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A Field Thermal Measurements Technique for Roofdeck Systems

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ABSTRACT

A procedure for field thermal measurement of building envelope systems using heat flow meters (HFM) is presented. HFM are first calibrated in the field at the measurement site using a field HFM calibrator (hereafter referred to as GFHC [1]). After calibration, the GFHC is removed and the calibrated HFM are attached to the building substrate at the measurement site for data acquisition. The location of the HFM during the data acquisition phase is identical to their location during the calibration phase. The HFM output is converted to a heat flux as a function of time by appropriate application of the HFM calibration curve. The underlying principles of the design and construction of the GFHC are provided. The convection and radiation factors that are specific to the particular environment in which measurements are carried out and which affect the HFM calibration are defined and derived from heat transfer theory supported by some experimental data, which are discussed in detail. During HFM calibration, heat fluxes in the range of 2 to 8 $Btu/ft^2 \cdot hr$(6 to 25 W/m^2) are steadily generated and measured for calibration at field conditions. A portable data-logging system capable of scanning 100 channels of information is used for data acquisition at variable scan rates. A computer performs all subsequent data reduction and reporting. The principles of operation of the GFHC are applicable to HFM calibration on nearly any substrate in most field environments.

INTRODUCTION

Sound quantitative thermal performance measurements of existing building envelope systems exposed to field conditions are currently lacking. Information from such measurements can be used to compare actual in-place performance with theoretically expected performance. In-place measurement also provides data on peak energy loads and average energy losses for the particular system under study. Improvements in design and construction of building envelope systems can materialize from these studies. Furthermore, in-place measurement is becoming a popular approach for assessing the thermal performance of building envelopes [2,3,4].

A properly calibrated heat flow meter (HFM) gives quantitative information about the rate of energy flowing through building envelope systems under actual use conditions. Unfortunately, despite widespread use of HFM, very little has been reported regarding HFM calibration when used for nondestructive thermal measurement of building envelopes. This paper addresses such a calibration technique. A field HFM calibrator (GFHC) was developed and constructed [1] to provide an on-site calibration of HFM while the HFM are exposed to the same environment as that of the building envelope system to be measured. The GFHC generates and meters a uniform heat flux ($\dot{q}$) through any building envelope such as a roofdeck substrate. A cluster of HFM are arranged within the 12 x 12-in.(0.30 x 0.30-m) metering area.

The field thermal measurements technique consists of HFM calibration followed by thermal measurement of the envelope with the calibrated HFM. During calibration, the HFM are attached to the GFHC substrate, which is closely connected to the building envelope substrate. The

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GFHC substrate is a replica of the building envelope substrate to be measured and is exposed to the same environment. The HFM electromotive force (emf), convection and radiation factors (H and RAD, respectively) and substrate surface temperature (t_s) are measured, evaluated and recorded. Experimental data coupled with heat transfer theory show that these factors must be accounted for to obtain accurate quantification of the HFM calibration parameter ($\dot{q}$/emf). After calibration, the GFHC is removed and the HFM are attached to the building envelope substrate for measurement. The HFM emf, t_s, and the H and RAD factors are measured and recorded to determine the heat flux through the building envelope.

The field measurements technique using the GFHC can be applied to roof-deck systems, wall systems, floor systems, etc. The GFHC is designed to calibrate HFM in most environments and on substrates of various configurations typically used in the field. In the remainder of this paper a roof-deck system is discussed as a representative example of building envelope systems.

FIELD THERMAL MEASUREMENTS USING HFM

Figure 1 shows two methods of in-place measurement using HFMs. Figure 1 (a) illustrates an HFM embedded within the roof-deck structure being measured. In this method the meter is in intimate contact with the surrounding roof-deck material and conductive heat transfer is controlling. This approach is not suitable for most purposes because it is destructive. Penetrating the existing roof-deck structure is messy and provides no guarantee that the measured structure is representative.

Figure 1 (b) illustrates an alternative method in which HFM are attached to the roof-deck substrate. This nondestructive approach was selected for in-place roof-deck system measurement. This method quantifies energy flow at a specific boundary of interest. Measurement of heat flux into or out of a building envelope can be obtained by attaching HFM on the substrate. However, the HFMs attached to the roof-deck substrate are exposed to unique environmental conditions identical to the particular roof-deck to be measured. In this configuration, the influence of convection and radiation are controlling for a particular substrate/HFM system.

HFM Characterization

The HFM generates an electromotive force (emf) that is proportional to a temperature difference (Δt) across a thin disk located within a protective covering. A very dense thermopile that consists of series-connected thermocouples is arranged across the disk. The emf induced is directly proportional to Δt;

$$\text{emf} = K'(\Delta t)\ en \tag{1}$$

where

emf = thermopile electromotive force, mv

e = sensitivity parameter dependent on the type of thermocouple, mv/°F(mv/°K)

n = number of thermopile junctions

Δt = temperature difference across the disk, °F(°K)

K' = constant related to the specific HFM construction.

The HFM can quantify the heat flow ($\dot{q}$) passing through a roof-deck substrate only if (1) its emf is measured and (2) the relationship between emf and $\dot{q}$ is established. The process of determining the relationship between emf and $\dot{q}$ is called the calibration of the HFM.

The technique of calibration of an HFM depends on the way it is being used in the field. The presence of the HFM can alter the heat flow patterns that would exist if the HFM were not present. The calibration technique used must account for this effect. In principle, the calibration should be performed in such a way that the HFM senses an environment it will sense in the measurement phase. For example, in Fig. 1 (a), the HFM is embedded in a roof-deck for in-place measurement. That HFM should be calibrated embedded in the same roof-deck material. If the HFM is used "exposed" as in Fig. 1 (b), proper techniques of calibration should be used so that the HFM senses the same environment. Determining what "the same environment" consists of and how it was obtained are significant issues addressed in this paper.

Before determining what "the same environment" means, experiments were performed to study HFM response to various environmental conditions. The American Society for Testing and Materials (ASTM) tests used and discussed were adapted to include all HFM experimental work. The HFM used satisfactorily met sensitivity, precision, and size requirements [5]. Furthermore, they are flat, moisture-proof, moderately rugged, and uniform in construction.

EXPERIMENTAL RESULTS

HFM Response to Temperature

Figure 2 shows that a nonlinear relationship exists between the HFM response parameter and HFM temperature for HFM#13. A sound least-squares fit of the data was determined:

$$\frac{\dot{q}}{emf} = 326.8 - 1.616\ t_h + 0.002296\ t_h^2 \qquad (2)$$

where

$\dot{q}$ = average steady-state heat flux, W/m^2

$\dot{q}/emf$ = HFM response parameter, $W/m^2 \cdot mv$

t_h = HFM temperature, °K

The non-linear relationship of response parameter versus t_h was commonly observed for this type of HFM. The t_h effect was rather small. A 3% reduction in the calibration parameter for a 18°F(10°K) fluctuation in temperature at about 75°F(297°K) was observed for HFM#13.

