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DEPARTMENT OF THE NAVY
CIVIL ENGINEERING LABORATORY

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CIVIL ENGINEERING LABORATORY
Naval Construction Battalion Center
Port Hueneme, California

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THE DEVELOPMENT OF METHODOLOGY FOR THE DETERMINATION OF R VALUES OF EXISTING STRUCTURES BY NON-STEADY STATE HEAT TRANSFER MEASUREMENTS

June 1976

An Investigation Conducted by
GEOSCIENCE LTD
Solana Beach, California

N62583/76 M W928

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Energy conservation surveys of Navy facilities often require data on in-place R-values of existing structures. Such information has been difficult to obtain due to transient conditions caused by day-and-night temperature changes. This study indicates R-values can be calculated within about a 6% accuracy from heat flux and inside-outside wall surface temperature data that have been integrated over a 24-hour period.

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I. INTRODUCTION

The U. S. Navy's Civil Engineering Laboratory is interested in determining the R factors of thermal insulation installed in existing buildings and houses by the in-situ measurement of heat flux rates to or from such structures as well as the corresponding temperature drops.

It is clear that R factors of thermal insulations are normally measured under steady state heat transfer conditions in special thermal insulation test apparatus wherein unidirectional heat flow exists. In order to measure R values for insulation in existing structures under nonsteady state heat transfer conditions, it is necessary to extract the R values from the transient temperature and heat flow fields utilizing fundamental heat transfer functions. Such procedures are described in this study.*

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* The work was performed under contract N62583/76 M W928 over the period May 1 to June 30, 1976. The effort consisted of 250 manhours.

II. NONSTEADY STATE HEAT TRANSFER SOLUTIONS (TASK 1)

In order to develop a background for the measurement methods used in this study, two representative, nonsteady state heat transfer systems are described below to illustrate the thermal behavior in walls and ceilings of existing housing structures. Although the systems presented are simplified in detail, they are sufficiently complete to illustrate the principles involved.

A. Periodic Heat Transfer System

Consider an idealized building wall (or ceiling) which has one side that is kept at a constant temperature and the other side that experiences a sinusoidal temperature change. This system approximates a real wall or ceiling whose inner air temperature remains constant (by a thermostat) and whose outer air temperature (and solar radiation) create a periodic heat flow. In the idealized system, the periodic heat flow is simplified by a sinusoidal surface temperature function and the inner and outer thermal resistances of the air are neglected because they are small compared to wall or ceiling R values.

The idealized problem is divided into two simpler ones that are then superimposed to obtain the complete solution.

One boundary value problem is defined by steady state in a wall (Figure 1),

$$0 = \frac{d^2 t}{dx^2} \tag{1}$$

$$t(x = 0) = t_a, \quad t(x = L) = t_b \tag{2}$$

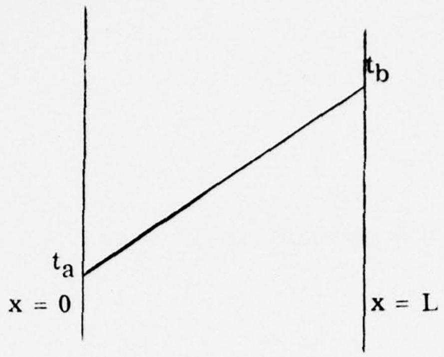

Figure 1. Steady state heat transfer in a wall.

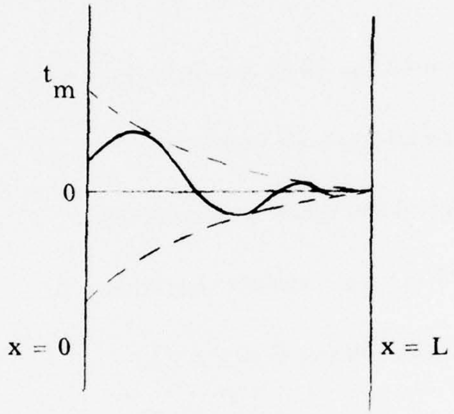

Figure 2. Sinusoidal heat transfer in a wall (with no net heat flow).

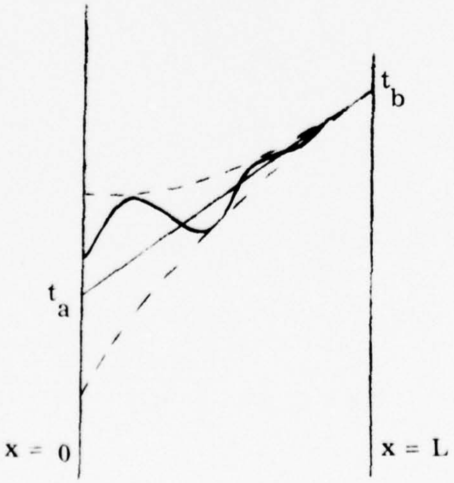

Figure 3. Sinusoidal heat transfer in a wall (with net heat flow).

