MEASURING ROOF SYSTEM THERMAL RESISTANCE

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ABSTRACT

This report describes factors that affect the thermal performance of roof systems, and a technique for field-measuring thermal resistance. This measurement technique utilizes a combination of infrared thermographic imaging, surface heat-flow meters and surface thermopiles. The thermal resistance of the roof system is computed from temperature difference across the roof and the measured heat flow through the roof.

A field test of the measurement procedure is detailed, along with an examination of the time period required to perform a roof thermal resistance measurement, as related to the thermal time lag for heat flow through the roof due to the effect of the thermal mass of the roof.

Roof thermal resistance determined via this measurement procedure is very accurate if measurements are performed over a sufficient time interval, the minimum interval depending upon the thermal mass of the roof system.

Key Words: Roof systems, measurement technology; moisture accumulation, nondestructive tests; thermal resistance.

1. INTRODUCTION

Buildings account for roughly one-third of the total United States energy consumption [1], and building roofs are major contributors to heat flow through building envelopes. Because low-slope roofs are readily accessible, they provide a high potential for heating and cooling energy conservation through retrofit.

Accordingly, the object of this report is [1] to identify factors that impair the thermal performance of exising built-up roof systems, and [2] to describe a technique for field-measuring the thermal resistance of roof systems.

Among the many factors affecting roof system thermal performance are design, workmanship, materials, age, weathering, and moisture intrusion. Actual thermal performance may differ substantially from design or expected performance. Wet insulation, in particular, can drastically reduce a roof system's thermal resistance [2].

The field-measuring technique for thermal resistance serves three potential purposes:

- to identify roofs with inadequate thermal performance
- to check actual thermal performance against design expectation
- to promote improved design procedures

The field-measuring technique utilizes a combination of infrared thermographic imaging, surface heat-flow meters, and thermopiles. Thermal resistance is computed from measured inside-to-outside surface temperature difference across the roof system cross section and measured heat flow through this cross section. Field validation of the measurement system was preformed and results examined and reported. The technique can be used to assess the thermal performance of many different types of roof systems.

2. FACTORS AFFECTING THE THERMAL PERFORMANCE OF ROOF SYSTEMS

In serving its principal function of protecting the enclosure beneath it from the weather elements, and to maintain desired environmental conditions within the occupied space, a roof must be able to withstand wind-uplift pressures, temperature cycles, and moisture conditions. Throughout a typical year, low-slope systems are subjected to rain, snow, solar radiation, ice, and to wide variations in surface temperature. A roof system must have structural integrity and durability to withstand these exposures. Increasing concern for energy conservation has added another factor to the list of desirable characteristics for roof systems, that of thermal efficiency. The methods utilized to achieve the goal of a thermally efficient roof are not always consistent with the methods that produce the most durable roof, since the strongest materials may not be good insulators, and the best insulators generally provide little structural strength. However, some types of failures will affect the integrity of the waterproofing membrane and insulation as well as the thermal performance. An example is splitting, which could lead to water penetration and mechanical and thermal degradation of the insulation due to moisture intrusion.

Moisture intrusion into insulation can drastically reduce a roof system's thermal resistance [3] and ultimately cause premature failure. Moisture can invade a BUR roof system from the exterior through leakage, from the interior as water vapor generated within the structure migrates outward, or can even be present during construction and entrapped upon application of the waterproof membrane. Failure of the membrane for any reason can produce moisture related problems.

3. BUR ROOF THERMAL PERFORMANCE ASSESSMENT PROCEDURES

Several methods are currently utilized for detecting moisture in BUR roof systems [1]. These methods include gravimetric techniques and nondestructive evaluation methods (NDE) such as nuclear backscatter, electrical capacitance and infrared imagery (thermography) [4]. Although most accurate, the gravimetric technique has the disadvantage of being a destructive test method. Data are not available on the accuracy, validity, and reliability of NDE methods to quantitatively detect moisture in roofs