This study was conducted in accordance with the ASTM Test for Steady-State Thermal Transmission Properties by Means of Heat Flow Meter (C518) [6]. The specimen consisted of sandwiched HFM between two 12 x 12-in.(0.30 x 0.30-m) 1-in.(25-mm) thick expanded polystyrene foam boards. The equipment controlled and measured test-heat fluxes ($\dot{q}$), oriented in a heat flow down direction that ranged between 5.0 to 5.7 $Btu/ft^2 \cdot hr$(15.8 to 18.0 W/m^2). HFM emf output was simultaneously recorded using a data-logger. The HFM temperature (t_h) was taken as the mean of the temperatures of the apparatus hot and cold face plates.

The $\dot{q}$/emf measured for HFM#13 using the C518 method was within 4% of the manufacturer's reported value for t_h=68°F(293°K). The manufacturer calibrates HFM using the ASTM Test for Steady-State Thermal Transmission Properties by Means of the Guarded Hot Plate (C177)[7]. The ASTM C518 and C177 methods of HFM calibration resemble the method of HFM application illustrated in Fig. 1 (a) since heat transfer is primarily by conduction.

HFM Response to Certain Environmental Factors

The HFM responses were quantified using the ASTM Test for Thermal Conductance and Transmittance of Built-Up Sections by Means of the Guarded Hot Box (C236)[8]. Unlike either ASTM C518 or C177 test methods, this method provides an environment for testing that more closely represents the HFM application shown in Fig. 1 (b). Figure 3 shows a simplified schematic of the guarded hot box (GHB). The specimen 72 x 72-in.(1.83 x 1.83-m) is mounted horizontally between the guard, metering, and environmental boxes in a heat flow down configuration. During steady-state GHB operation, the energy generated within the metering box is equivalent to the energy passing through the 60 x 60-in.(1.52 x 1.52-m) metering area of the specimen. The specimen's hot and cold surface temperatures are maintained constant and uniform throughout the test. A complete description of the equipment and design of the GHB was presented by Perrine et al [9]. GHB calibration was performed prior to the start of the experimentation using a testing procedure described by Orlandi, et al [10].

The specimen used for the experiment was an extruded polystyrene foam board 2-in.(51-mm) thick . A flat 24-gauge galvanized steel sheet, closely bonded to the specimen, simulates the underside of a roof-deck. The HFM were attached to the steel sheet exposed to the environmental box. The emissivity of the exposed HFM surface was adjusted to be close to the emissivity of the steel substrate by application of a thin piece of metal foil to the HFM. A series of ten experiments with uniform heat fluxes of 1.8, 2.7 and 3.5 $Btu/ft^2 \cdot hr$(5.7, 8.5 and 11.0 W/m^2) oriented downward were conducted. The air speed generated inside the environmental box was controlled at three distinct levels of operation ranging between approximately 0.5 to 7 mi/hr (0.2 to 3.1m/s). Therefore, three distinct levels of local heat transfer coefficients were obtained at these air speeds for each flux operation. A uniform steel substrate temperature was measured at 16 points within the metering area of the specimen. The average steel substrate temperatures ranged between 80.7 and 83.2°F(300.0°K and 301.4°K) for the runs so that the t_h effect on $\dot{q}$/emf was negligible.

Influences of Convection/Radiation. Figure 4 illustrates a significant dependence of the response parameter for HFM#1 on the local heat transfer coefficient observed. The local heat transfer coefficient is defined as

$$h_{loc} = \frac{\dot{q}}{t_s - t_r} \tag{3}$$

where

h_{loc} = local heat transfer coefficient, $Btu/ft^2 \cdot hr \cdot °F(W/m^2 \cdot °K)$

$\dot{q}$ = average steady-state heat flux through the substrate, $Btu/ft^2 \cdot hr(W/m^2)$

t_s = mean steel substrate temperature observed 0.5-in.(13-mm) from HFM#1, °F(°K)

t_r = mean air temperature measured 3-in.(76-mm) from the steel substrate, °F(°K)

The $\dot{q}$/emf increased twofold as h_{loc} ranges from 0.24 to 1.7 $Btu/ft^2 \cdot hr \cdot °F(1.4$ to $9.7\ W/m^2 \cdot °K)$ The average of at least four 0.5 hr. readings were taken to compute the data after steady-state conditions were achieved. The three controlled fluxes are represented within each of the three clusters of data shown in Fig. 4. Other HFM tested showed similar $\dot{q}$/emf behavior as a function of h_{loc}. The manufacturer's reported $\dot{q}$/emf measured in accordance with the ASTM C177 method was 14.9 $Btu/ft^2 \cdot hr \cdot mv(47\ W/m^2 \cdot mv)$ for HFM#1 while it ranges from 4 to 8 $Btu/ft^2 \cdot hr \cdot mv$ (12 to 25 $W/m^2 \cdot mv$) in this series of experiments. This marked difference is due to the difference in the method of testing, h_{loc} variation, substrate/HFM interaction, etc.

Figure 5 shows $\dot{q}$/emf data plotted as a function of the radiative heat transfer driving force defined as RAD.

$$RAD = \sigma(t_s^4 - t_i^4) \tag{4}$$

where

RAD = radiation heat transfer driving force, $Btu/ft^2 \cdot hr(W/m^2)$

t_i = mean temperature of surrounding surfaces, °R(°K)

σ = Stefan-Boltzmann universal constant = $0.171 \times 10^{-8} Btu/ft^2 \cdot hr \cdot °R^4 (5.67 \times 10^{-8}\ W/m^2 \cdot °K^4)$

A significant dependency of $\dot{q}$/emf on RAD was observed. This is not surprising since h_{loc} and RAD are correlated in our GHB (correlation coefficient $r = -0.8$). The observed relationship between h_{loc} and RAD may not exist in all environments because of independent interactions among surroundings in the building envelope not encountered in the GHB.

The dependence of the HFM response parameter on the environmental conditions described above can be explained readily by examining heat balance equations across the HFM thickness. For the same heat flux $\dot{q}$ through the substrate, as h_{loc} increases and RAD decreases, the temperature difference across the HFM decreases, which results in a decrease in emf output. Thus $\dot{q}$/emf increases. The HFM response parameter is also dependent on the relative thermal conductivities of the substrate and HFM materials. For example, different $\dot{q}$/emf values may be expected if the HFM were mounted directly on insulation instead of on metal.

