Title
TECHNICAL DESCRIPTION: THE ENVELOPE THERMAL TEST UNIT

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ABSTRACT

Although much information is available on the steady-state thermal performance of walls in a laboratory environment, there is little information concerning either the steady-state or dynamic performance of walls in situ. This report describes a measurement apparatus, the Envelope Thermal Test Unit (ETTU), developed to measure the in situ thermal performance of walls. It includes a description of ETTU's operation, its construction, and the results of tests in the laboratory and in the field. The apparatus is described in detail, including technical specifications of the hardware. The ETTU measurements are compared with predictions made by computer simulation of the heat transfer through the test walls. These comparisons, based upon application of the Simplified Thermal Parameter theory to the interpretation of ETTU measurements, show good agreement with the computer simulations for all of the walls tested, except for the thick concrete wall. It was found that the measurements on the concrete wall were affected by large lateral heat flows.

INTRODUCTION

The conduction of heat through a building's walls represents a significant fraction of its energy load during the heating season. Although much information is available on the steady-state thermal performance of walls in a laboratory environment, there is little information concerning either the steady-state or dynamic performance of walls in situ. Existing field measurements indicate that in-situ wall resistances can show significant degradation compared with standard calculations. The goal of the walls research at LBL is to develop a complete methodology for determining the dynamic thermal performance of walls in the field. The methodology contains two relatively independent components: (1) a measurement apparatus capable of both controlling and measuring instantaneous heat flows and surface temperatures on both sides of a wall, and (2) a calculation procedure capable of interpreting heat flows and surface temperatures in terms of physical wall parameters. Once complete, this system can be used to determine the behavior of a wide variety of wall constructions and placements in the field.

This report describes our measurement apparatus, the Envelope Thermal Test Unit (ETTU). It includes a description of ETTU's operation, its construction, and the results of tests in the laboratory and in the field. The application of our Simplified Thermal Parameter theory to the interpretation of ETTU measurements is also briefly described.

THE ENVELOPE THERMAL TEST UNIT

The Envelope Thermal Test Unit (ETTU) is a microcomputer-controlled device that can measure wall performance *in situ*. This device determines the thermal properties of a wall by heating the wall surfaces and simultaneously measuring the heat fluxes and surface temperatures on both sides of the wall. Unlike conventional laboratory hot boxes, ETTU makes measurements on walls in buildings, rather than on laboratory-built wall specimens. The measurements are designed to be independent of weather and do not alter the surfaces of the wall.

ETTU consists of two fully instrumented thermal insulation *blankets* pressed against opposite sides of the test wall. These blankets, which are the heart of ETTU, are fitted with temperature sensors and wafer-thin electric resistance heaters front and back. Knowing the thermal characteristics of each blanket, they serve as large-area heat flux meters on either side of the wall. Controlling the power supplied to the heaters, the blankets produce the desired heat fluxes at the wall surface.

A typical wall evaluation involves *driving* the wall with prespecified fluxes on one side and measuring the resulting flux on the *receiving* side, as well as measuring the temperature responses on both sides. On the drive side, the heater on the wall surface (primary heater) is supplied with the electric power required to provide the desired heat flux. To insure that this heat flux goes into the wall, rather than being divided between the wall and the surroundings, the heater on the back side of the blanket (secondary heater) is also powered. The power to the secondary heater is controlled to maintain a zero (or minimal) temperature difference across the blanket, thus minimizing heat flow from the wall surface to the surroundings. On the receiving side of the wall, only the primary heater is powered. It thus provides high-frequency, small-amplitude perturbations to the heat flux leaving the wall. The two ETTU blankets are functionally identical, so that the drive side is chosen by simply changing a parameter in the microcomputer program that controls the experiments and stores the data on floppy disk.

Having stored time histories of surface temperatures and heat fluxes on both sides of the wall, the thermal resistance and dynamic characteristics of a wall can be determined from an ETTU test.

General Description

The ETTU blankets are fitted with temperature sensors (thermistors) and heaters, and are pressed against both sides of a wall with wooden support structures. A cross section of one of these structures is shown in Figure 1. Behind the blankets are plastic (polycarbonate) cross-flow air channels, used for removing heat on the receiving side. By drawing ambient air through the channels on the receiving side, the back side of the receiving blanket is maintained at close to ambient conditions. The plastic channels are insulated from ambient conditions with 9.5 cm (3.75 in.) of extruded polystyrene insulation. This insulation reduces the power requirement of the secondary heaters on the drive side, and minimizes bi-dimensional heat flows through both the driving and receiving blankets. The insulation also reduces the temperature drop across the plastic channels, thereby reducing thermal stress.

The entire blanket assembly rests on two adjustable-height legs that have rubber feet. It is pressed against the wall by two support tubes with turnbuckles. The support tubes extend from mid-height of the blanket assembly to the floor, and are restrained from sliding by vertical poles that extend from ceiling to floor, again tightened with turnbuckles (see Figure 4). The outdoor blanket assembly is also held against the wall with the two support tubes, although the means for keeping these tubes from sliding varies from site to site. (The feet could be dug into the ground, or push against a stake in the ground, or push against some weight on ground such as ETTU's shipping crate, etc.)

The wall-side heaters are protected from surface irregularities on indoor or outdoor walls by thin -- 0.16 cm (0.06 in.) -- rubber sheets. The ETTU blanket assembly without the protective rubber sheet is shown in Figure 2.

ETTU measures the thermal characteristics of a wall in the central 0.6 m by 0.6 m (2 ft by 2 ft) region of the 1.2 m by 1.2 m (4 ft by 4 ft) thermal blankets. The data analysis uses only the temperatures and fluxes measured in this center section. The edges guard against multi-dimensional heat flows in the measurement section.

Blanket Calibration

Because the ETTU blankets serve as large-area heat-flow meters, their thermal characteristics must be known precisely. In addition to the thermal conductivity of the blankets, the ETTU data acquisition system takes into account the dynamic characteristics of the blankets when calculating the heat flux at the wall surface. It uses the time constant and thermal conductivity of the blanket, including the temperature dependence of the thermal conductivity. These values were determined by calibration based on known heat inputs from the electric resistance heaters. By placing the two blanket assemblies face to face, the thermal characteristics were determined from the temperature responses to step changes in heater power at the primary heaters. From these calibrations, the heat flux at the wall surface can be determined to within 0.1 W/m^2 (0.03 Btu/hr ft^2), whereas the temperatures are measured to within 0.1 ^{o}C (0.18 ^{o}F).