Thermal resistance determinations for BUR roof systems have also been performed utilizing heat-flow meters and thermocouples [5]. In using this method, the heat flow through a roof and the temperature difference between its interior and exterior surfaces are measured. The roof system's thermal resistance is subsequently calculated from the relation:

$$R = \frac{\Delta T}{Q} = \frac{\int_0^P \Delta T \; d\tau}{\int_0^P Q \; d\tau} \qquad [1]$$

where ΔT = temperature difference
Q = heat flow
P = period of integration

For accurate determination of thermal resistance, measurements must be made over a sufficiently long period [p] to reduce the transient effects from heat storage and thermal time lag, since heat flow lags behind temperature difference. These effects are most noticeable in roof systems with large amounts of thermal mass, such as BUR roof systems with concrete decks. The ability of a roof system to store heat rather than transmit it with little time delay results in a time lag between temperature difference and resulting heat flow. This factor can be described as the thermal capacitance of a roof.

The technique utilized in this study for assessing the thermal resistance of BUR roof systems consists of a combination of thermographic imaging and local measurements using heat-flow meters and thermopiles.

The technique starts with a thermographic scan of the roof surface to obtain an apparent temperature profile map of the top of the BUR roof system. This scan must be performed in the dark, allowing enough time to elapse following sundown to enable residual solar radiation effects to dissipate. At this time of day, the outdoor temperature is steadier than at other times, and variations in surface temperature will stem predominantly from differences in thermal resistance of the BUR roof system and surface convection effects, if wind conditions vary at different roof locations. In addition, sufficient interior-to-exterior temperature difference must be present, approximately 20°F (11°C) minimum, to obtain accurate results. Regions of the roof surface whose temperature appears to vary from the majority of the roof surface are marked with spray paint or otherwise identified for subsequent examination. Apparent temperature variation of some portions of the roof surface may actually be due to differences in emittance or special conditions (such as water, ice patches or metal surfaces). Variations in surface temperature can also indicate hot air exhausting onto a roof from a vent, hot rooms directly below a roof, differences in underlying construction, or wet or otherwise defective insulation. Close examination of suspect regions usually yields an accurate assessment of the cause of the apparent temperature variation.

Areas identified as regions of hotter or colder surface temperatures are instrumented for thermal-resistance measurements, made with heat-flow meters and thermopiles. An actual measurement system is described in Section 4. A heat-flow meter produces a millivolt signal proportional to the heat flux passing through its body. When attached flush with a surface, the heat flowing through that surface can be measured. A thermopile is a series of pairs of thermocouple junctions attached to opposite surfaces of a roof or wall to measure the temperature difference between the two surfaces. The thermopile will develop a voltage proportional to the temperature difference being measured.

The heat flow meters are attached to either in the interior or exterior roof surface, and the thermopile is attached to the interior and exterior surfaces of the roof. Heat-flow meters should not be attached directly to a metal deck because the metal deck will act as a fin, possibly disrupting the accuracy of the measurement due to the effect of two-dimensional heat flow. For metal decks, the heat flow meters should be installed on the exterior roof surface, rather than on the interior metal surface. For concrete or wood decks, the heat flow meters can be attached directly to the interior surface of the deck.

The thermal resistance value for a particular area of the roof is determined by dividing the integrated temperature difference, as measured by the thermopile, by the integrated heat flow, as measured by the heat flow meter.

Areas of low thermal resistance can be examined for moisture content through coring of roof samples followed by an oven-drying procedure, or by a non-destructive moisture detection procedure.

4. THERMAL RESISTANCE MEASUREMENTS

Measurements were made on the roof of Building 226 at the National Bureau of Standards. The building was constructed in 1963 with a 40,000 ft^2 (2716 m^2) roof system consisting of a concrete deck, glass fiber insulation and built-up roofing. A photograph of the roof surface is shown in figure 1. Details of the design of the roof system were utilized to compute its thermal resistance. The components of the roof system and their thermal resistances are listed in Table 1.

The actual thermal resistance of the roof may vary from the computed thermal resistance if different insulation thickness is used instead of the design thickness, or if the thermal properties of the actual materials differ from handbook values. Variations may also occur due to local irregularities in construction materials, assembly techniques, workmanship, or the presence of moisture.