HFM Surface Emissivity Influence. The dependence of $\dot{q}$/emf on the emissivity of the HFM exposed surface attached to the steel substrate is significant. Table 1 compares $\dot{q}$/emf data for 12 HFMs observed with respect to changes made only to the HFM exposed surface emissivity. GHB operating levels were held constant for the two runs studied at low h_{loc} operation. In Run #1 the HFM exposed surfaces were left unchanged (emissivity = 0.9). For Run #2 the HFM exposed surface emissivities were either changed or remained unchanged as shown in Tab. 1.

Response parameters for HFM#1, #6, and #15 changed significantly when large step changes were made to their exposed surface emissivities. As the HFM exposed surface emissivity decreased from 0.9 to 0.1-0.4, HFM emf decreased as a result of the increased resistance of the HFM system. Therefore, $\dot{q}$/emf increased for HFM#1, #6, and #15 as lateral losses around the HFMs became more important. When either small changes or no changes in emissivity were made, a change in $\dot{q}$/emf within 5% was observed.

THEORETICAL CONSIDERATIONS

A discussion of convective and radiative heat transfer theory [11,12] is presented regarding environmental factors affecting HFM/substrate relationships.

Convective Heat Transfer

Convective heat transfer is affected by fluid (air in this case) flow phenomena. The type of fluid flow present is either natural or forced. In natural convection, the motion is caused mainly by density differences that results from a temperature gradient from the surface to the air. This flow can range from laminar to turbulent. In the forced convection case, the motion arises from pressure gradients caused, for instance, by a blower.

Heat transfer by convection can be represented for either natural or forced convection by

$$\dot{q}_c = hA\ (t_s - t_r) \tag{5}$$

where

$\dot{q}_c$ = heat transfer due to convection, $Btu/ft^2 \cdot hr (W/m^2)$

For natural convection, this empirical relationship holds

$$Nu = c(Gr)^{n1}(Pr)^{n2} \tag{6}$$

where

$$Nu \text{ (Nusselt number)} = \frac{hL}{k} \tag{7}$$

$$Gr \text{ (Grashof number)} = \frac{L^3 \rho^2 g\, \beta (t_s - t_r)}{\mu^2} \tag{8}$$

$$Pr \text{ (Prandtl number)} = \frac{Cp\,\mu}{k} \tag{9}$$

L = characteristic length of roof-deck substrate

t_s, t_r = surface and air reference temperatures

g = universal gravitational constant

β = coefficient of volumetric expansion for air (dependent on temperature only for ideal gas conditions)

ρ, μ, k, C_p = physical property data of air (density, viscosity, thermal conductivity, heat capacity)

c, n1, n2 = constants dependent on orientation, geometry, and roughness of the substrate; heat flow direction; and the fluid-flow regime.

Therefore, h for natural convection is dependent only on L, t_s, t_r and heat flow direction for substrate geometry in the presence of air at atmospheric pressure.

For forced convection the following empirical relationship holds

$$Nu = c'(Re)^{n1'}(Pr)^{n2'} \tag{10}$$

where

$$\text{Re (Reynolds number)} = \frac{LV\rho}{\mu} \tag{11}$$

V = bulk velocity of air

c', $n1'$, $n2'$ = constants dependent on substrate geometry and orientation and V.

Therefore, h for forced convection is dependent only on V, L, t_s, and t_r for any substrate. Altogether, convective heat transfer theory shows that h is a function of L, t_s, t_r, V, direction of heat flow, substrate orientation, geometry and roughness, physical property data of air at $(t_s + t_r)/2$, and pressure.

Radiative Heat Transfer

Heat transfer by radiation is affected by many factors. These influences include emissivities of the roof-deck substrate (ε_s) and of enclosure surfaces in the environment (ε_i), areas of the substrate (A_s), and areas of the enclosure surfaces (A_i); view angles and distances between the roof-deck substrate and enclosure surfaces; reflectivities of the enclosure surfaces (∂_i); the medium between the substrate and surrounding surfaces, and the temperatures of the substrate (t_s) and enclosure surfaces (t_i). The relationship is given by:

$$\dot{q}_R = \sigma \left[A_s \varepsilon_s t_s^{\ 4} - \sum_{i=i}^{n} B_{is} A_i \varepsilon_i t_i^{\ 4} \right] \tag{12}$$

where

$\dot{q}_R$ = rate of net radiative heat transfer from the roof-deck substrate to n surfaces in the environment

σ = Stefan-Boltzmann universal constant

B_{is} = absorption factor, which defines all of the energy emitted from enclosure surface i that is absorbed by the roof-deck substrate. B_{is} is a function if ∂_i, ε_s, ε_i, the medium between the roof-deck substrate and the enclosure surface and the view factor relationships between the roof-deck substrate and the enclosure surface.

All factors in Eq 12 are dependent on the properties and conditions of the roof-deck substrate and environment. HFM calibrated using the ASTM C236 method are limited to the environment inside the GHB. Therefore, there is no guarantee that the HFM calibration data obtained in the GHB would hold in any field environment encountered.

RECOMMENDED CALIBRATION PROCEDURE AND FIELD MEASUREMENT TECHNIQUE - GENERAL DESCRIPTION

Based on experimental and theoretical considerations, it can be appreciated that a calibration parameter, now defined by the response parameter ($\dot{q}$/emf), describes the relationship between $\dot{q}$ and HFM emf as a function of many variables. These variables are, respectively, convection factor (H), which will discussed in a later section, radiation factor (RAD), HFM and roof-deck substrate interaction, roof-deck substrate geometry, surface temperature, and properties of the enclosure of which the roof-deck is a part. These factors can satisfactorily characterize the environment in which HFM calibration is to be performed. The data can then be applied to actual field measurement with a one-to-one correspondence. Then and only then can an HFM be used to quantify the heat flow passing through a roof-deck substrate.

In order to achieve the calibration defined above, a field HFM calibrator (GFHC) was designed and constructed as described in a later section. HFM calibration is then performed in the field where in-place thermal measurement is to be made. The procedure can be described in the following manner. First, a representative sample site is selected for measurement. The HFM are then calibrated at the selected location using the GFHC. During calibration, the HFM are attached to the GFHC substrate. The GFHC substrate surface is made a replica of the roof-deck substrate to be measured. The GFHC and HFM are exposed to the field environment during calibration. A cluster of HFM are calibrated within a 12 x 12-in. (0.30 x 0.30-m) metering area of the GFHC.