The solution to this equation set is

$$t = t_a - (t_a - t_b) \frac{x}{L} \qquad (3)$$

where

t , temperature at any point x within the resistance R

t_a , temperature of one wall surface

t_b , temperature of the other wall surface

L , thickness of the wall across resistance R

x , distance through the wall $(0 \leq x \leq L)$

The second boundary value problem to be considered is sinusoidal heat transfer in a wall with no net heat flow; this system (see Figure 2) is defined by,

$$\frac{\partial t}{\partial \theta} = a \frac{\partial^2 t}{\partial x^2} \qquad (4)$$

$$t(x = 0, \theta) = t_m \cos \frac{2\pi\theta}{\theta_o} \qquad (5)$$

$$t(x = L, \theta) = 0 \qquad (6)$$

where

θ , time

a , thermal diffusivity

t_m , the amplitude of the sinusoidal temperature variation at $x = 0$

θ_o , period of the temperature variation

The solution of this boundary value problem is accomplished as follows:[1] The solution for a semi-infinite solid is used to describe the first term of the temperature function in the region $0 \leq x \leq L$. Next, a second term is developed whose surface temperature at $x = L$ is the same as that of the first term. The first term, however, decays with distance in the + x direction and the second term decays with distance in the - x direction (starting at $x = L$). This process continues so that when many terms are superimposed, a solution for the boundary value problem defined by Equations (4), (5), and (6) results, namely,

$$t = t_m \left\{ e^{-b\frac{x}{L}} \cos\left(\frac{2\pi\theta}{\theta_o} - b\frac{x}{L}\right) - e^{-b(2-\frac{x}{L})} \cos\left(\frac{2\pi\theta}{\theta_o} - b(2-\frac{x}{L})\right) + e^{-b(2+\frac{x}{L})} \cos\left(\frac{2\pi\theta}{\theta_o} - b(2+\frac{x}{L})\right) + \ldots \right\} \quad (7)$$

The complete periodic solution (see Figure 3) is the sum of Equations (3) and (7),

$$t = t_a - (t_a - t_b)\frac{x}{L}$$

$$+ t_m \sum_{N=0}^{N=\infty} (-1)^N e^{-b\left(N+\delta+(-1)^N \frac{x}{L}\right)} \cos\left(\frac{2\pi\theta}{\theta_o} - b\left(N+\delta+(-1)^N \frac{x}{L}\right)\right) \qquad (8)$$

where

$$b = \sqrt{\frac{\pi L^2}{a\ \theta_o}}$$

δ = 0 for even N values

δ = 1 for odd N values

B. Step Function System

Another unsteady state heat transfer system of interest involves a step function change in the outside surface temperature of a wall that has been at steady state. The description of this boundary value problem follows:

$$\frac{\partial t}{\partial \theta} = a\frac{\partial^2 t}{\partial x^2} \qquad (9)$$

$$t(x, \theta = 0) = f(x) = t_a - (t_a - t_b)\frac{x}{L} \tag{10}$$

$$t(0, \theta) = 0, \quad t(L, \theta) = t_b \tag{11}$$

The solution of this problem is[2]

$$t = t_b \frac{x}{L}$$

$$+ \frac{2}{\pi} \sum_{n=1}^{n=\infty} e^{-\frac{n^2 a \pi^2 \theta}{L^2}} \sin \frac{n \pi x}{L} \left[(-1)^n \frac{t_b}{n} + \int_0^L f(x) \sin (n\pi \frac{x}{L}) \, dx \right] \tag{12}$$

III. APPLICATION OF NONSTEADY STATE HEAT TRANSFER SYSTEMS (TASK 2)

A. Specific and Step Function Applications

The periodic heat transfer system described in the previous section was evaluated for a simple wall consisting of a two-inch thick cork board. Equation (8) was used to determine relative phase shift between the maximums of the temperature difference across the cork board and the heat flux as measured by a heatmeter located on the opposite side of the wall from which the sinusoidal surface temperature variations were added to the system. The heat flow equation was obtained from Equation (8) by differentiating it with respect to x to obtain the temperature-distance derivative and evaluating it at $x = L$. The theoretical phase difference between the maximums in the temperature differences across the resistance R and the heat flow at $x = L$ was found to be 11 hours. In the next section this result is compared to some experimental data obtained in a laboratory system.

