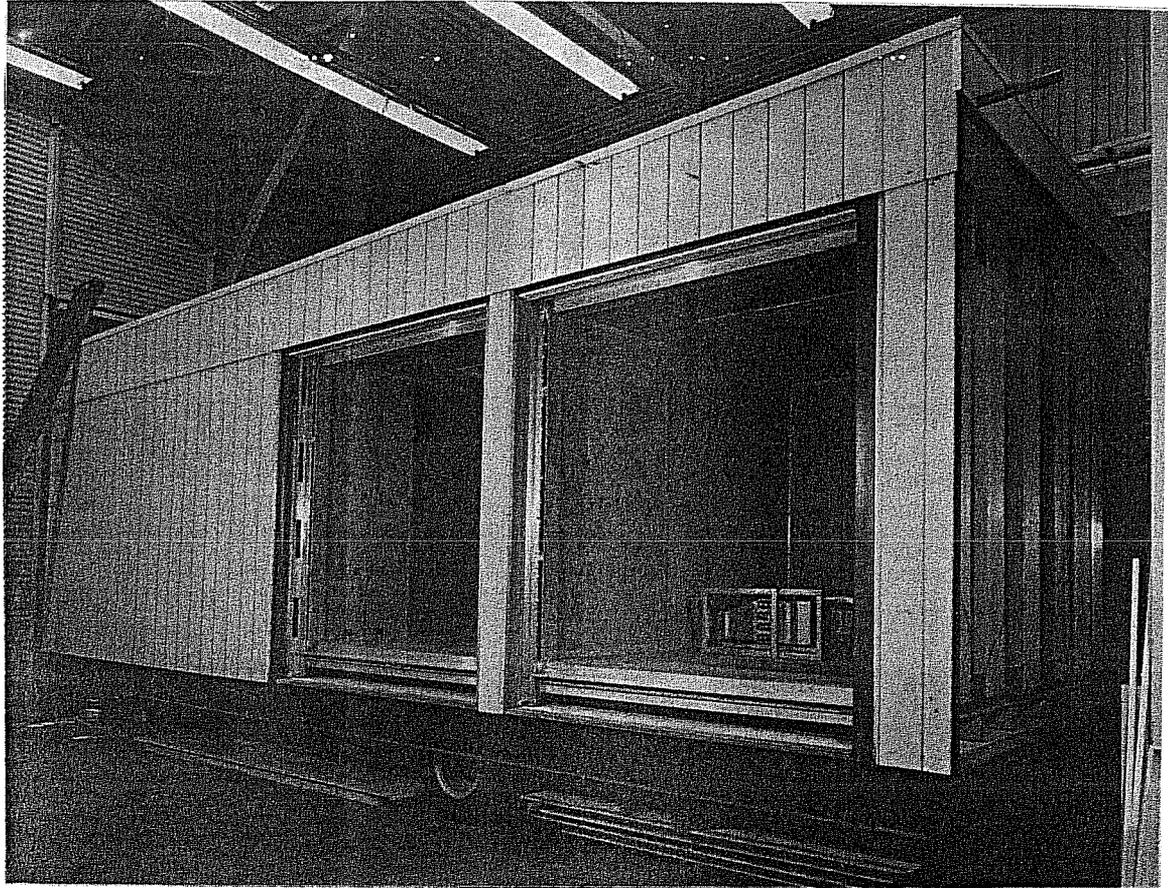
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XBL 811-125A

Figure 1. Design of the Mobile Window Thermal Test (MoWiTT) Facility. (a) Planned field configuration. (b) Layout of a test module. (c) Cross section through the center of a test chamber, showing mounting of alternative window or skylight systems. (d) Detailed envelope cross section.