4.1 Thermographic Survey

A thermographic scan of the roof surface was performed to obtain an apparent temperature map. The scan was performed on a cold night, 29°F (−1.6°C), under a partially overcast sky. Wind speed was less than 5 mph (8 kh); average roof-surface temperature was 25°F (−4°C). The major portion of the roof surface appeared to be fairly uniform in temperature, varying by less than 0.9°F (0.5°C). (See Figure 2.) Roof surface areas surrounding the large central vents are seen to be warmer than the majority of the roof. This is more apparent in Figure 3. In the color thermograms, the warmest area of the roof surface appears to be 1.8°F (1°C) warmer than the remaining areas. Visual inspection of the warmer portions of the roof surface revealed no obvious differences in roof construction materials from the majority of the roof

COMPONENT	THERMAL RESISTANCE °F (B + U/hr. ft.^{2})	(m^2.K/W)
5-in. (12.7 cm) Concrete Deck*	0.40	0.07
Glass Fiber Insulation 1-1/16 in. (27 mm) (Conductance) 0.24 $\frac{B+U^{**}}{hr.\ ft.^2 F}$ 1.36 $\frac{w}{m^2.K}$	4.17	0.73
Built-Up Roofing* • *Asphalt Primer* • *4 Plies of Felt* • *3 Layers Asphalt* • *Asphalt Flood Coat* • *Slag*	0.33	0.06
TOTAL THERMAL RESISTANCE	**4.90**	**.86**
*From ASHRAE Handbook (6)	**From Design Specification	

TABLE 1
Computed thermal resistance of test roof.

surface, and there were no differences in surface emittance to account for warmer apparent surface temperature. One of the warmer roof surface areas was chosen as the location for the heat-flow meter and thermopile (see Figure 4). The cylindrical object in the center of the thermogram is a liquid nitrogen Dewar flask used as a marker.

4.2 Sensor Installation

A heat-flow meter was spot-glued to the interior surface of the concrete roof deck. The meter consisted of a thin cylindrical wafer containing an imbedded thermopile. The millivolt signal generated from this imbedded thermopile is proportional to the heat flow through the wafer. The heat-flow meter was connected to an analog integrator, which recorded hourly averaged values of heat flow, and a date logger, which recorded instantaneous values at adjustable time intervals. The temperature difference between the interior and exterior roof surfaces was measured with a copper-constantan thermopile consisting of three pairs of junctions attached to the surfaces. The three exterior thermopile junctions were attached to the outer surface of the roof with a room-temperature vulcanizing silicone adhesive. The corresponding interior thermopile junctions were taped to the inner roof surface (concrete deck). The thermopile was connected to an analog integrator and to the data logger.

4.3 Measurements

The roof system's thermal resistance value for the instrumented location was determined by dividing the hourly integrated temperature difference by the hourly integrated heat flow, as measured by the heat-flow meter. Measurements were made for several weeks to obtain an average value for the thermal resistance. Figure 5 shows the data obtained during a typcial nine day measurement period.

The hourly average thermal resistance of the roof, RI, was determined by dividing the hourly average temperature difference by the hourly average heat flow in discrete hourly increments. The values ΔT (temperature difference), Q (heat flow) and RI (hourly thermal resistance), are plotted in Figure 6 at hourly intervals. RAV, noted in Figure 5, is the cumulative average of RI or:

$$RAV = \frac{\sum_{i=1}^{t} RI_i}{t} \quad \frac{RI_1 + RI_2 + \ . \ . \ . \ RI_t}{t} \qquad [2]$$

where t = elapsed time (hours) or number of readings.

The instantaneous hourly value of the thermal resistance is seen to vary strongly with the temperature difference across the roof. Maximum heat flow is seen to lag behind maximum temperature difference by approximately 12 hours, due to the thermal capacitance of the roof.

The measured overall thermal resistance at this location of the roof was found to be:

$$5.06 \ \frac{h \cdot ft^2 \cdot F}{Btu} \ (0.89 \ \frac{m^2 \cdot K}{W}),$$

based on the nine days of measurement. This is 3.3% higher than the design value of 4.90 (.86). The RAV line gives a good example of how long measurements must be made to negate the effect of random daily temperature fluctuations on the average thermal resistance value. After 67 hours of measurement the cumulative average thermal resistance, RAV, stayed within 10% of the final value (5.06 $\pm$ .506). After 133 hours, RAV stayed within 5% of the final value (5.06 $\pm$ .253). These time factors would vary according to roof type and temperature conditions, but for a roof of this type, three to six days of data collection would be necessary to obtain a representative value for the thermal resistance. The time required for cumulative averaging will vary from one roof to another depending on the thermal capacitance (thermal mass) of the roof. Shortening this time span could result in inaccuracies due to random fluctuations or variable daily temperature cycles.