The step function system was also evaluated for the cork board wall utilizing Equation (12); specifically, a calculation was made to determine how long it would take a steady state condition to reestablish itself after it was disturbed by a step function surface temperature change. It was found that a time constant for this system based on a ten percent deviation value was equal to 11.6 hours. This result is also compared to some experimental information in Section IV.

B. General Definition of the R Value in Terms of Heat Flow and Temperature-Difference Time Integrals for Periodic Operation

If the outer surface temperature of a building wall (or ceiling) is exposed to periodic environmental temperature variations (as a result of solar radiation and air temperature changes), the R value of the wall or ceiling can be obtained by relating it to the quotient of the ratio of the mean temperature difference to the mean heat flux over a repetitive 24-hour period, as shown below:

$$\frac{\overline{\Delta t}}{\frac{\bar{q}}{A}} = \frac{\frac{1}{\theta_o}\int_o^{\theta_o} \Delta t(\theta)\, d\theta}{\frac{1}{\theta_o}\int_o^{\theta_o} \frac{q}{A}(\theta)\, d\theta} = \frac{\int_o^{\theta_o} (\Delta t_{per} + \Delta t_{ss})\, d\theta}{\int_o^{\theta_o} \left(\left(\frac{q}{A}\right)_{per} + \left(\frac{q}{A}\right)_{ss}\right) d\theta}$$

$$= \frac{\int_o^{\theta_o} \Delta t_{per}\, d\theta + \int_o^{\theta_o} \Delta t_{ss}\, d\theta}{\int_o^{\theta_o} \left(\frac{q}{A}\right)_{per} d\theta + \int_o^{\theta_o} \left(\frac{q}{A}\right)_{ss} d\theta} = \frac{0 + \int_o^{\theta_o} \Delta t_{ss}\, d\theta}{0 + \int_o^{\theta_o} \left(\frac{q}{A}\right)_{ss} d\theta}$$

$$= \frac{\Delta t_{ss}}{\left(\frac{q}{A}\right)_{ss}} = R \qquad (13)$$

2

In other words, for a periodic system, the ratio of the temperature difference and heat flux integrals over a day period, θ_o, reduces to the steady temperature difference-heat flux ratio which is defined as the R value.

IV. LABORATORY VERIFICATION TESTS (TASK 3)

A. Steady State ASTM C-177 and C-518 R Value Determinations for Cork Test Panels

Geoscience's ASTM C-177 apparatus was used to determine the R values of two 48 x 48 x 2-inch cork board panels which later were used to simulate a wall system that is exposed to periodic heating on one side. The two cork panels installed in the ASTM C-177 apparatus are shown in Figure 4. A flat plate heater system separates the two cork panels. The inner heater is used to generate unidimensional heat flow in the R value measurement effort and the outer heater performs a guard function. A thermopile system is woven between the edges of the inner and outer heaters; when one heater power is so adjusted relative to another that the output signal of the thermopile between the two heaters is zero, or nearly so, all of the heat release of the central heater leaves in a one-dimensional manner from its two surfaces (no flux fringing). This feature is mandatory to yield an accurate, steady state R value for the two slabs. Figure 5 shows the overall view of the ASTM C-177 apparatus including the power control and measurement equipment. Figure 6 shows a closeup view of an unplugged surface thermocouple hole and the ends of the two cork boards separated by the flat plate heater system. Heat flux meters in the metering and guard zones are also visible in Figures 4 and 5; these sensors constitute the ASTM C-518 method.

Steady state R values as determined by the two methods are shown in Table I.