In addition to HFM emf and measured $\dot{q}$ generated with the GFHC, data that characterize the environment are monitored and recorded to obtain an accurate HFM calibration. After calibration, the GFHC is removed and the calibrated HFM are applied to the building roof-deck substrate at the same selected site for measurement in the same manner. All pertinent data needed to quantify the thermal performance of the roof-deck system are then acquired.

GFHC DESIGN CONSIDERATIONS

The GFHC design requirements are:

1. reasonable field measurement accuracy
2. calibration of HFM by providing a known downward oriented heat flux within the same order of magnitude of heat flux to be measured through the roof-deck system
3. a universal device for measurement of any representative roof-deck substrate material and configuration in most environments
4. a sound and moisture proof structure
5. a lightweight structure for easy use.

Figure 6 illustrates the GFHC and the roof-deck system to be measured. The GFHC is composed of top and bottom sections. The permanent top section generates and meters a heat flux to the bottom section, which serves as the substrate for HFM calibration. As such, the bottom section is made as a replica of the building roof-deck substrate to be measured. The thickness of the GFHC bottom section above the roof-deck substrate does not influence HFM calibration within the framework of linear heat transfer theory. The GFHC sections are closely coupled using a mechanical support system forming a structural unit. The GFHC is suspended from the joists close to the building roof-deck substrate with the bottom section facing down for HFM calibration.

The GFHC design concept is primarily based on heat transfer Eqs 5 through 12. The GFHC bottom-section substrate configuration and surface preparation (e.g., painting, etc.) should closely match that of the roof-deck substrate to be measured. This ensures that the convection and radiation factors observed during HFM calibration have the same meaning as those observed during the measurement stage.

The minimum characteristic length (L) of the GFHC is estimated using Eqs 8 and 9. In the case of natural convection, the transition from laminar to turbulent flow regimes takes place when

$$Gr \cdot Pr = 10^9 \tag{13}$$

for a 10°F(5.6°K) temperature difference between the GFHC surface and air, given k, ρ, μ and Cp data for air at 70°F(294°K), Eq 13 gives

$$Gr \cdot Pr = (1.6 \times 10^6) \frac{L^3 \Delta t}{ft^3 {}^\circ F} = 10^9 \tag{14}$$

where

$$L = \left[\frac{10^9}{1.6 \times 10^6 \ (10)}\right]^{1/3} = 4.0 \text{ ft} = 1.2\text{-m}$$

The distance between the GFHC bottom section surface and the building roof-deck substrate must be considered. Equation 12 shows that $\dot{q}_R$ is dependent on the absorption factor, which is related to the view factor relationship that exists between the GFHC/environment system during measurement. This difference in view factor becomes less significant as the distance between the floor and roof-deck increases. Appendix A estimates a 2% difference in view factor between calibration and measurement steps for a building with a floor-to-floor roof-deck substrate height of 20 ft(6.1-m).

With respect to the heat transfer within the GFHC (depicted in Fig. 7), the energy balance is

$$\dot{Q}_T = \dot{Q}_S + \dot{Q}_L \tag{15}$$

where

$\dot{Q}_T$ = measured heat flow rate through the GFHC top section metering area, Btu/hr(W)

$\dot{Q}_S$ = rate of heat flow entering the bottom section of the GFHC, Btu/hr(W)

$\dot{Q}_L$ = rate of lateral heat loss, Btu/hr(W)

The accuracy of the device depends on how small $|\dot{Q}_T - \dot{Q}_S|$ is. Then the design of the GFHC should be such that $\dot{Q}_L$ is near zero. This can be accomplished with the following combination of design conditions:

1. The layers between the top and bottom sections of the GFHC should be thin and of low thermal conductivity.

2. The metering area should be small relative to the overall lateral GFHC dimensions.

3. The lateral temperature distribution at the interface should be as uniform as possible throughout.

GFHC CONSTRUCTION

The GFHC top section construction details are illustrated in Fig. 8. The unit is 48 x 48-in. (1.22 x 1.22-m) and 3-in.(76-mm) thick with a 12 x 12-in.(0.30 x 0.30-m) metering area. Two heater elements 36 x 36-in.(0.91 x 0.91-m), 0.005-in.(0.13-mm) thick are positioned in the center of the top section composite. These elements consists of a lightweight composition of lamellar graphite with a copper conductor bonded between two layers of dielectric polyester film. Each heater element was specifically designed to provide uniform heat fluxes through the metering area spanning 2 to 8 Btu/ft^2·hr(6 to 25 W/m^2). The uniformity of flux generated through the metering area was within 2% of the measured average heat flux at the 95% confidence level.

Two calibrated homemade meters [1] 48 x 48-in.(1.22 x 1.22-mm), 1-in.(25-mm) thick are used to meter the GFHC-generated heat flow. These two homemade meters, #1 and #2, consist of expanded polystyrene foam boards with a density of 1.5 lbs/ft^3(24 kg/m^3). Meter #1 measures the heat flux through the metering area ($\dot{Q}_T$) and meter #2 measures the heat flux leaving through the top of the GFHC. Two 48 x 48-in.(1.22 x 1.22-m) aluminum sheets, 0.050-in.(1.3-mm) and 0.032-in.(0.81-mm) thick, border the top and bottom of meter #1 providing temperature uniformity and a protective barrier at the bottom of the GFHC top section. The bottom aluminum sheet was cut along the perimeter of the metering area to eliminate lateral losses ($\dot{Q}_L$) through the aluminum.

All layers were bonded together with epoxy, eliminating air entrainment, to form a flat, rigid, lightweight, and permanent GFHC top section. A wet lay-up process was used to provide a protective coating for the outer five sides of the GFHC, leaving the 0.032-in.(0.81-mm) aluminum sheet exposed on the bottom. The protective casing guards the top section components while creating a moisture barrier and structurally sound unit.

Meters #1 and #2 were calibrated in accordance with ASTM C236. Each meter is equipped with a 16-junction-pair thermopile and nine thermocouples on each side. Five of these thermocouples are arranged inside the metering area on each side of the meters as shown in Fig. 8 to provide mean-temperature information. Figure 9 shows meter #1's calibration parameter as a function of mean temperature. The test-heat fluxes generated in the GHB for these runs ranged between 2.1 and 6.8 Btu/ft^2·hr(6.6 and 21.5 W/m^2). A least-squares fit of the data gives

$$\frac{\dot{q}}{emf} = -0.844 + .01124\ t_m \tag{16}$$

where

$\dot{q}$ = average steady-state heat flux through the specimen, W/m^2

$\frac{\dot{q}}{emf}$ = calibration parameter of meter #1, W/m^2·mv

t_m = metering area mean temperature, °K

A similar relationship was obtained for meter #2.