The close agreement between measured and calculated thermal resistances indicates that the thermal performance of the BUR roof system was as would be expected based on design parameters. Moisture intrusion or other factors affecting thermal conductance were not believed to be present, since the roof thermograms indicate fairly uniform surface temperatures, and since the measured thermal resistance at the warmest spot on the roof showed no reduction from design value.

To investigate the actual moisture content of the roof, samples of 1-1/16 in. thick fiberglass insulation and membrane were taken from a location near that of the thermopile. Moisture content of the insulation was determined gravimetrically and was found to be very low, only 0.2 percent by weight.

The membrane consisted of four plies of asphalt-saturated organic felt with a slag surfacing in an asphalt flood coat. The moisture content of the membrane was also determined gravimetrically and was found to contain 3 g of water per ft^2 of area (.09 m^2). The average amount of interply asphalt in the sample was about 10 lb/100 ft^2 (4.5 kg/9 m^2).

5. COMPUTER SIMULATION OF BUR SYSTEMS

A computer simulation procedure [7] was utilized to examine the effect of the thermal mass of the roof on the time period required for accurate measurement of thermal resistance using the technique described in the previous sections of this report. The thermal mass of the concrete deck produced the long thermal response time. A steel deck would drastically reduce the response time, since the 5-in. concrete slab weighs about 30 times as much as a steel deck.

A mathematical model was used to calculate heat flow through the roof system, using the measured hourly indoor and outdoor surface and air temperatures observed during the field test as input parameters. A response factor technique was employed to first compute surface heat transfer coefficients and subsequently calculate heat flow through the roof system. To validate the model, the BUR roof system used for the field test was modeled, and heat flow through the roof calculated and compared with actual measured values. A typical four-day period is shown in Figure 6. Computed heat flow is plotted, beginning with the ninth hour, to allow start-up time for the model (since heat flow lags behind the driving force, temperature differential).

Agreement between measured and calculated heat flow is satisfactory, since input temperature parameters were in hourly increments, thus imparting some scatter to the calculated heat flow.

Next, the concrete deck was replaced with a steel deck in the model, and heat flow through that roof system was calculated for the same temperature parameters. Figure 7 presents the inside-to-outside temperature difference conditions used for the simulation period, as well as calculated heat flow through the roof system with steel deck. This lightweight roof system has little time lag; maximum heat flow follows maximum temperature difference within one hour.

As previously noted, hourly values of thermal resistance (RI) were computed based on the ratio of the measured hourly temperature difference and the calculated hourly heat flow. The cumulative average of the thermal resistance (RAV) was also calculated. RI and RAV for the BUR roof system with steel deck are also plotted in Figure 7.

Since the steel roof deck provides negligible thermal resistance [6], the thermal resistance of the BUR roof system modeled with the steel deck would be expected to be the value for the BUR roof system with concrete deck less the thermal resistance of the concrete deck, or 4.90 minus 0.40 equals: $4.50 \frac{°F \cdot ft^2 \cdot h}{Btu}$ (.79 $m^2 \cdot K/W$).

At the end of the four-day simulation period, the cumulative average for the thermal resistance of the steel deck system is seen to be: $4.58 \frac{h \cdot ft^2 \cdot F}{Btu}$ (0.81 m^2 K/W), or 2% higher than the design value. RAV stays within 10% of its final value (4.58 $\pm$ .46) after 5 hours elapsed measurement time, and within 5% (4.58 $\pm$ .23) after only 7 hours elapsed measurement time. RI is seen to approach RAV for long periods of time during night hours, and in general RI varies much less for the roof system with steel deck as compared with the concrete deck. This indicates that temperature conditions were fairly near steady-state relative to the thermal response time of the system with steel deck, during night hours. RI variation for the steel deck is less than for the concrete deck since the short thermal response time means that heat flow will fluctuate more closely in response to temperature conditions, therefor hourly values of heat flow and temperature difference are more closely related, causing their ratio to more accurately reflect the actual thermal resistance. RI deviates most from RAV when the temperature difference is changing rapidly.