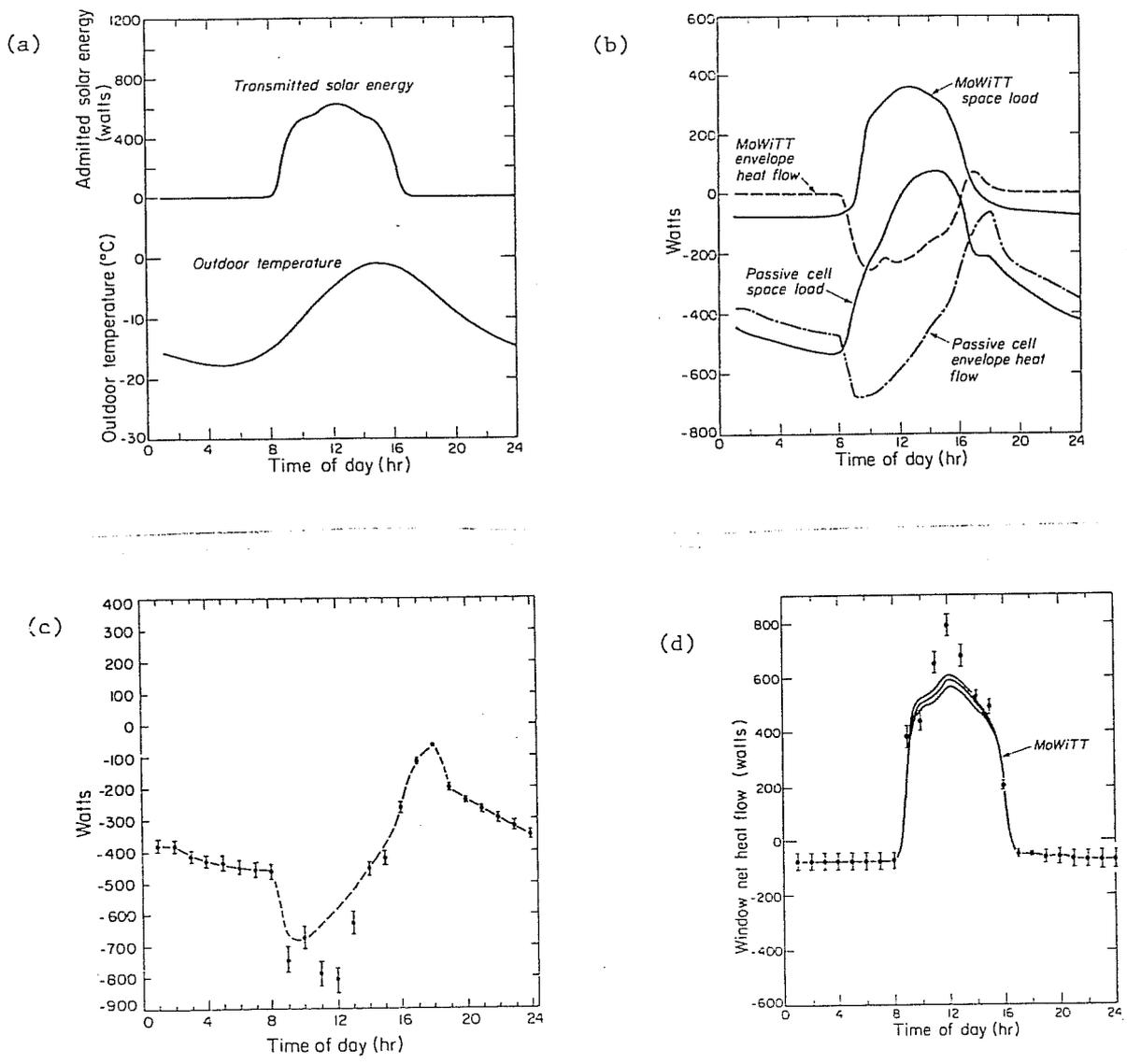
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Figure 2. The first module of the MoWiTT during the latter stage of construction.