Data Acquisition and Experimental Control

The data acquisition and experimental control for ETTU are accomplished with a Z-80 based microcomputer system, which stores control programs and data on a dual floppy disk drive[1] (see Figure 3). The system includes: 1) digital-to-analog converters for controlling the power supplies for the heaters, 2) logic drivers for turning cooling fans on and off and switching currents to the appropriate heaters, and 3) analog-to-digital converters for measuring temperatures and heater voltages. The remaining major components are four programmable DC power supplies, which power the heaters as directed by the computer. The entire operation is run by an integrated program that allows the user to adjust experimental control and data acquisition parameters.

Data Interpretation

Researchers at LBL use the theory of Simplified Thermal Parameters (STP) to characterize the thermal behavior of a wall from the temperature and flux histories measured with ETTU.[2] The STP model was developed to provide a simple, direct means of presenting or interpreting data obtained with ETTU. Conventional wall models determine wall performance from the known thermal properties of each wall layer. The STP model, on the other hand, determines overall wall performance parameters from measured data using system identification techniques (i.e. the wall is treated as a black box). The Simplified Thermal Parameters can be used directly to predict wall performance or can be translated into more conventional parameters such as response factors.

The Simplified Thermal Parameters describing a wall are obtained from time series data of wall surface temperatures and fluxes. These time series are transformed into frequency domain, and a least squares fit is used determine the values of the adjustable-parameter transfer functions. The adjustable parameters in the transfer functions (i.e. the Simplified Thermal Parameters), can subsequently be used in either frequency or time domain to predict wall thermal performance.

FIELD OPERATION

ETTU was specifically designed as a field measurement device. Although the two blanket assemblies are functionally identical, one side is designed to be exposed to the weather. It is varnished and caulked, and fitted with a small tent to prevent rain from flowing down the wall onto the blanket.

As with any field measurement device, ETTU has certain requirements for appropriate test sites and operation. First, the test wall must be at least 1.2 m by 1.5 m (4 ft by 5 ft), and must be able to accommodate the legs and vertical supports. An even larger wall section is preferable because windows, doorways, or other structural discontinuities increase lateral heat flow in the wall. The indoor location also must be able to accommodate the microcomputer system. Figure 4 shows the ETTU blanket assembly and data acquisition system installed in the field. During operation, a reasonably stable indoor environment is also preferable. The noise ETTU generates under normal operation is within reason, approximately equivalent to the noise generated by a refrigerator or air conditioner. The only noise comes from the cooling fans for the computer, the cooling fans on the receiving side of ETTU, and the floppy disk drive at each data storage.

ETTU can be moved with a 1/4-ton van and requires two people for transport and set-up, which takes approximately one-half day. After installation, operation is completely automated; the experimental control and data acquisition functions are integrated into the microcomputer system.

Heat Fluxes

Wall tests made with ETTU are normally multiples of 24 hours in length. This avoids the unbalanced heat flows that occur when other than an integral number of (naturally occurring) diurnal cycles are analyzed. The wall is driven only at frequencies that are harmonics (or multiples) of one cycle per 24 hours, again to insure an integral number of cycles at each frequency. The ETTU control program drives the wall with heat fluxes at the fundamental frequency and all of its harmonics up to the high-frequency limit, superimposed onto a steady-state heat flux. The high-frequency limit is determined by the time constant of ETTU's insulation blankets (about 3 min) and the time constant of the wall being tested. The table-driven heater fluxes follow a pink-noise distribution, which is similar to the better-known white-noise distribution. White noise contains all frequencies at equal magnitudes with random phase relationships, whereas pink noise weights the magnitude at each frequency by the inverse of that frequency, thereby weighting lower frequencies more. The larger amplitudes of the fundamental frequency and its lower harmonics serve to favor these frequencies when a least-squares fit is used to determine the STPs of the wall.

To reduce lateral heat flows, ETTU should be operated so as to make use of the weather-induced heat flows (temperature drops) through the wall. It should be noted that ETTU operates by specifying the flux on the drive side, implying that the drive-side temperature will float to whatever is required to establish the desired flux. If the ETTU-imposed heat fluxes are in the opposite direction of the weather-induced fluxes, there will be a large flow discontinuity at the edge of the ETTU blanket, causing large lateral heat flows. The drive side should therefore be on the high-temperature side of the wall for optimal performance. This implies that the drive side should be inside the building during winter operation and outside during summer.

Another reason for respecting the weather-induced heat fluxes and temperature differences is to limit the surface temperature of the drive side. If the low-temperature side is chosen as the drive side, its temperature would have to be increased above that of the high-temperature side to induce the desired heat flow. At overly high temperatures, the thermistor outputs become non-linear, and the wall surface finish on the drive side could be damaged. Our tests, performed in a mild climate, had drive-side temperatures between 25 °C (77 °F) and 50 °C (122 °F).

REFERENCE WALL MEASUREMENTS

The current ETTU prototype (ETTU 1.3) has been tested in the laboratory and in the field. The laboratory work included tests of a well-defined insulating material (NBS Standard Reference Material 1450b), as well as tests of built-up specimens of typical residential walls.

The reference material tests were performed by constructing 1.8 m by 1.8 m (6 ft by 6 ft) wall sections from 0.6 m by 0.6 m (2 ft by 2 ft) reference material samples and 0.6 m by 1.2 m (2 ft by 4 ft) sections of the same, but uncalibrated, material. For these tests, ETTU determined the thermal resistance of the reference material to within approximately 6% of the quoted value. The results are summarized in Table 1.

TABLE 1: Conductivity Tests of NBS Reference Material.

Sample	Flux [W/m^2]	T_{drive} [^oC]	$T_{receive}$ [^oC]	R_{ref} [m^2 $^oC/W$]	R_{meas} [m^2 $^oC/W$]	Error
1	13.6	41.1	30.6	0.70	0.77	10%
1	13.6	41.8	31.6	0.70	0.75	7%
1	17.5	48.0	35.2	0.69	0.73	6%
1	17.5	47.0	34.2	0.69	0.73	6%
2	13.6	40.8	31.0	0.70	0.72	3%
1 + 2	14.0	50.7	31.0	1.38	1.41	2%

The wall tests were performed indoors on built-up 1.8 m by 1.8 m (6 ft by 6 ft) wall sections. The walls were made from extruded polystyrene, plywood, and gypsum board, with and without wooden studs. The results of these tests were compared with the results of a one-dimensional-heat-flow computer simulation of the wall without studs. The simulation determined the U-value of the wall to be 0.82 W/m^2 ^oC (0.14 Btu/hr ft^2 ^oF) and the time constant to be 0.11 hours. ETTU's test of the wall without studs yielded 0.78 W/m^2 ^oC (0.14 Btu/hr ft^2 ^oF) for the U-value and 0.10 hr for the time constant. The ETTU test of the wall with studs determined the U-value to be 0.75 W/m^2 ^oC (0.13 Btu/hr ft^2 ^oF) and the time constant to be 0.12 hours.