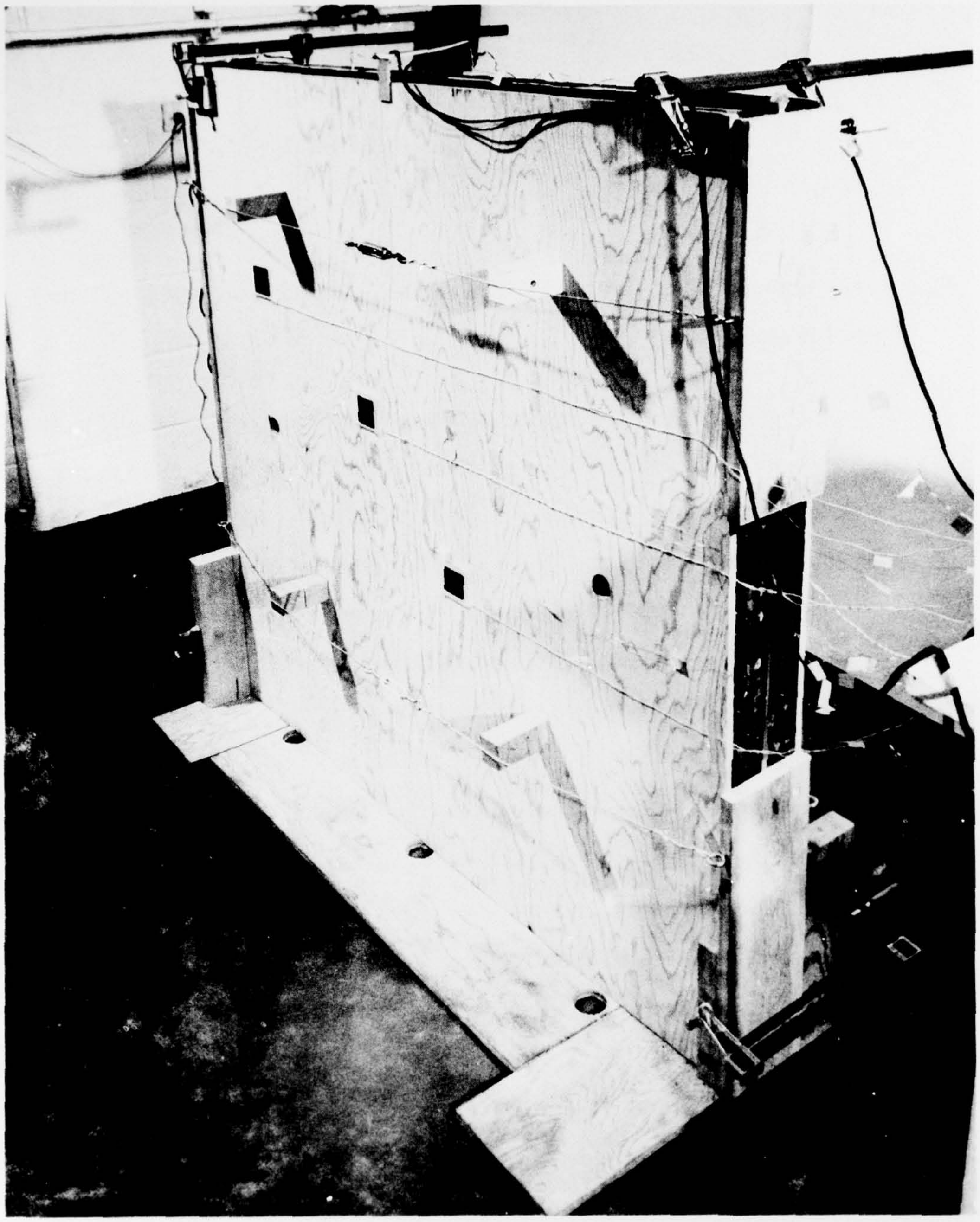

Figure 4. Two cork panels installed in an ASTM C-177 apparatus.