The GFHC bottom section, unlike the permanent top section, is uniquely designed for each in-place roof-deck system measurement. Therefore, the GFHC is capable of incorporating substrates of different geometries and materials. A wall system also can be measured using the GFHC. The top and bottom sections are mechanically fastened together. A thin layer of vacuum grease is placed in between both sections to ensure close contact. The GFHC is suspended from the top of the joists using four chain-hoist units.

MEASUREMENT OF ENVIRONMENTAL FACTORS

The GFHC design and construction provides a means of accounting for effects of convection and radiation in order to characterize various environments in which calibration takes place. Therefore, during calibration, data leading to the radiation factor (RAD) and the convection factor (H) are collected simultaneously. The HFM calibration parameter, $\dot{q}$/emf, is represented by a calibration curve that incorporates the most important uncorrelated factor(s) that accurately explain $\dot{q}$/emf response. HFM emf measured on the building roof-deck substrate is converted to heat fluxes using this calibration curve.

The Radiation Factor, RAD

The radiation factor, RAD, represents the radiative heat transfer driving force. It is calculated using Eq 4 by measuring the substrate surface temperature and the representative enclosure surface temperature in the surroundings. RAD is evaluated during HFM calibration and subsequent building roof-deck measurement with the calibrated HFM.

The Convection Factor, H

H, the convection factor, is defined and derived in Appx B and is given by

$$H = \frac{t_s - t_x}{t_s - t_r} \cdot \frac{1}{x} \qquad (17)$$

where

H = temperature (dimensionless) gradient, m^{-1}

t_s = substrate surface temperature, °K

x = normal distance from substrate surface to the position where t_x is measured, $0.125 \leq x \leq 1.0$-in. $(0.0032 \leq x \leq 0.025$-m) typically, m

t_x = air temperature at a distance x perpendicular to the substrate surface, °K

t_r = air temperature at a reference distance r perpendicular to the substrate surface with r = 3-in. (0.076-m), typically °K

H can be evaluated during HFM calibration and building roof-deck measurement with the calibrated HFM. Exact location of thermocouples measuring t_x and t_r with respect to the GFHC and building substrate surfaces is critical. H increases in accuracy but decreases in precision as t_x and t_r are located closer to the substrate surface. Since GFHC and building roof-deck substrates are exposed to similar environments, the relative H measurement is valid despite any measurement error caused by the close proximity of t_x to the substrate surface. Moreover, all thermocouple junctions are shielded to minimize the influence of radiation from near-by surfaces.

OTHER FACTORS TO BE CONSIDERED

The HFM must be applied to the building substrate as mounted on the GFHC substrate surface during calibration. A very thin layer of vacuum grease is used to apply the HFM to the substrate. Care must be taken to keep the substrate free of grease in the vicinity of the HFM.

The HFM leads are taped about 1-in.(25-mm) from the disk to help maintain sound contact between the HFM and substrate surface. All thermocouples are identically applied to both GFHC and building substrates. The emissivity of the exposed HFM surface is matched as closely as possible to the substrate emissivity. This minimizes lateral losses along the substrate surface.

A common approach of masking the HFM with a sufficient quantity of protective material to partially desensitize the HFM with respect to environmental factors is worth consideration. When masking, the amount of protective material used must be weighed against the increased size of the metering system obtained. This affects:

1. handling and simplicity

2. ability to provide sound contact to irregular substrate geometries typically encountered

3. thermal performance of the building roof-deck system to be measured

DATA ACQUISITION AND DATA REDUCTION

A portable data-logging system capable of scanning up to 100 channels of data is used to acquire temperature, HFM emf, and other pertinent data. The data-logger has variable scan rate capability, and simultaneously outputs to a paper-tape printer and a magnetic-tape cassette drive. The data-logger's worst-case error percent of emf reading is within 0.02% and has a worst-case resolution of temperature measurement within 0.2°F(0.1°K). A computer performs all subsequent data reduction using the cassette for input.

CONCLUSIONS

Field measurement of building roof-deck systems nondestructively with HFMs can be achieved using the field thermal measurements technique as described in this paper. The procedure, which incorporates the GFHC, accounts for convection and radiation factors in the field environment together with other less important factors, such as substrate surface temperature. This approach can be applied effectively to in-place measurement of other building structures, e.g., wall systems. The GFHC can accommodate HFM calibration on substrates of various geometries. Incorporation of a thermographic imaging system with this heat flow quantification technique would add insight into the overall thermal performance of the roof-deck system. Further progress relating to in-place measurement of roof-deck systems using the GFHC technique will be reported in the future.

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APPENDIX A

Estimation of radiation view factor differences with and without the GFHC suspended below the building roof-deck substrate:

The GFHC and floor system can be approximated by two parallel disks with the area of the floor much greater than the area of the GFHC. Then the view factor for the GFHC and floor system (F_{12}) is defined

$$F_{12} = \frac{r_2^2}{r_2^2 + d^2} \tag{18}$$

where

r_2 = radius of the floor "disk" in view of the GFHC, m

d = distance between the floor and the GFHC or the building roof-deck substrates, m

For r_2 = 35 ft(10.7-m) and d=20 ft(6.1-m) without the GFHC and d=19.2 ft(5.9-m) with with GFHC installed;

$$F_{12} \text{ without GFHC} = \frac{(10.7)^2}{(10.7)^2 + (6.1)^2} = 0.755$$

$$F_{12} \text{ with GFHC} = \frac{(10.7)^2}{(10.7)^2 + (5.9)^2} = 0.767$$

$$\text{\% Difference between } F_{12} = \frac{(0.767-0.755)\ 100}{0.755} = 1.6\%$$

provided the GFHC substrate is about 9.5-in.(0.2-m) from the bottom of the building roof-deck substrate.