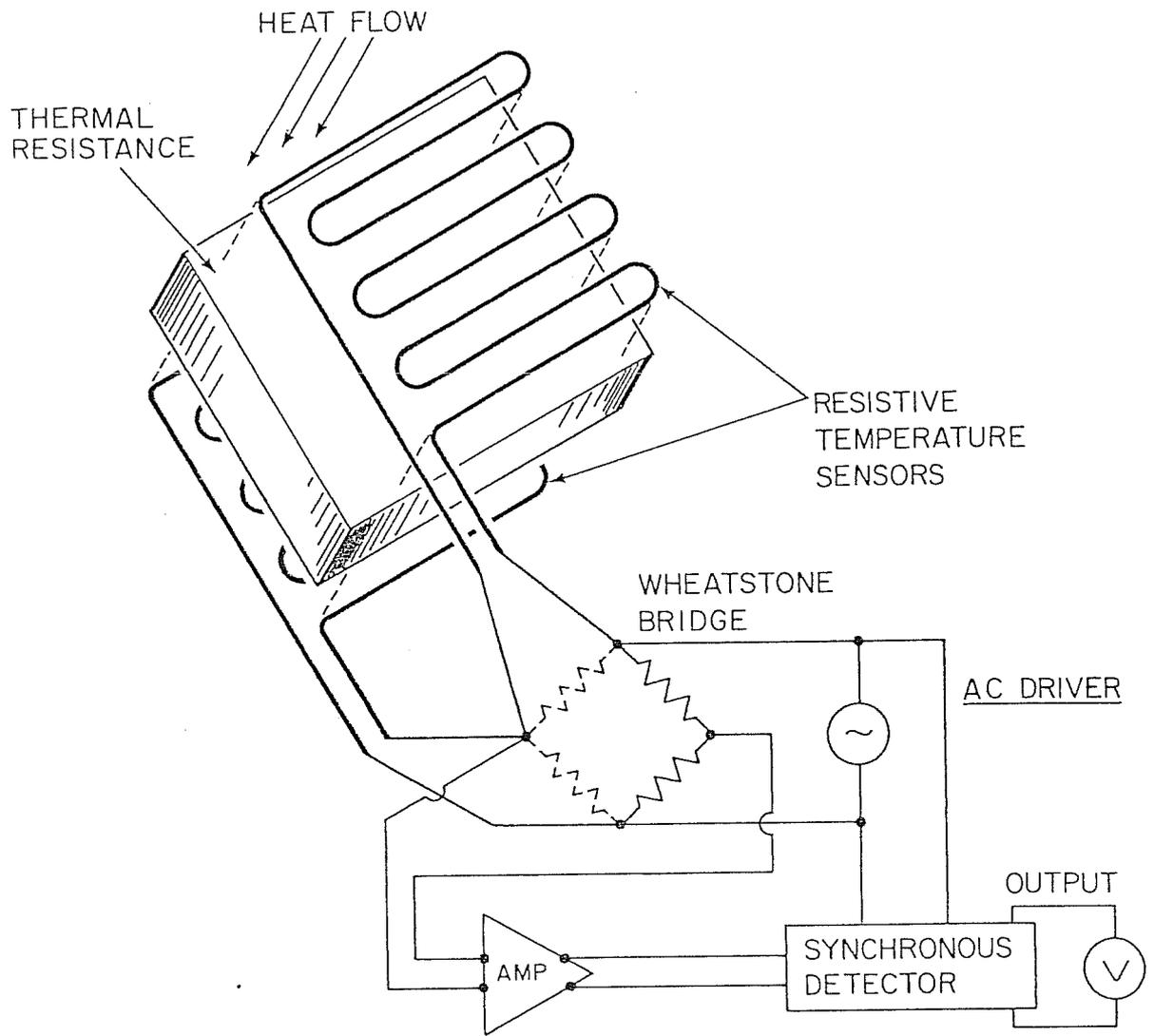
XBC 829-7775

Figure 3. Completed MoWiTT module being moved into position for calibration.