This analysis indicates that the thermal resistance of roof systems with metal decks could be accurately measured using this technique in a fairly short time period, and probably within one day, depending on weather conditions.

Based on the thermal resistance measurements performed on the roof system with a concrete deck and the results of the simulation of a system with a steel deck, the required elapsed measurement time is presented in Figure 8 as a function of roof system time lag. Time lag for the steel deck system was estimated to be 3/4 hour. An exact determination was difficult because measurements were made in hourly increments.

Most systems would probably fall somewhere between the two types examined here with respect to thermal mass and consequent thermal time lag. Additional information is needed concerning the thermal time lag of various different deck constructions to develop accurate criteria for required elapsed measurement time.

CONCLUSION

Many factors can influence the themal performance of a roofing system, including design, materials, workmanship, exposure conditions and moisture.

Thermally inefficient roofs can be identified through the utilization of roof thermal assessment procedures. A procedure utilizing a thermographic imaging system, in conjunction with local measurements using heat flow meters and thermopiles, can be valuable in determining the thermal resistance of roof systems. The thermal resistance can be calculated using the measured integrated heat flow through the roof, provided data are obtained over a sufficiently long time period to negate inaccuracies due to thermal capacitance. A field test of the measurement procedure yielded a measured thermal resistance value for a system within 3.3% of the design thermal resistance for that roof. The 1-1/16-in (27 mm) thick glass fiber insulation contained 0.2 percent moisture by weight.

The thermal mass of a roof system strongly affects the amount of elapsed measurement time required to determine its thermal resistance accurately. Analysis indicates that a typical BUR system with a concrete deck will require 3 to 6 days of measurement time, while a similar roof system with a steel deck would require less than one day.

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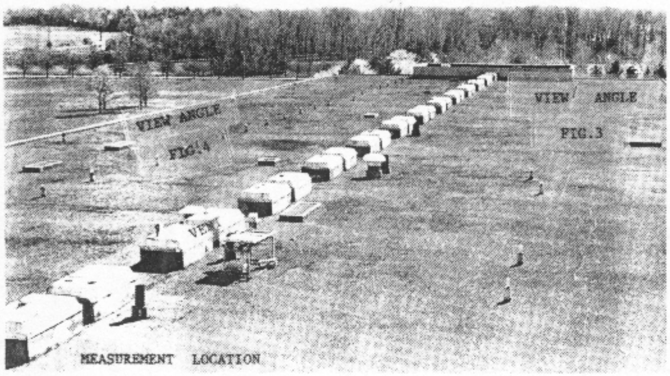