As typical examples of the measurements made with ETTU, figures 5 through 7 show the temperatures and fluxes measured in the ETTU test of the insulated stud wall. In Figure 5, we see a typical time series plot of drive-side heat fluxes. The heat flux variations, with a fundamental frequency of one cycle every 12 hr, are centered on a steady-state flux of 10 W/m^2 (3.2 Btu/hr ft^2). The flux on the receiving side, plotted in Figure 6, is leaving the wall (negative). The fluctuations in receiving side flux are smaller than those on the drive side for two reasons: 1) the fluxes generated by the receiving side heater are much smaller than those on the drive side, and 2) the large amplitude fluctuations on the drive side are attenuated by the wall before reaching the receiving side. The slow asymptotic increase in flux leaving the wall is due to the time lag associated with raising the temperature of the entire wall section. The surface temperatures on both sides of the wall are plotted in Figure 7. The fluctuations in temperature mimic those of the flux, being more prominent on the drive side.

FIELD VERIFICATION

Although ETTU 1.3 performed well under laboratory testing, field testing was also necessary for evaluating the device. Two field test sites were chosen, each representing a different type of wall construction. The first was an insulated stud wall in a typical single-family residence. The second wall was a somewhat atypical example of large-building construction. It was an insulated, 0.22 m (8.5 in.) thick concrete wall in a university building.

The tests at the two sites confirmed our expectations for field operation. Field installation proved to be relatively quick, and the apparatus operated reliably for all tests. The stud wall results were acceptable, but the concrete wall tests were plagued by problems with lateral heat losses. For the stud wall, ETTU measured a U-value of 0.60 $W/m^2\ ^oC$ (0.11 $Btu/hr\ ft^2\ ^oF$) and a time constant of 0.18 hr. The values determined with a computer simulation of the wall were: a U-value of 0.57 $W/m^2\ ^oC$ (0.10 $Btu/hr\ ft^2\ ^oF$) and a time constant of 0.11 hr. On the other hand, ETTU determined the U-value and time constant of the concrete wall to be 0.50 $W/m^2\ ^oC$ (0.088 $Btu/hr\ ft^2\ ^oF$) and 4.2 hr, compared with 0.92 $W/m^2\ ^oC$ (0.163 $Btu/hr\ ft^2\ ^oF$) and 7.2 hr determined by the computer simulation. The large discrepancy for the concrete wall is not surprising because approximately 50% of the heat entering the wall on the drive side was lost by lateral conduction.

Both field studies, but especially the concrete wall tests, exposed some of the expected limitations of the apparatus. Because ETTU measures the thermal characteristics of a wall by actively imposing a series of surface heat fluxes, its operation should be independent of the weather. It was found that this independence is limited because lateral heat losses increase sharply whenever ETTU imposes fluxes very different from those naturally occurring in the wall. This was most apparent when measuring the thick, conductive concrete wall under mild weather conditions. For both walls, measurements improved when the ETTU-induced fluxes were in the direction of the weather-induced heat flux. These results indicate that, although ETTU's active heating system increases the useful frequency range of the measurements, the device still depends somewhat on the weather to provide a steady heat flow through the wall.

FUTURE DIRECTIONS

The present Envelope Thermal Test Unit (ETTU 1.3) is capable of measuring the thermal resistance and dynamic characteristics of both homogeneous and multi-layer walls. The present analysis program determines the Simplified Thermal Parameters of a wall without accounting for lateral heat losses. Because the program does not account for lateral heat losses, the accuracy is reduced for thick conductive walls. Two possible solutions to this problem are: 1) to design a passive measurement device that utilizes weather-induced heat fluxes and temperature differences, thereby reducing or eliminating lateral heat losses, or 2) to modify the Simplified Thermal Parameter analysis program to account for lateral heat flows. A new passive device would be much lighter and less expensive than the present active device, but would rely on weather-induced fluxes to provide the frequencies of interest. Because the fluxes would be smaller than those in the active device, the temperature and heat flux measurements would have to be more accurate and precise. The blankets would also have to be much thinner and less massive so as not to damp out or perturb the heat flows at the various frequencies. On the other hand, the modifications to the program (the second alternative) could improve results from either an active or a passive measurement device.

REFERENCES

1. B.V. Smith, P.E. Condon, The LBL-EPB Data Acquisition System: Its Description and Construction, October, 1980, Lawrence Berkeley Laboratory Report LBL-11739.

2. M.H. Sherman, J.W. Adams, R.C. Sonderegger, Simplified Thermal Parameters: A Model of the Dynamic Performance of Walls. Presented at DOE/ASTM Conference on Thermal Insulations, Materials, and Systems for Energy Conservation in the 80's, Clearwater, FL, December 8-10, 1981 (Lawrence Berkeley Laboratory Report LBL-13503).

APPENDIX:
TECHNICAL DESCRIPTION AND SPECIFICATIONS

Thermal Insulation Blankets

ETTU's thermal insulation blankets are 1.2 m by 1.2 m (4 ft by 4 ft) squares of smooth-skin extruded polystyrene, 1.8 cm (0.7 in.) thick. Both blankets have 16 thermistors on each side, each thermistor glued to a wafer-thin copper disk, 10 cm (4 in.) in diameter. The thermistors are YSI thermolinear networks (YSI-44203), which include precision resistors, and are linear between -30 °C and 50 °C. The blankets also have wafer-thin electric resistance heaters on both sides. The heaters are thin Mylar films plated with continuous copper strips to provide uniform heat fluxes (see figures 2 and 8). The side of the blanket closest to the wall (primary side) has two separate heaters, one for the 0.6 m by 0.6 m (2 ft by 2 ft) center section, and one for the edge section.

Four programmable power supplies heat the drive-side primary center, drive-side primary edge, drive-side secondary, and receiving side primary. (The drive-side primary center is separated from the drive-side primary edge to allow for separate control of the edge heater flux.) A multiplexer sends power to the appropriate heaters as directed by the control program, allowing the two sides to be used interchangeably as drive side or receiving side. Because the drive-side center and drive-side edge are connected in parallel when used as a receiving side heater, the ratio of their electrical resistances must be equal to the inverse of the ratio of their areas. The edge section has three times the area of the center section, so the edge resistance is approximately equal to one-third the center resistance (R_{edge} = 26 ohms; R_{center} = 73 ohms). This arrangement provides a relatively uniform heat flux on the receiving side. On the other hand, the secondary heater covers the entire surface, and has a much lower electrical resistance (8.8 ohms) to accommodate the higher power requirements.

The four programmable DC power supplies (Hewlett-Packard 6291a) that drive ETTU's electric resistance heaters are controlled by analog signals from the data acquisition microcomputer. The computer uses digital to analog converters (DAC) to send the analog voltages that direct the power supplies to provide the desired currents. The heater power, or the output of the power supplies, is determined by measuring the output voltage and the input (current-controlling) voltage. Knowing the relationship between the output current and the input voltage, the power output is determined by direct multiplication.