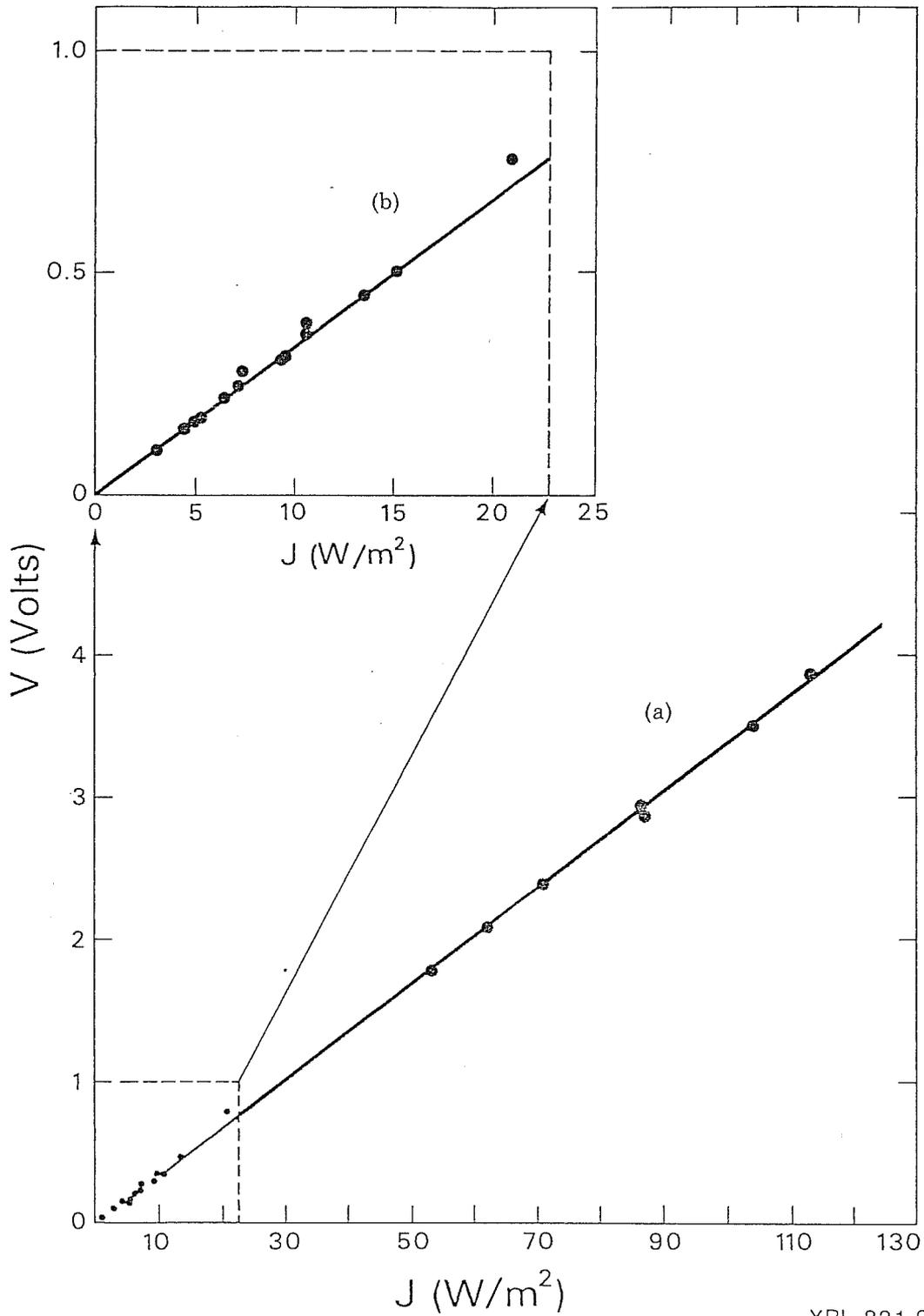
XBL 8110-1404A

Figure 4. BLAST simulation of a triple-glazed window measurement comparing the MoWiTT and a passive test cell. (a) Assumed outdoor temperature and solar energy transmitted through the window. (b) Calculated space loads (solid curves) and envelope heat flows (dashed curves) for the MoWiTT and for the passive cell. (c) Measurement of envelope heat flow in the passive cell. Dashed curve: BLAST calculation of the envelope heat flow. Points with error bars: envelope heat flow measured with discrete heat-flow sensor grid. (d) Derived values for the net heat flow through the window. Solid curves are the mean, +1 standard deviation, and -1 standard deviation for measurements by the MoWiTT. Points with error bars are the corresponding quantities for the passive cell with discrete heat-flow meter grid.