APPENDIX B

Derivation of H, a variable that represents the convection factor in the field thermal measurements technique:

The rate of heat transfer from the roof-deck substrate into the air medium at the surface for typical field situations can be approximated by the one-dimensional conductive heat transfer equation,

$$\dot{q} = -k\ A \left(\frac{dt}{dx}\right)_{x=o} \tag{19}$$

where

$\dot{q}$ = rate of heat flow passing through a thin layer of air at the substrate surface, Btu/hr(W)

k = thermal conductivity of air, Btu-in/ft^2·hr·°F(W/m ·°K)

A = heat transfer area of the thin layer of air, ft^2(m^2)

t=t(x) = air temperature as a function of x, normal distance from the substrate surface, °F(°K)

From Eq 5 the following relationship holds

$$\dot{q}_c = h\ A\ (t_s - t_r) \tag{5}$$

Combining Eq 5 and 19 gives

$$-k \left(\frac{dt}{dx}\right)_{x=o} = h\ (t_s - t_r) \tag{20}$$

and

$$h = \frac{-k \left(\frac{dt}{dx}\right)_{x=o}}{t_s - t_r} \cong k \frac{t_s - t_x}{t_s - t_r} \cdot \frac{1}{x} \tag{21}$$

Then, the convection factor H is defined as follows:

$$H = \frac{t_s - t_x}{t_s - t_r} \cdot \frac{1}{x} \tag{17}$$

TABLE 1

Change in HFM Response Parameter ($\dot{q}$/emf) For 12 HFM Before and After Changes Made to HFM Exposed Surface Emissivity For Two ASTM C236 Runs with $\dot{q}$ = 2.7 $Btu/ft^2 \cdot hr$(8.5 W/m^2), h_{loc} = 0.25 $Btu/ft^2 \cdot hr \cdot °F$(1.4 $W/m^2 \cdot °K$) and t_s = 82°F(301°K)

HFM NUMBER	RUN #1: $\dot{q}$/emf FOR "UNCHANGED" SURFACE $Btu/ft^2 \cdot hr \cdot mv$ ($W/m^2 \cdot mv$)	RUN #2: EXPOSED SURFACE MATERIAL CHANGE	RUN #2: ESTIMATED EMISSIVITY	RUN #2: $\dot{q}$/emf $Btu/ft^2 \cdot hr \cdot mv$ ($W/m^2 \cdot mv$)	% DIFFERENCE IN $\dot{q}$/emf AS COMPARED WITH RUN #1
1	2.1(6.6)	"High gloss" aluminum	< 0.1	4.1(12.9)	95
2	2.2(6.9)	No change	0.9	2.3(7.2)	4
3	2.1(6.6)	No change	0.9	2.2(6.9)	5
4	2.1(6.6)	Masking tape	0.9	2.1(6.6)	0
5	2.1(6.6)	Masking tape painted with a black adhesive	0.9	2.1(6.6)	0
6	1.9(6.0)	Masking tape painted with aluminum paint	0.4	2.2(6.9)	15
7	2.3(7.3)	No change	0.9	2.4(7.6)	4
8	2.1(6.6)	No change	0.9	2.2(6.9)	5
9	2.4(7.6)	Masking tape painted with a black adhesive	0.9	2.4(7.6)	0
13	2.4(7.6)	No change	0.9	2.5(7.9)	4
14	2.2(6.9)	"High gloss" aluminum painted with a black adhesive	0.9	2.2(6.9)	0
15	2.1(6.6)	"High gloss" aluminum	< 0.1	3.7(11.8)	79