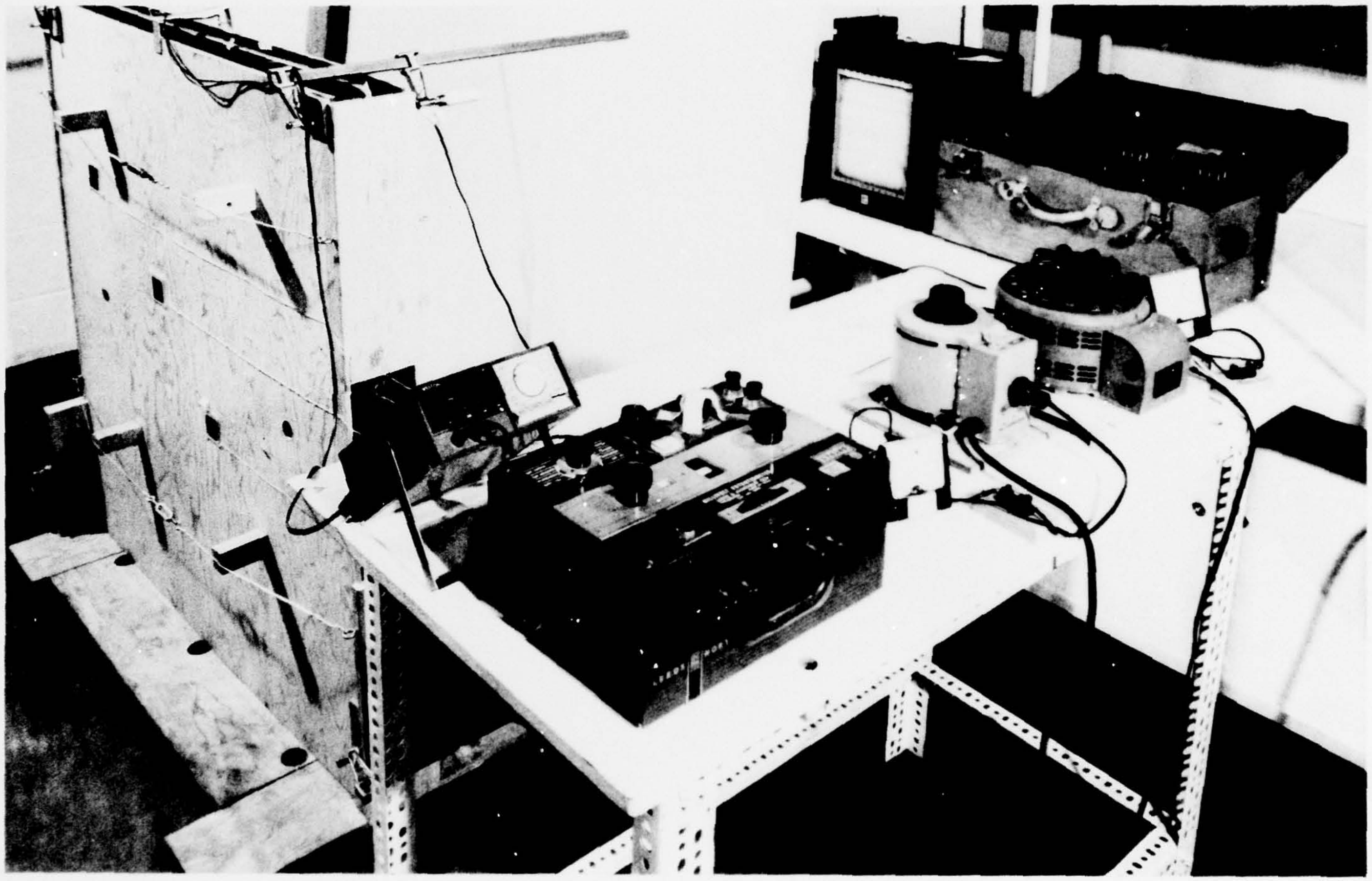

Figure 5. Overall view of the ASTM C-177 apparatus including power control and measurement equipment.