Blanket Support Structures

The ETTU blanket supports are constructed with "2 x 6" lumber (4 cm by 13 cm), and are 1.22 m (4 ft) high by 1.52 m (5 ft) wide (see Figure 1). They enclose the instrumented insulation blankets, the plastic cooling channels, and the back-plane insulation. The back-plane insulation is protected with a sheet of 3/8 in. plywood.

The plastic cooling channels are made of double-skinned high-temperature polycarbonate sheets (see Figure 9). The 1.3 cm (0.5 in.) square channels are oriented horizontally and fitted with headers on either side. Each header has two muffin fans that aspirate alternate channels to insure a uniform temperature distribution on the back of the receiving side blanket.

Each support structure rests on two adjustable-height metal poles that have rubber feet, and is held against the wall with two adjustable-length metal poles having rubber feet. The latter two poles are on swivels, which enable them to form a diagonal between mid-height of the support structure and the floor. The rubber feet of these diagonal poles are prevented from sliding by a set of vertical poles that extend from ceiling to floor. The turnbuckles on the vertical poles allow them to serve as a braces for the diagonal poles to press the support structures against the wall. (Note: the diagonal poles are also fitted with turnbuckles). For exterior installation, the means for preventing the diagonal poles from sliding depends upon the site. The feet could be dug into the ground, or push against a stake in the ground, or push against some weight on ground such as the ETTU's shipping crate.

SPECIFICATIONS

Blanket assemblies

Quantity	2
Height	1.22 m (4 ft)
Width	1.52 m (5 ft)
Depth	0.14 m (5.5 in.)
Weight	41 kg (90 lb)

Blankets

Quantity	2
Dimensions	1.78 cm by 1.22 m by 1.22 m (0.7 in. by 4 ft by 4 ft)
Material	smooth-skin extruded polystyrene
Thermal Conductance (U-value)	$1.434 + 0.0063{*}T\ [^{o}\mathrm{C}]\ \ \mathrm{W/m^{2}}\ ^{o}\mathrm{C}$
Time constant	2.7 min

Temperature sensors

Quantity	32 per blanket (16 on each side)
Sensor type	YSI thermolinear network (YSI-44203) thermistors
Linear range	-30 to 50 ^{o}C

Heaters

Quantity	3 per blanket	
Description	thin copper strips deposited on Mylar film	
Resistances	drive-side center	73 ohms
	drive-side edge	26 ohms
	drive-side secondary	8.8 ohms
	receiving side	19 ohms

Computer

Type	Z-80 based multi-bus microcomputer
Manufacturer	Monolithic Systems
Memory	64k RAM
Data Storage	dual floppy disk drive
Additional boards	four ADC/DAC boards (12-bit) real-time clock board

Power Supplies

Quantity	4
Type	Hewlett-Packard Model 6291a DC power supply
Current range	0-6 amps
Voltage range	0-43 volts

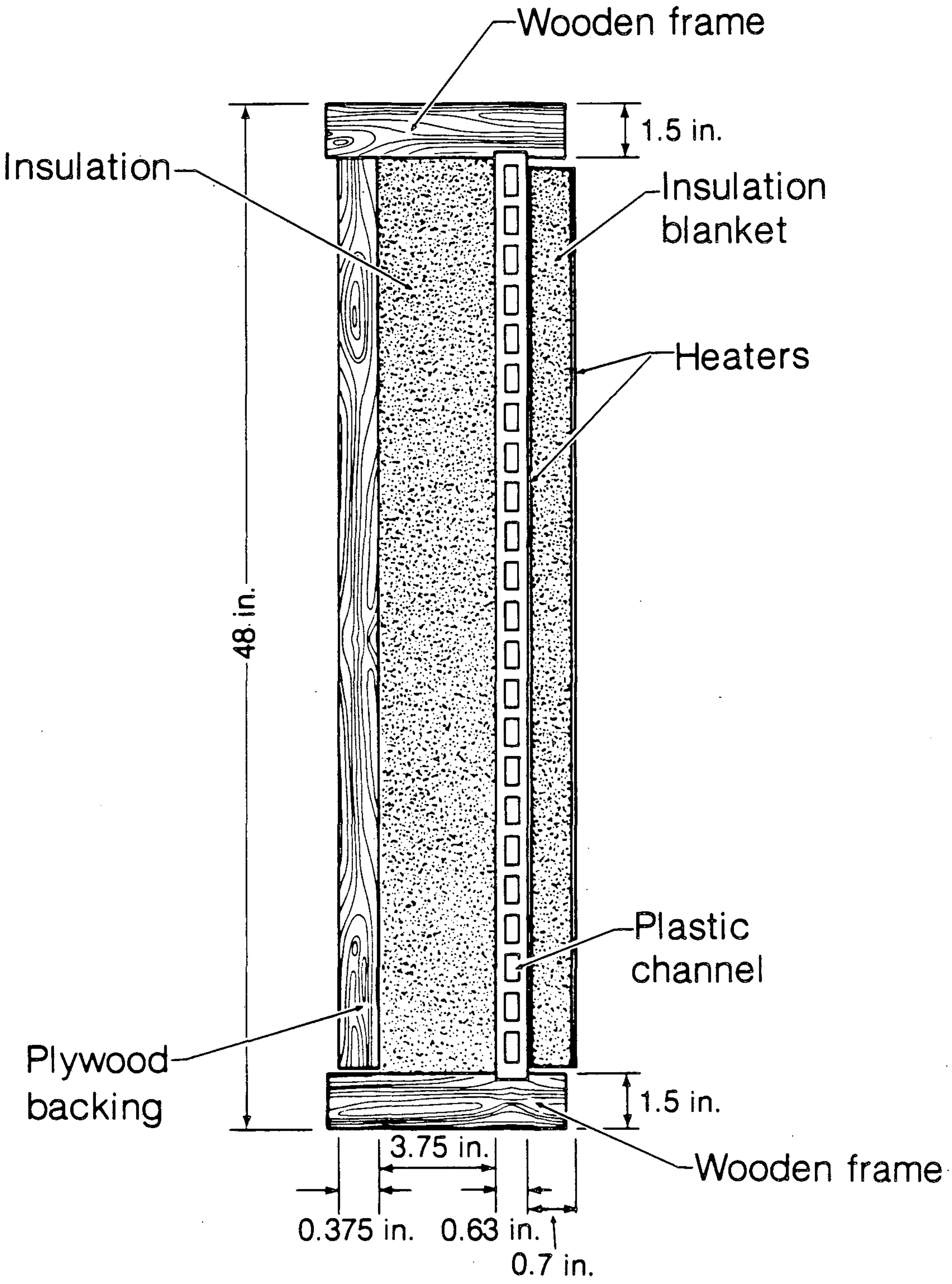

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Figure 1. Cross-sectional view of ETTU blanket within its support structure.