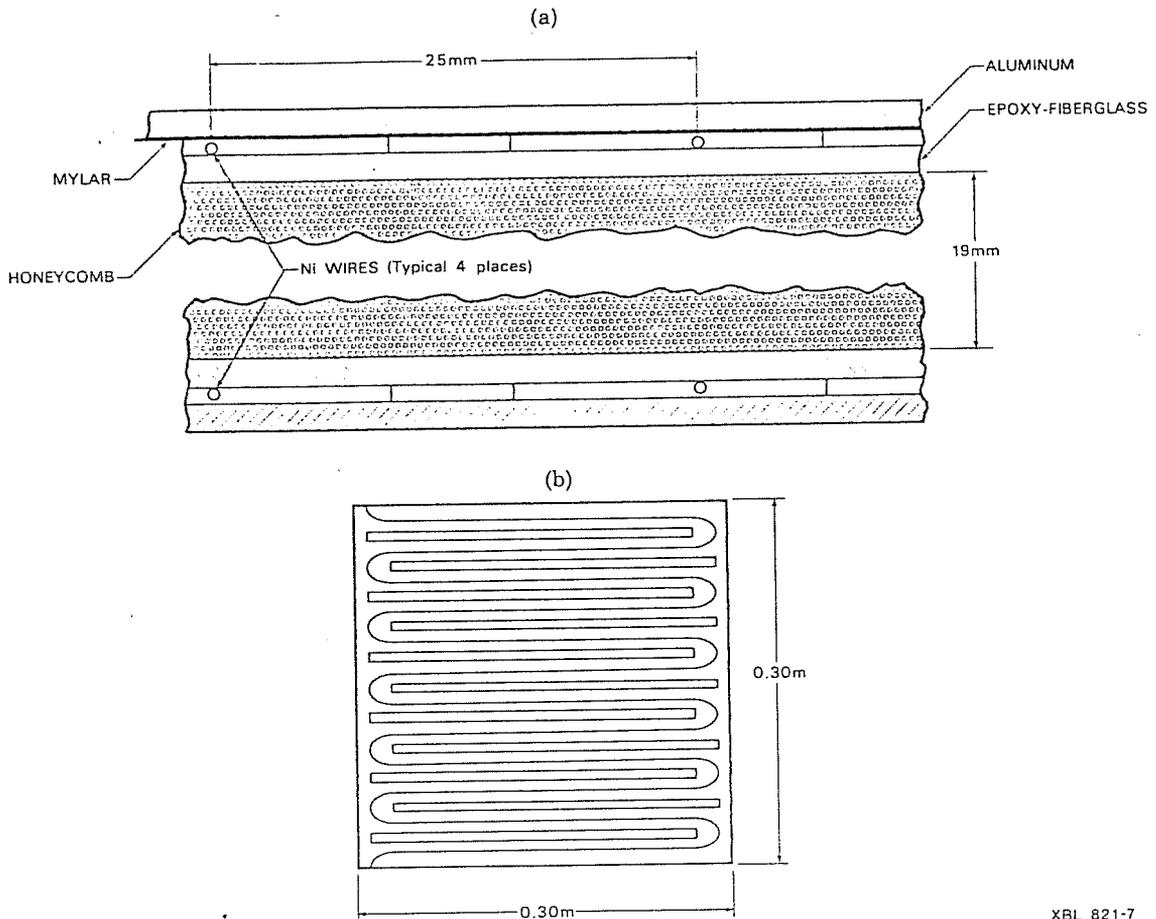
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Figure 5. Schematic description of the heat-flow sensor.