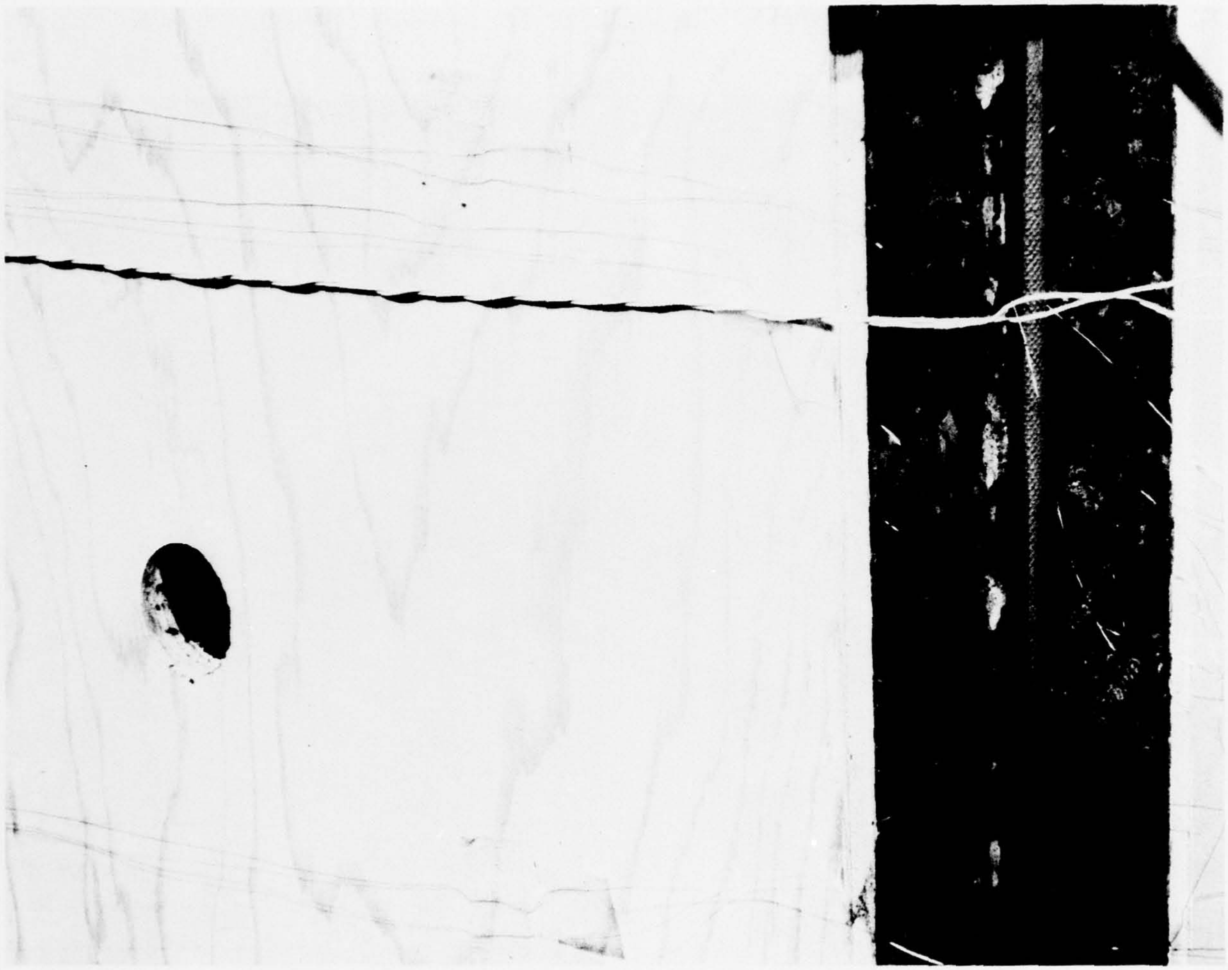

Figure 6. Close-up view of an unplugged surface thermocouple hole and the ends of the two cork boards.

TABLE I.

Steady State R Values by ASTM C-177 and C-518

Run	R_{C-177} hr ft^2 °F/Btu	R_{C-518} hr ft^2 °F/Btu	Δt_R °F
a	7.13	7.55	34.0
b	6.78	7.17	35.8

B. Simulated Periodic Heating of Cork Test Panels

The ASTM C-177 and C-518 system shown in Figure 4 was also used to perform periodic wall heat flow simulation tests. Specifically, the steady state heater system electrical inputs were left on for sixteen-hour periods (from 5:00 p.m. to 9:00 a.m.) and then interrupted with eight-hour periods of no heater power (from 9:00 a.m. to 5.00 p.m.). Such an arbitrary cyclic schedule simulates the case for a house or building wall in the summertime which is exposed to a period of solar radiation and warmer outside air temperatures during the daytime;* for this situation, air conditioning is normally used to keep the room temperature at some comfortable, constant temperature. Heat flux meter output signals and temperature differences

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*The choice of sixteen hours of power on and eight hours off was arbitrary; the order could have been reversed. The times for changing the power were related to the arrival of company personnel and the time required to make manual measurements.

across the cork board were recorded by a Honeywell recorder that contained a switching circuit so that the temperature differences and corresponding heat flows could be measured by one recorder. The results obtained for a 48-hour period (two successive periodic days) can be seen in Appendix A. In addition to the recorder traces, additional system heat flows and temperature differences were recorded manually throughout the daytime periods and part of the nights; a typical data set can be seen in Appendix B.

The R value results for the simulated, periodic heating data were evaluated for two consecutive days and the results are shown in Table II. Equation (13) was used to make the evaluations.*

TABLE II.

Transient R Values as Determined by Equation (13)

Date	R hr ft^2 °F/Btu
June 22, 1976	6.85
June 23, 1976	6.68

C. Comparisons of Steady State and Transient R Values

Table III shows a comparison between the steady state and transient R values determined for the cork board wall:

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*The integrations were performed numerically using the $\Delta t(\epsilon)$ and $q/A(\theta)$ measurements at half hour time intervals over the 24-hour period.

TABLE III.

Comparison of Steady State and Transient R Values for
A Two-Inch Thick Cork Board Wall

Mean R_{ss}, hr ft^2 °F/Btu	Mean R_{trans}, hr ft^2 °F/Btu	Deviation, %
7.16	6.77	5.6

D. Comparison of Experimental Performance with Predictions

It is also of interest to review the experimental results in the light of the idealized mathematical sinusoidal and step function models. Although the experimental apparatus was not operated as a sinusoidal or step function surface temperature system, the periodic heating used does have similar features. From the Δt and q/A traces in Appendix A, it is clear that time constants, to say the ten percent value, are of the order of eight to ten hours. This result is in general agreement with the 11 and 11.6 hour time constants for the sinusoidal and step-function predictions, respectively, given above.

V. OPERATING MANUAL (TASK 4)

The material in this section consists of an outline of the operating procedures that are suggested for use in measuring R values of existing structures that are exposed to nonsteady state heat transfer conditions.