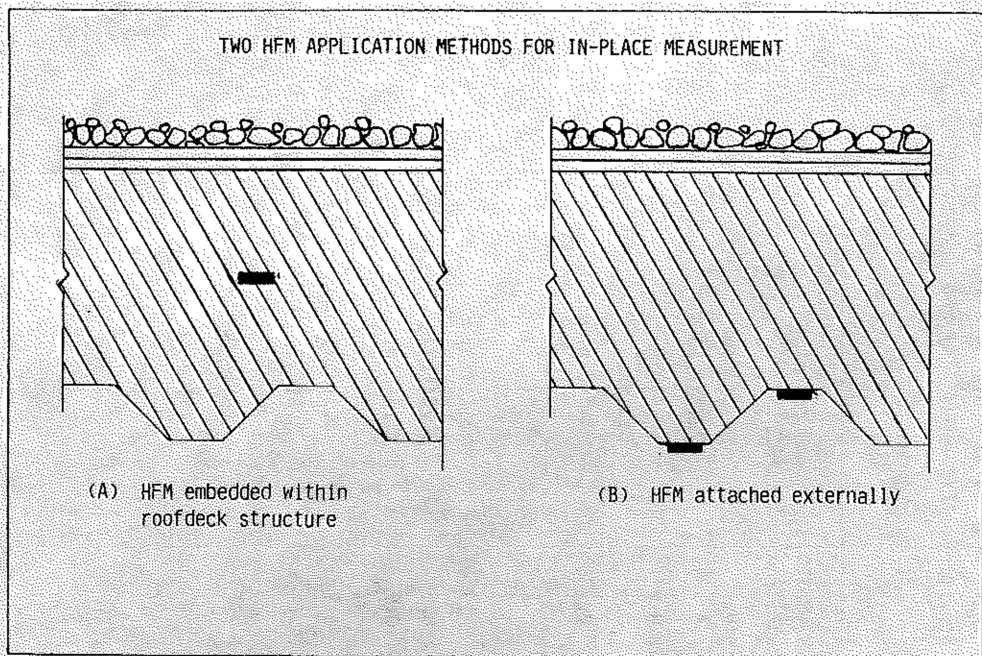

Figure 1. Two HFM application methods for in-place measurement

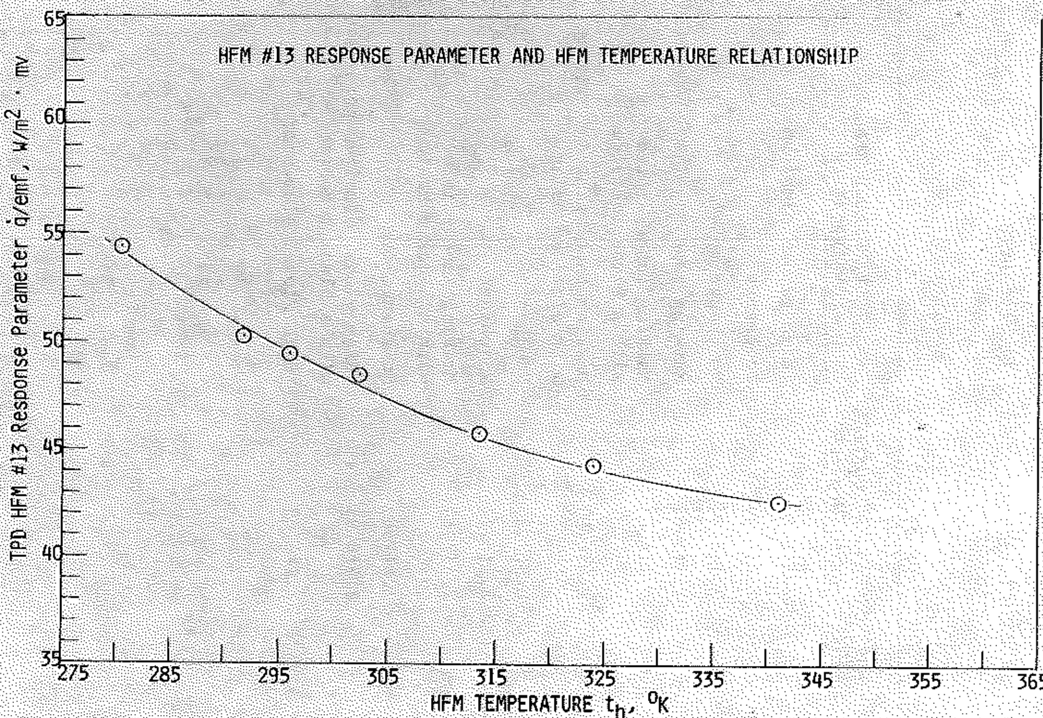

Figure 2. HFM #13 response parameter and HFM temperature relationship

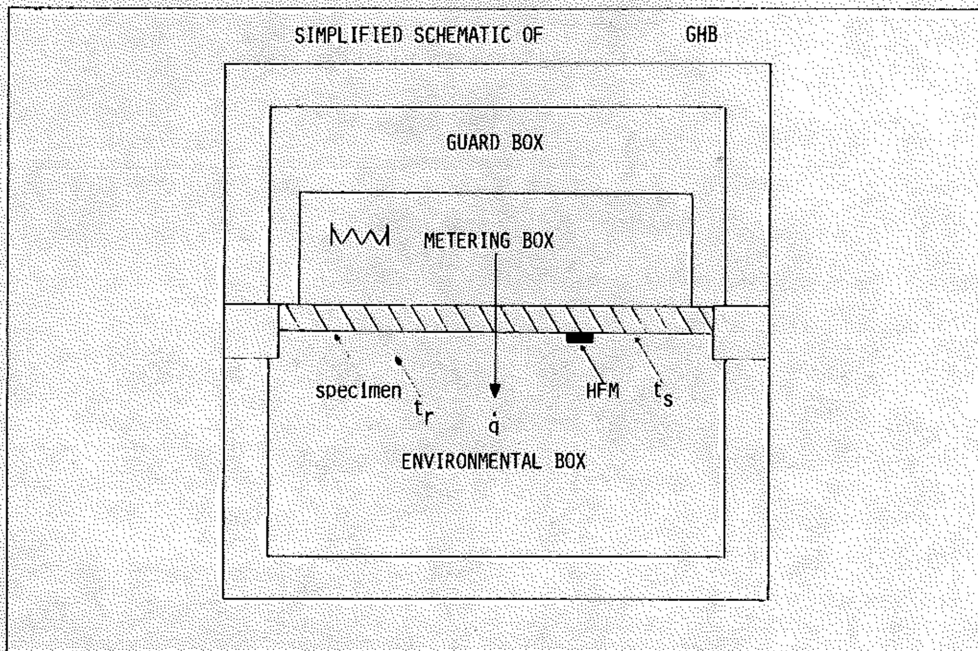

Figure 3. Simplified schematic of sample GHB[9]