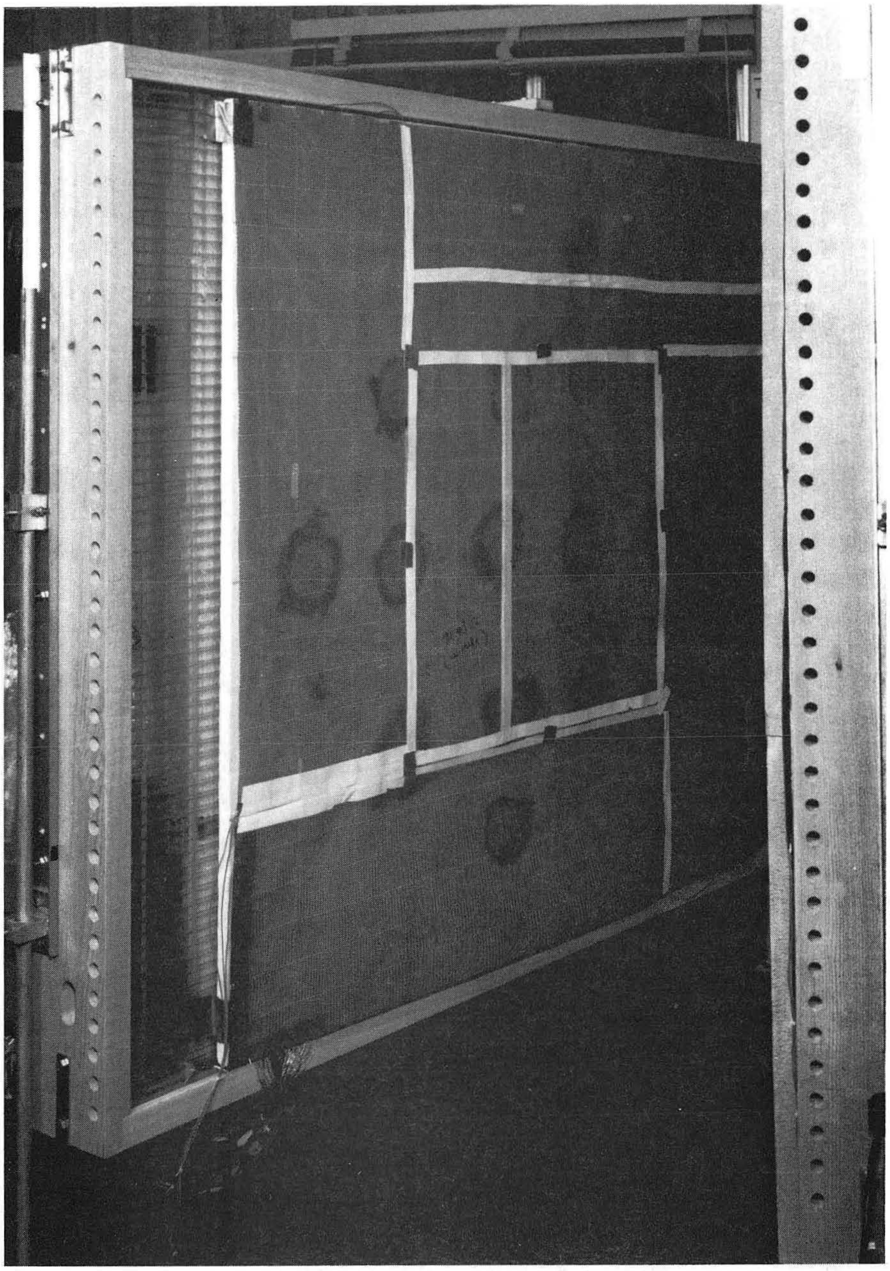

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Figure 2. ETTU blanket within its support structure, not including protective rubber sheet.

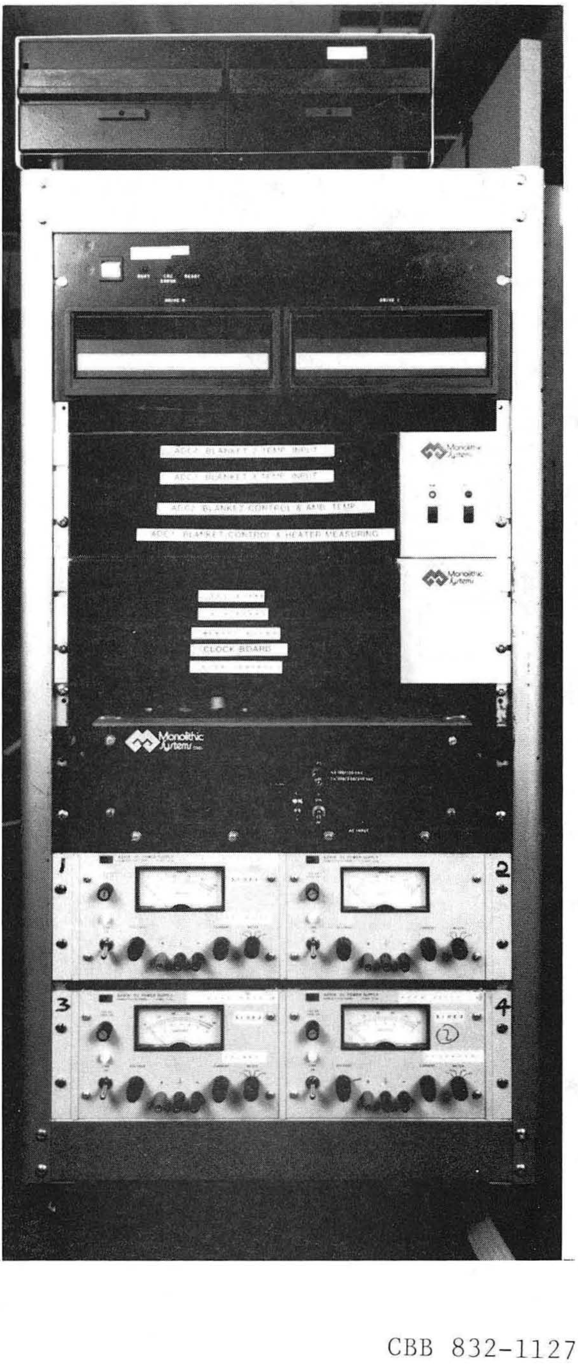

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Figure 3. Data acquisition and experimental control rack, including computer, dual floppy disk drive, and programmable power supplies.