FIGURE 1
Photograph of roof surface

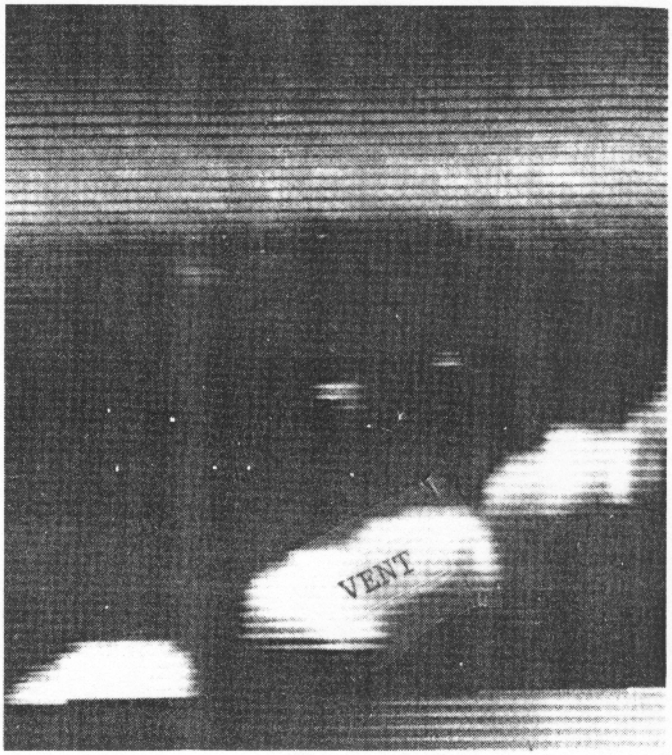

FIGURE 3
Roof thermogram near vents

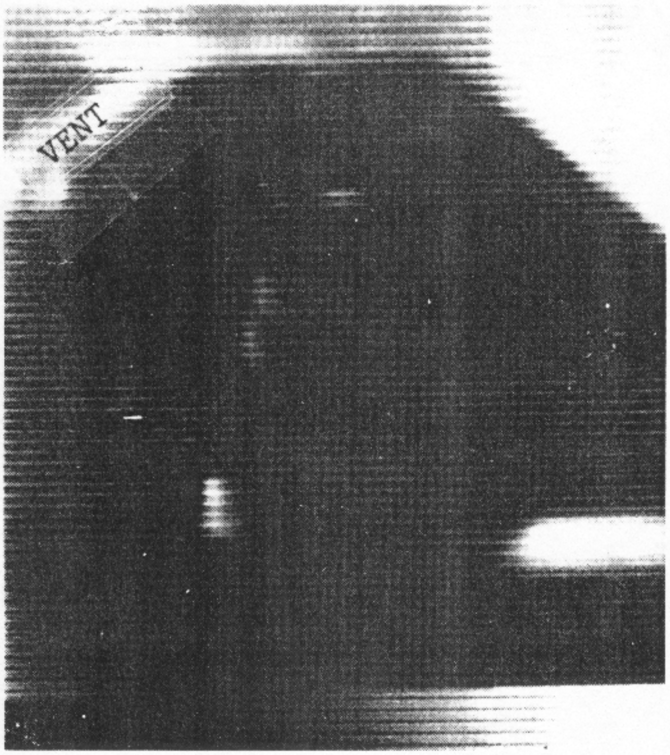

FIGURE 2
Roof thermogram

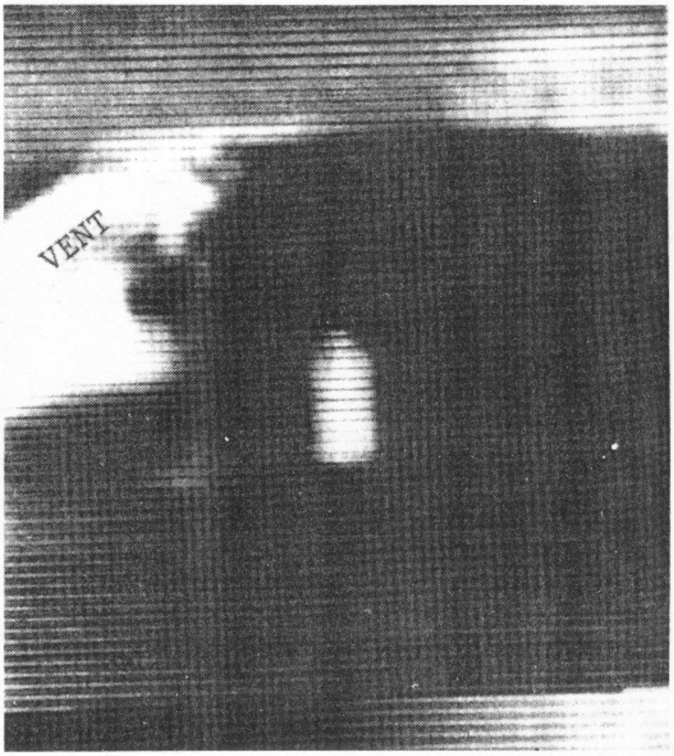

FIGURE 4
Roof thermogram at Measurement Location (Location marked by cylinder)