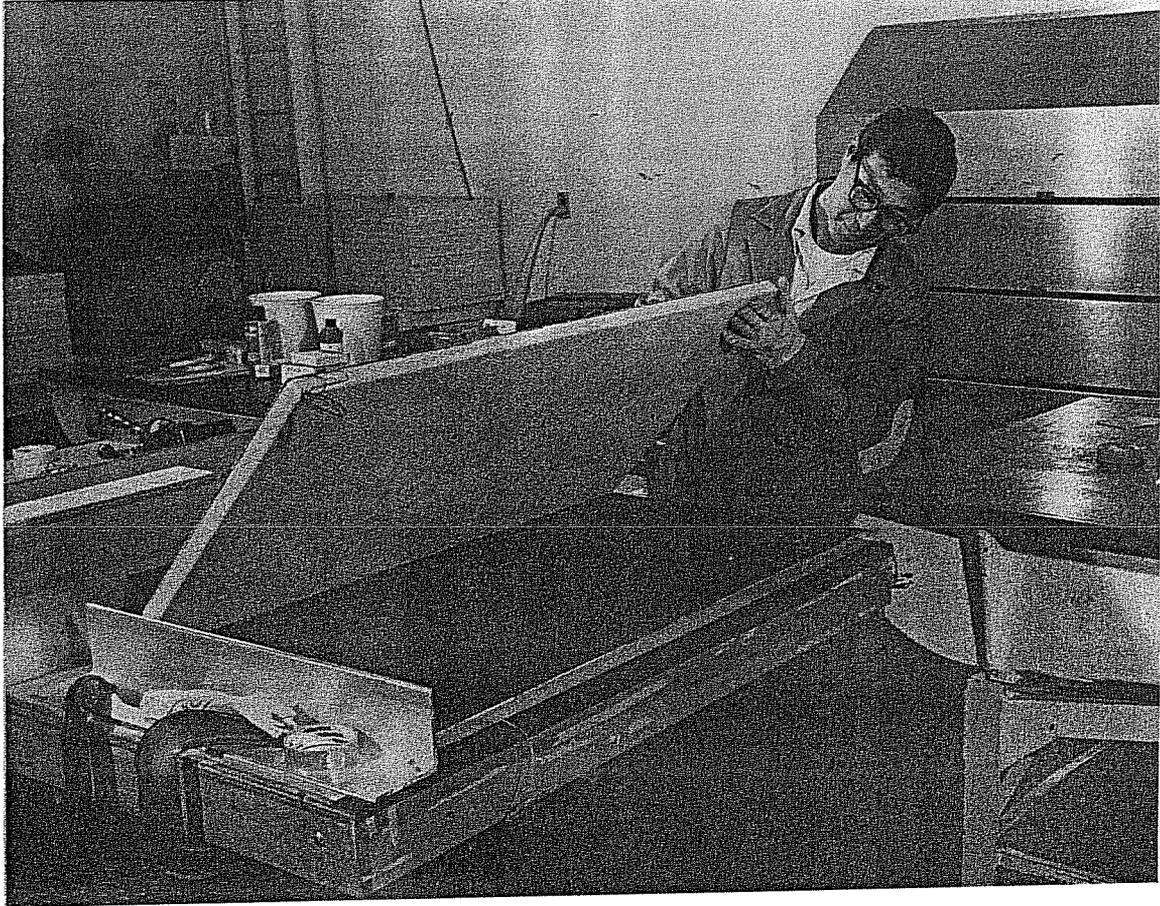
XBL 821-6

Figure 6. Calibration of a prototype heat-flow sensor. (a) Complete calibration. (b) Expanded view of the small-signal region of the curve. Points are measurements made in the guarded hot plate and corrected to a $77^{\circ}F$ ($25^{\circ}C$) mean sensor temperature. The line is a least-squares fit to the data and has a slope of $37.6 mV(W/m^2)^{-1}$.



XBL 821-7

Figure 7. Heat-flow sensor construction. (a) cross section of a "unit cell" of the heat-flow sensor. (b) Plan view of the sensor wires.