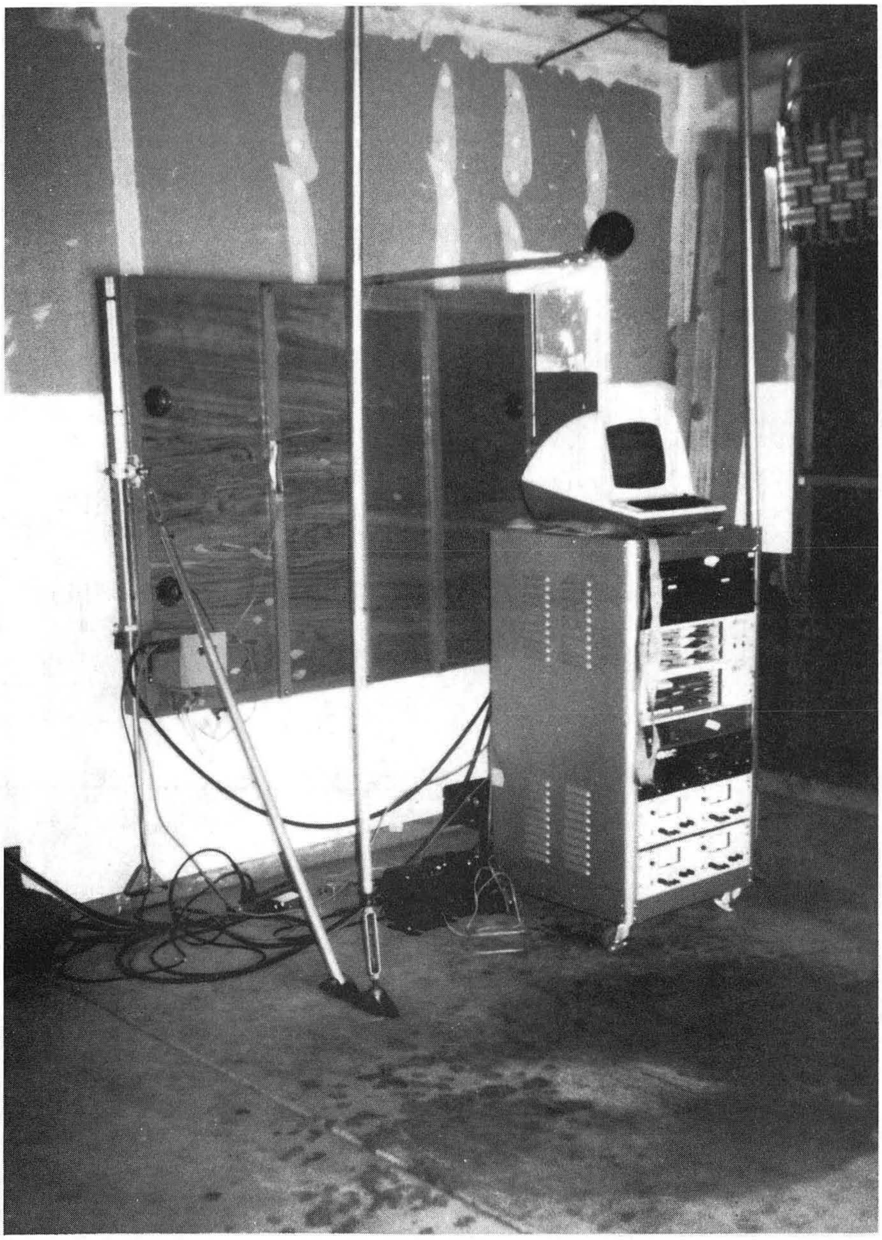

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Figure 4. ETTU blanket assembly and data acquisition system installed in the field.

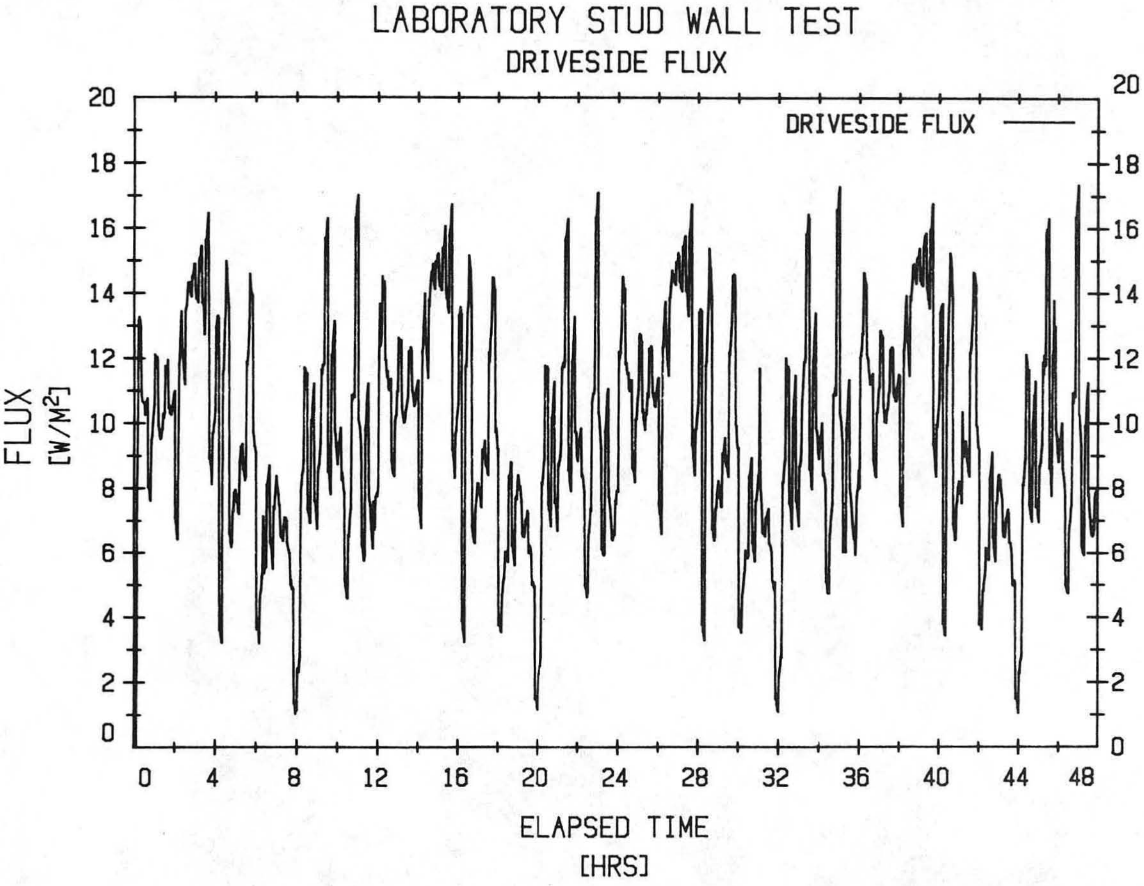

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Figure 5. Driveside flux for laboratory test of insulated stud wall (fundamental frequency = one cycle every 12 hours).