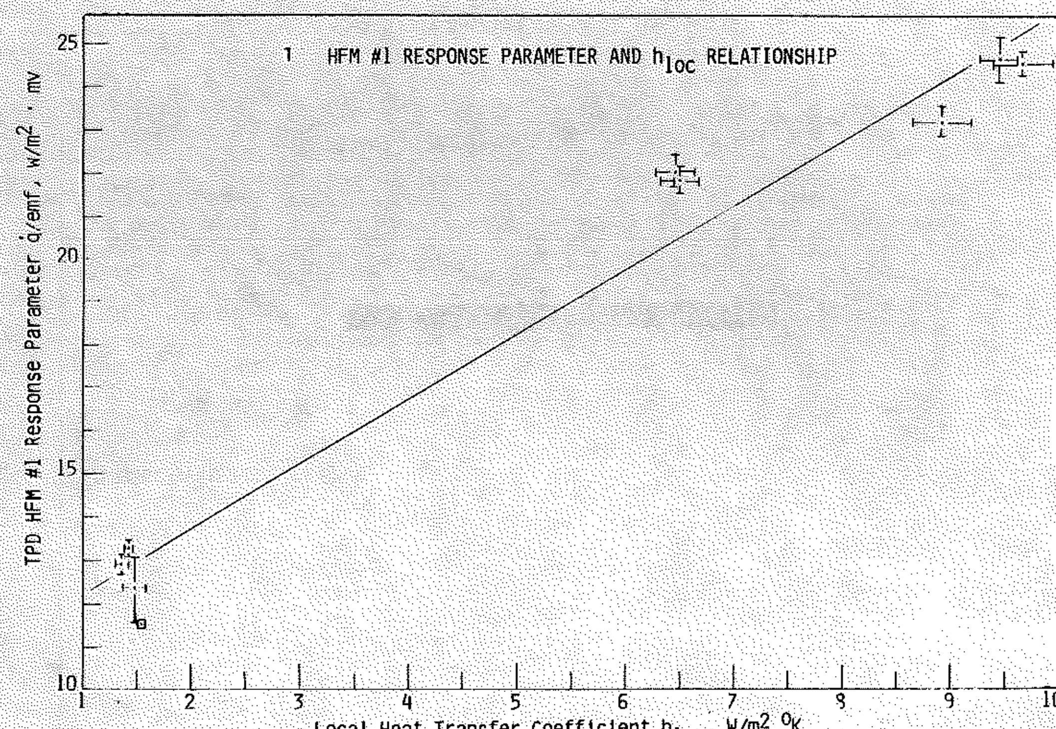

Figure 4. HFM #1 response parameter and h_{loc} relationship

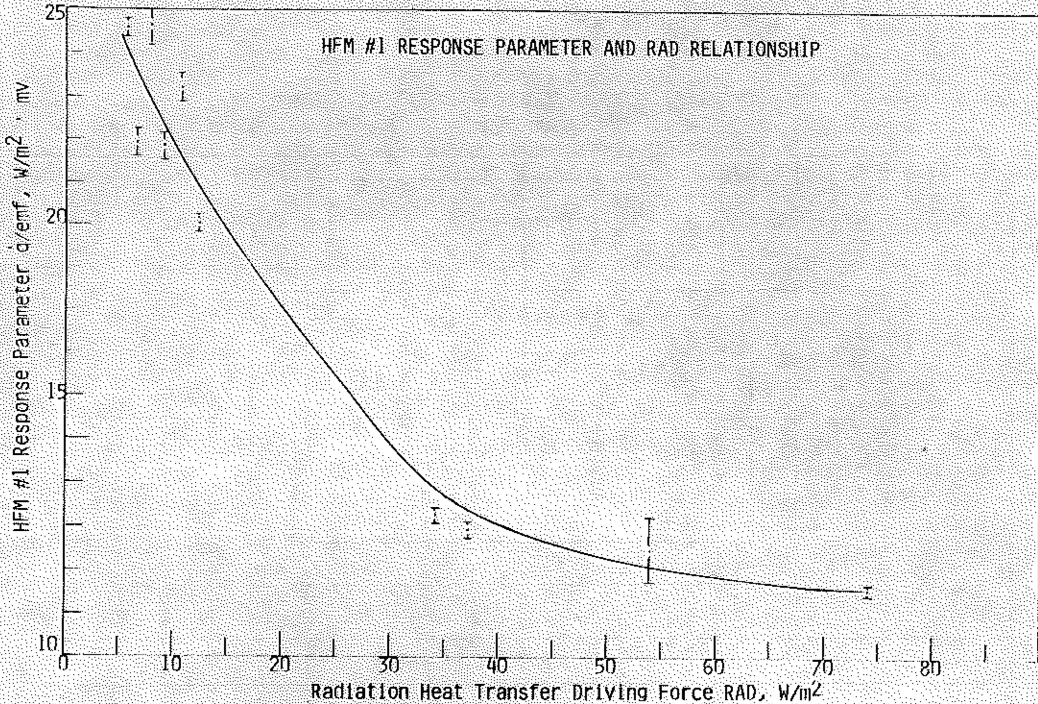

Figure 5. HFM #1 response parameter and RAD relationship

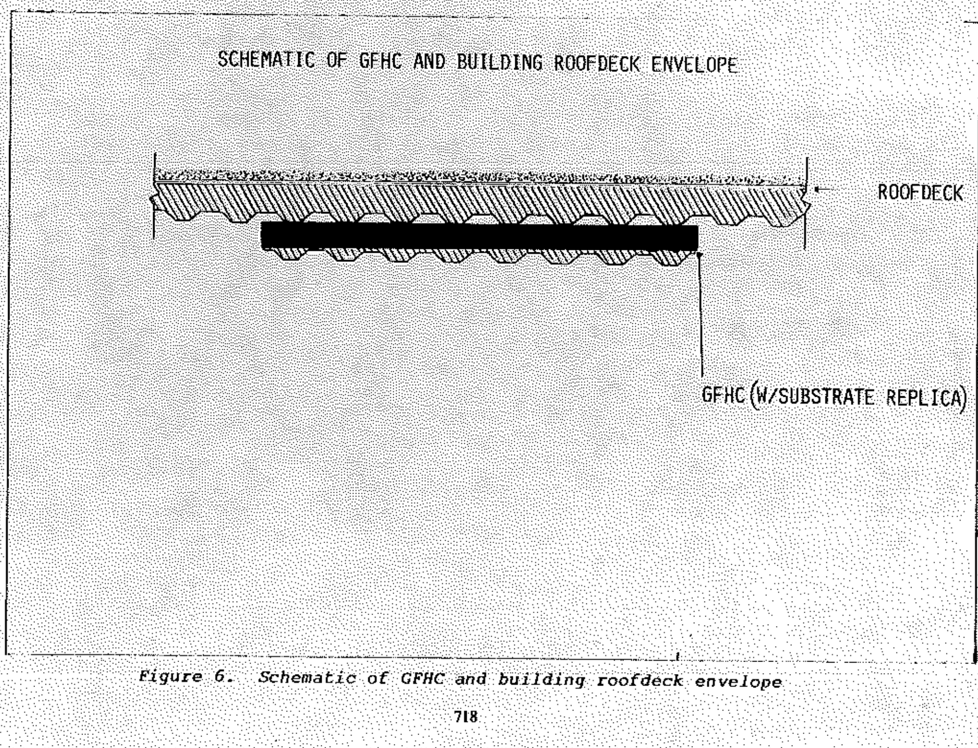

Figure 6. Schematic of GFHC and building roofdeck envelope

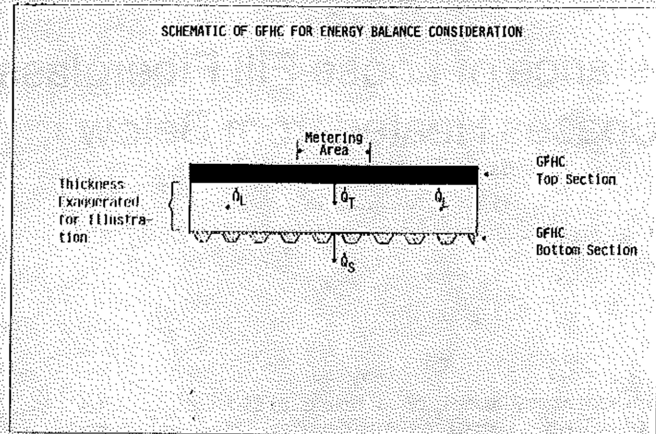

Figure 7. Schematic of GFHC for energy balancd consideration

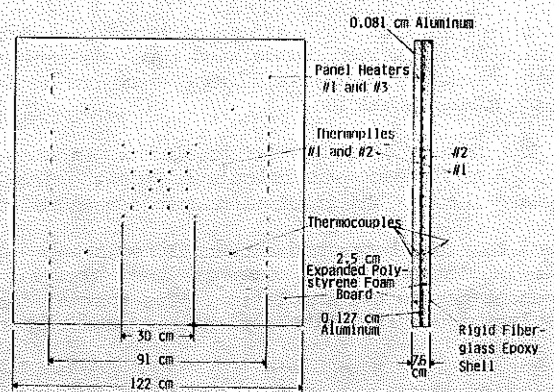

Figure 8. Schematic of GFHC top section

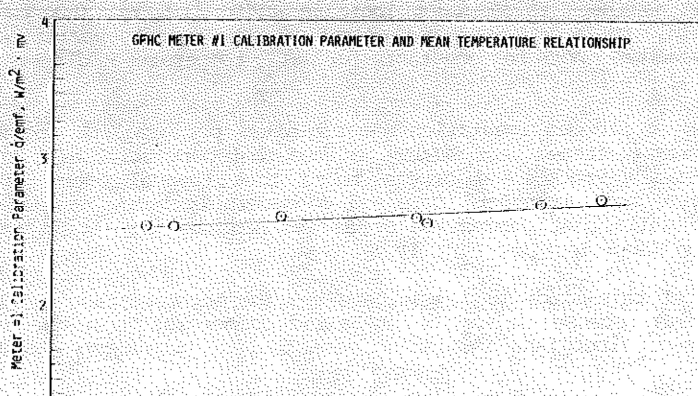

Figure 9. Homemade meter #1 calibration parameter and mean temperature relationship