A. Instrumentation

The instrumentation for such a measurement system would consist of (1) a heat flux transducer, (2) a Δt thermopile, (3) a potentiometer or microvoltmeter for the monitoring of the output signals, and (4) a millivolt recorder for output signal trace recordings.

The heat flow transducer must be sensitive enough so that small heat fluxes of the order of 0.1 Btu/hr ft^2 can readily be measured. The Δt thermopile should have enough junction sets so that large mullivolt readings result from temperature differences across walls or ceilings as small as two or three degrees Fahrenheit. The potentiometer or microvoltmeter should be sensitive enough to measure five microvolts; the millivolt recorder should also have this sensitivity.

B. Installation

The heat flux transducer can be affixed to either side of a wall or ceiling to be studied. If the sensor is located on the outside wall of a building, however, it is suggested that a thin layer of insulation (small compared to the wall R value) be added to the heat flux transducer to reduce the environmental thermal noise. The Δt thermopile which is used to measure the temperature difference across a wall or ceiling resistance should be located in the same vicinity where the heat flux transducer has been located; the junction sets on the outer wall should also be thermally insulated a little. These two sensors can be attached to the surfaces by a sticky adhesive or by masking tape. Window areas or ceiling crawl holes can be used to position the Δt thermopile. The heat flux transducer and Δt thermopile sensor set can be located in various regions of a building where it is thought information on R values is required.

C. Modes of Operation

1. Periodic Operation

If it is desired to determine the R value for a sinusoidal or periodic cycle (a 24-hour period), the data obtained by the instruments described above should be substituted into Equation (13) and then evaluated as discussed on page 16.

2. Quasi-Steady State Operation

From the heat flow temperature traces shown in Appendix A, it is noted that after 3:00 a.m. in the morning, the heat flow and temperature difference traces for insulations with R values of about 10 appeared to have reached a quasi-stationary state. The R value determined from the data in this region agree very closely with the steady state R value data sets shown at the beginning of the trace in Appendix A. Therefore, another method of evaluating R values would be to make transient measurements early in the morning prior to the rise of the sun and then to use these quasi-steady state values to determine an R value. If the wall R is significantly greater than 10, quasi-steady state may not be reached and then the method cannot be used.

VI. REFERENCES

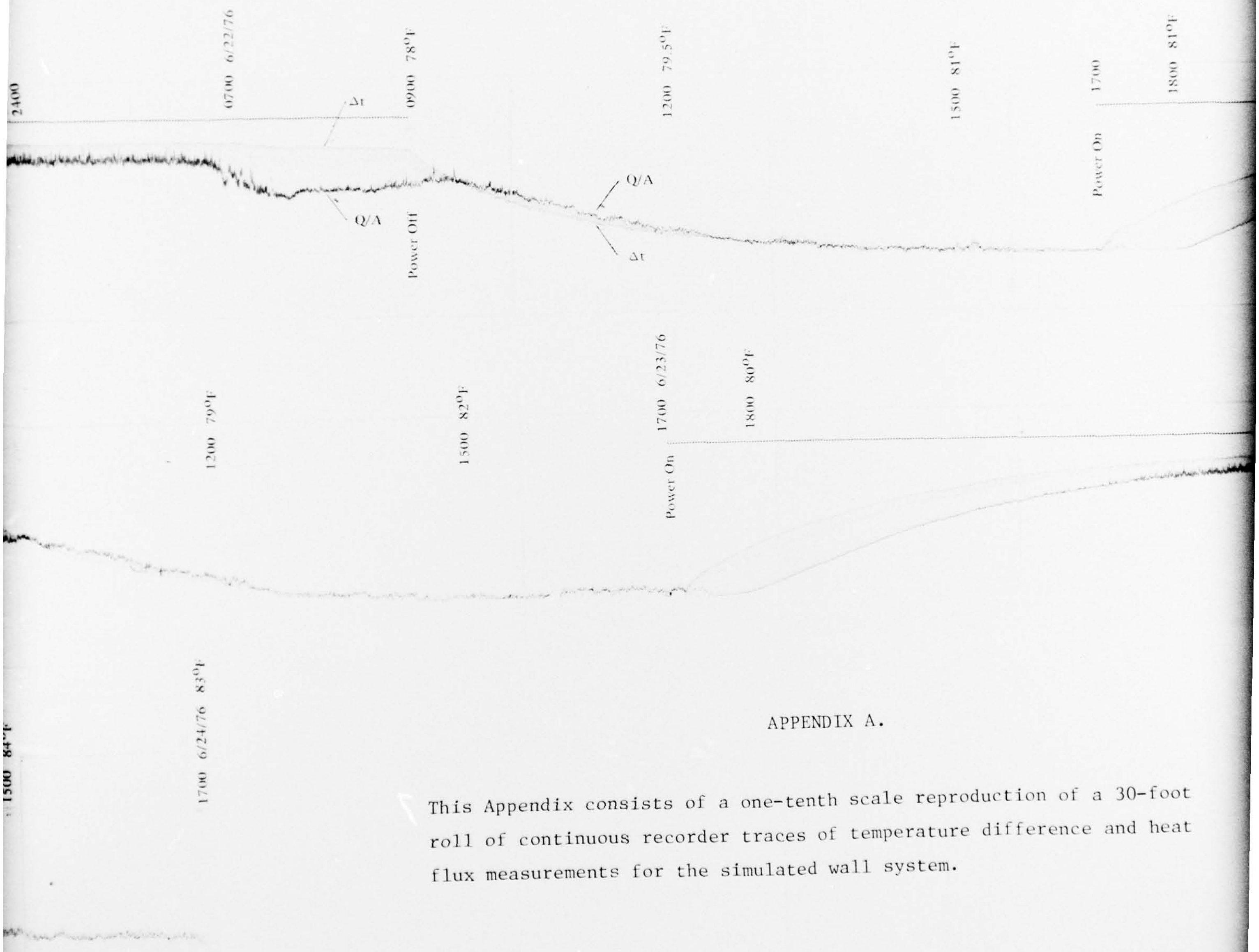
1. Boelter, L. M. K.; Cherry, V. H.; Johnson, H. A.; and Martinelli, R. C., "Heat Transfer Notes," University of California Press, p VI-22, 1946.