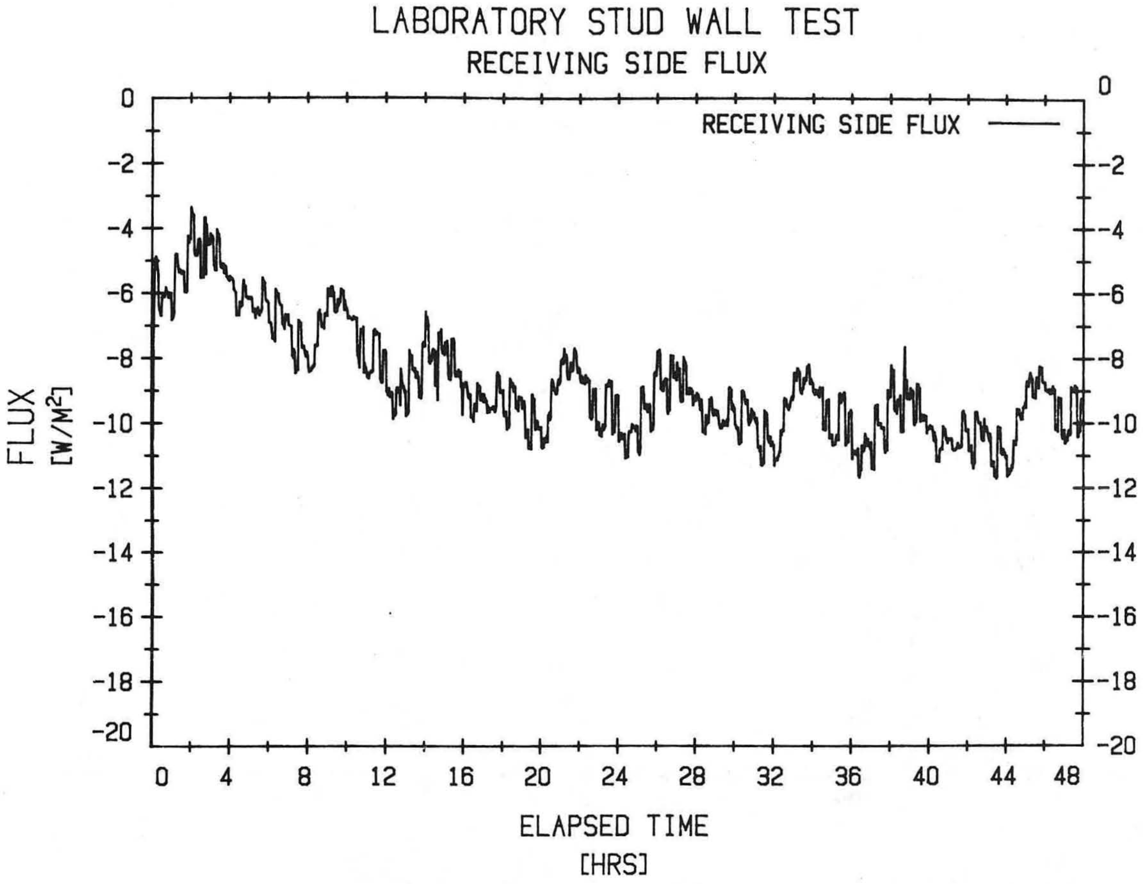

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Figure 6. Receiving side flux for laboratory test of insulated stud wall.

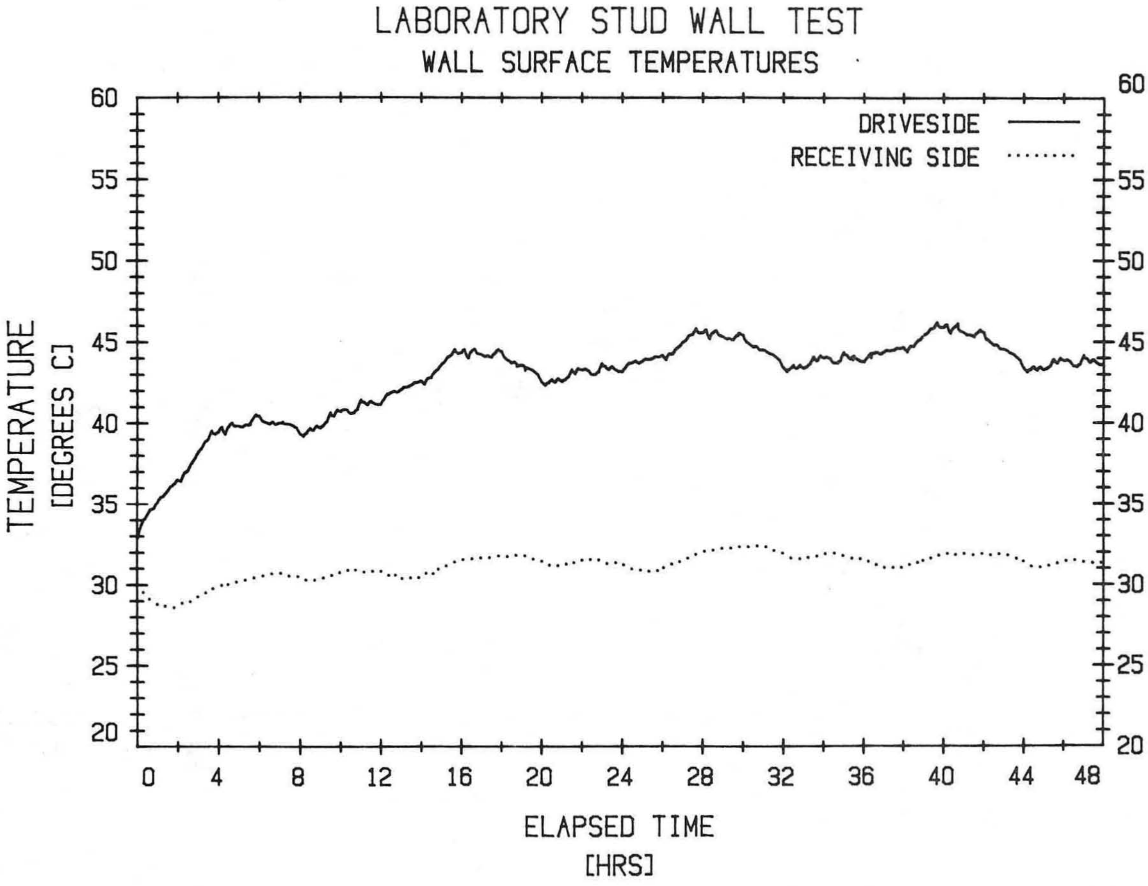

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Figure 7. Driveside and receiving side temperatures for laboratory test of insulated stud wall (fundamental frequency = one cycle every 12 hours).