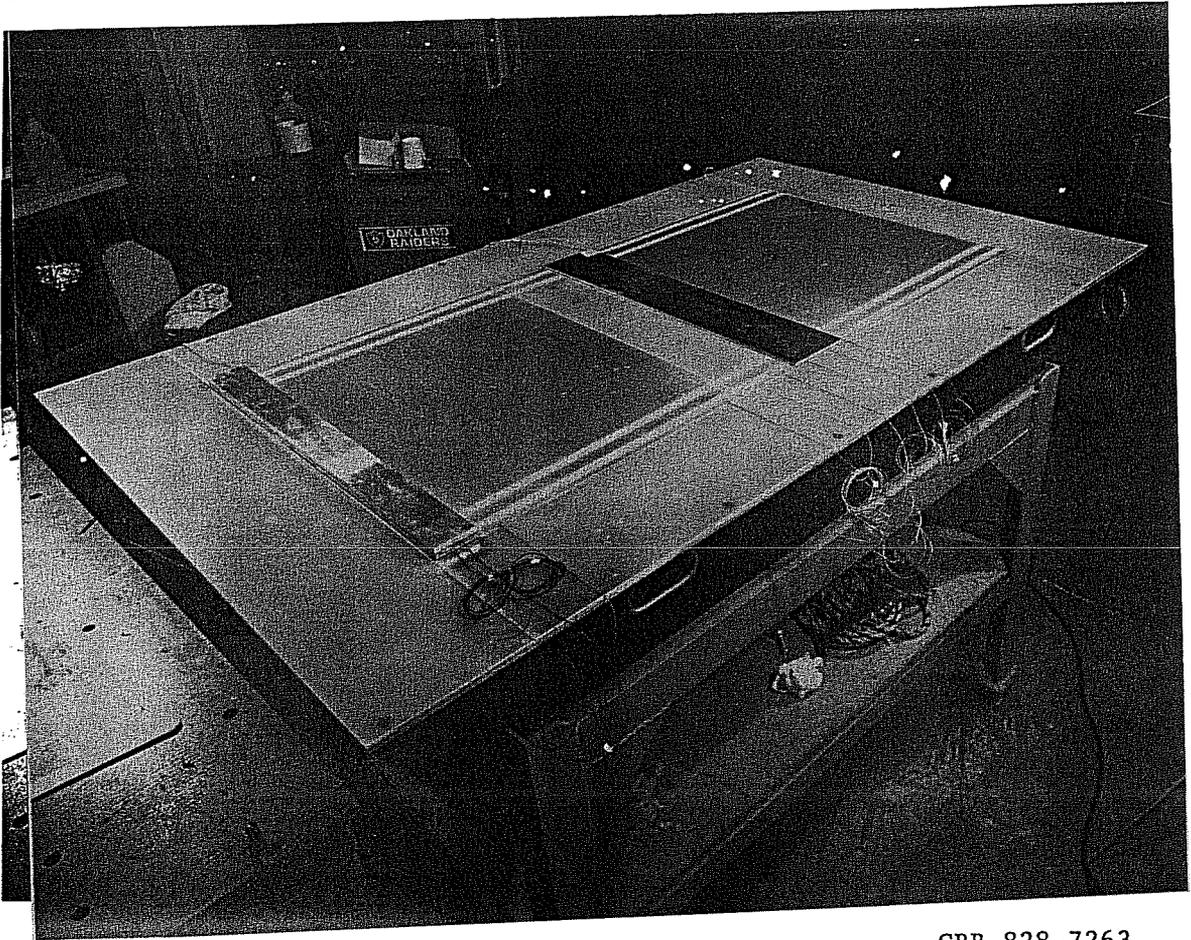
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Figure 8. Construction of large heat-flow sensors: Bonding a sensor wire plane to the thermal insulator.



CBB 828-7550

Figure 9. Completed large heat-flow sensors for first calorimeter chamber.



CBB 828-7263

Figure 10. Large calibrated hot-plate under construction.