2. <u>Fourier Series and Boundary Value Problems</u>, R. V. Churchill, McGraw-Hill Co, p 108, 1941.

VII. APPENDICES


Power On
1700 6/21/76
Q/A
Δt
2400
2400 6/22/76
0600 72°F
0700
Q/A
Δt
Power Off
0900 78°F
Power Off
Q/A
Δt
0900 78°F
1200 84°F
1500 84°F

2



APPENDIX A.

This Appendix consists of a one-tenth scale reproduction of a 30-foot roll of continuous recorder traces of temperature difference and heat flux measurements for the simulated wall system.

3

APPENDIX A.

endix consists of a one-tenth scale reproduction of a 30-foot continuous recorder traces of temperature difference and heat surements for the simulated wall system.

Appendix B. A Typical Data Sheet of Manual Measurements Made During the Transient Wall Heating Test Experiments

Date/Time	q/A_x Metering Section Side 1	q/A_{113} Guard Section Side 1	q/A_{122} Metering Section Side 2	t_i Upper Side 1	t_i Lower Side 1	t_o Upper Side 1*	t_o Lower Side 1	t_i Upper Side 2	t_i Lower Side 2	t_o Upper Side 2	t_o Lower Side 2	Δt Side 2	t_{air} ^oF	TP Δmv	t Heater	E_c	I_c
22 Jun 76																	
0837	0.620	0.489	0.273	0.845	0.843	–	0.06	0.814	0.791	0.05	0.039	0.758	78	0.32	0.87	7.83	0.658
0903 power off																	
1000	0.496	0.411	0.256	0.457	0.445	–	0.016	0.388	0.368	0.005	0.029	0.396	78	0.721	0.470	0	0
1100	0.338	0.269	0.182	0.235	0.229	–	-0.058	0.220	0.203	-0.051	0.067	0.275	79	0.584	0.247	0	0
1200	0.251	0.180	0.125	0.101	0.096	–	-0.085	0.096	0.079	-0.085	0.101	0.179	79.5	0.402	0.201	0	0
1400	0.089	0.071	0.061	-0.041	-0.052	–	-0.123	-0.055	-0.063	-0.118	0.170	0.083	80.1	0.183	-0.038	0	0
1450	0.073	0.010	0.042	-0.070	-0.080	–	-0.120	-0.078	-0.082	-0.118	0.138	0.060	81	0.113	-0.068	0	0
1550	0.028	0.039	0.016	-0.089	-0.087	–	-0.120	-0.090	-0.100	-0.115	0.128	0.049	82	0.754	-0.080	0	0
2100	0.605	0.587	0.291	0.758	0.753	–	0.060	0.759	0.648	0.064	-0.042	0.673	80	0.106		8.00	0.679
23 Jun 76																	
0550	0.788	0.698	0.363	1.001	1.021	–	0.176	0.990	0.972	0.151	-0.145	0.831	72	0.42	1.035	8.08	0.675

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*This thermocouple circuit open.