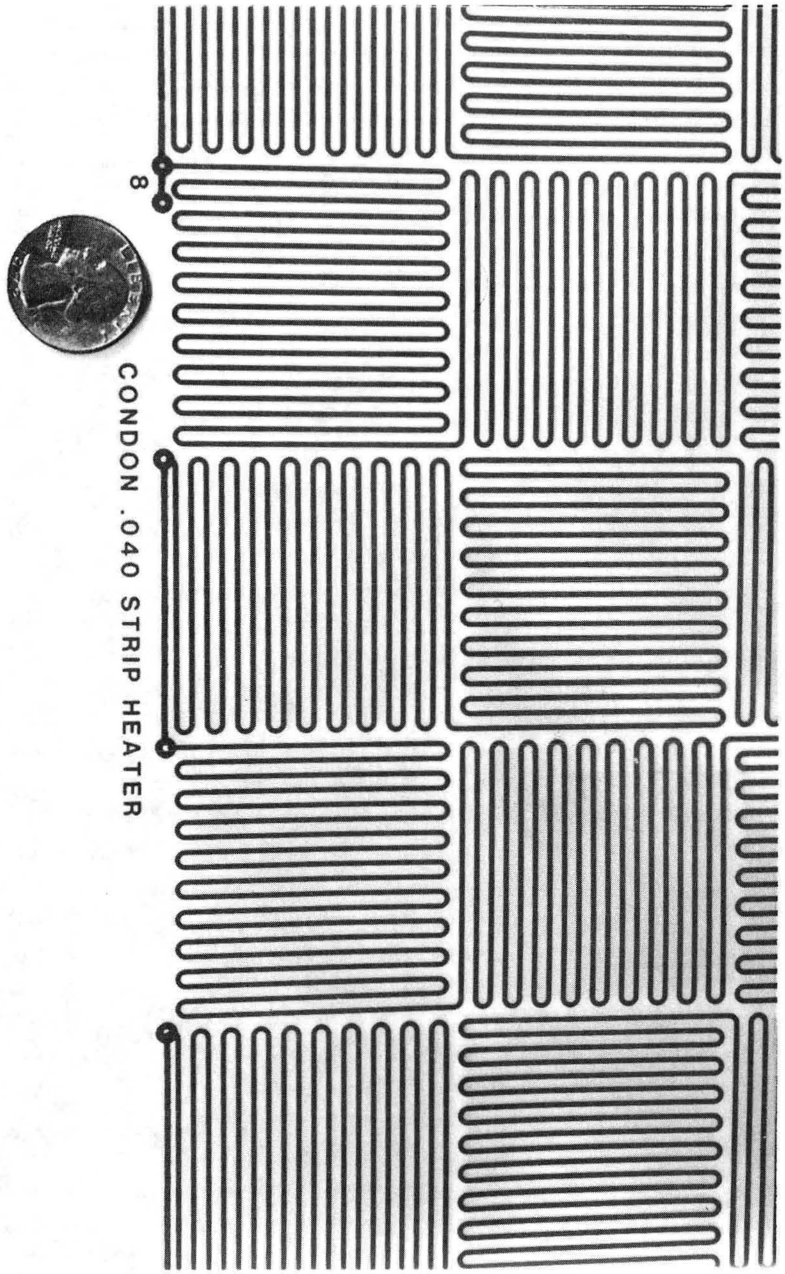

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Figure 8. Section of copper-strip electric resistance heater.

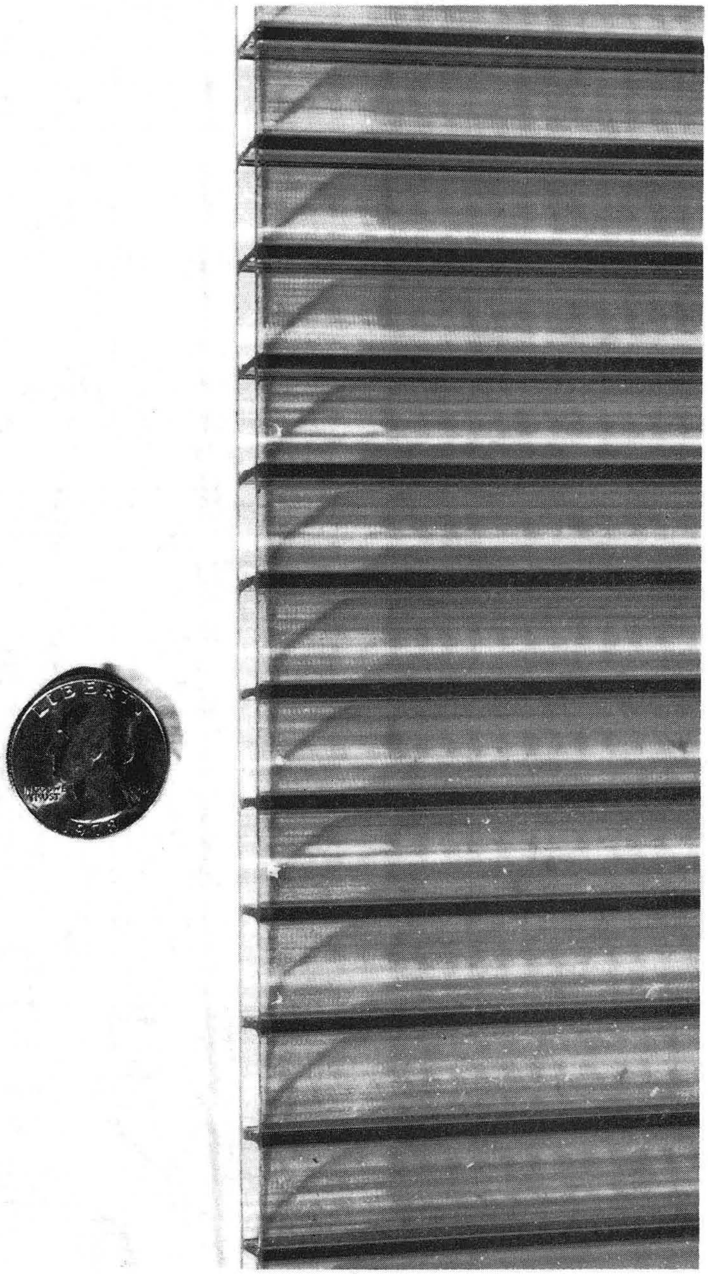

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Figure 9. Section of plastic air channel.

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