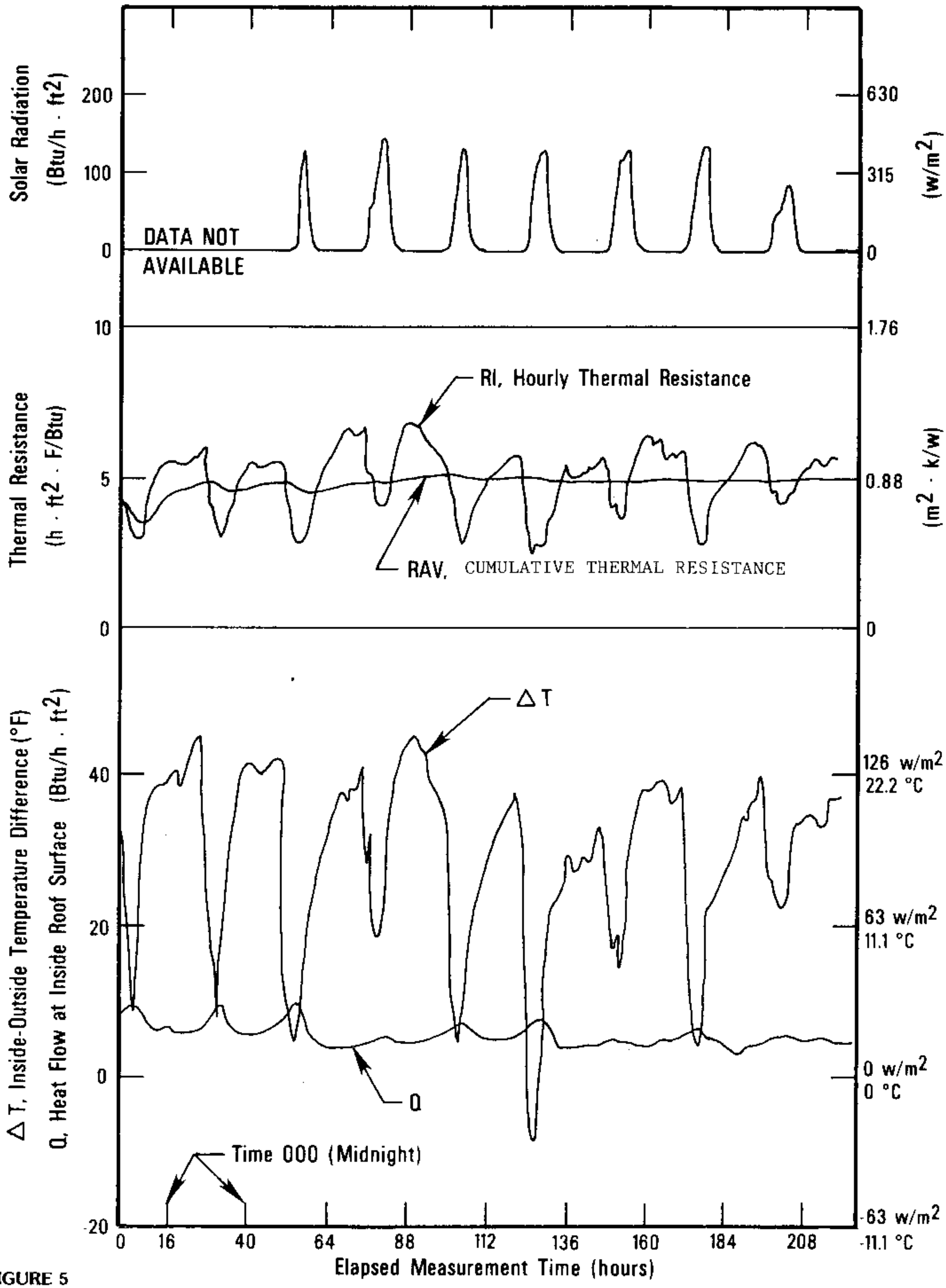
Solar Radiation (Btu/h · ft2)
(w/m2)
200
100
0
630
315
0
DATA NOT AVAILABLE
10
5
0
1.76
0.88
0
Thermal Resistance (h · ft2 · F/Btu)
(m2 · k/w)
RI, Hourly Thermal Resistance
RAV, CUMULATIVE THERMAL RESISTANCE
ΔT
40
20
0
-20
126 w/m2
22.2 °C
63 w/m2
11.1 °C
0 w/m2
0 °C
-63 w/m2
-11.1 °C
Q
Time 000 (Midnight)
ΔT, Inside-Outside Temperature Difference (°F)
Q, Heat Flow at Inside Roof Surface (Btu/h . ft2)
0
16
40
64
88
112
136
160
184
208
Elapsed Measurement Time (hours)

FIGURE 5

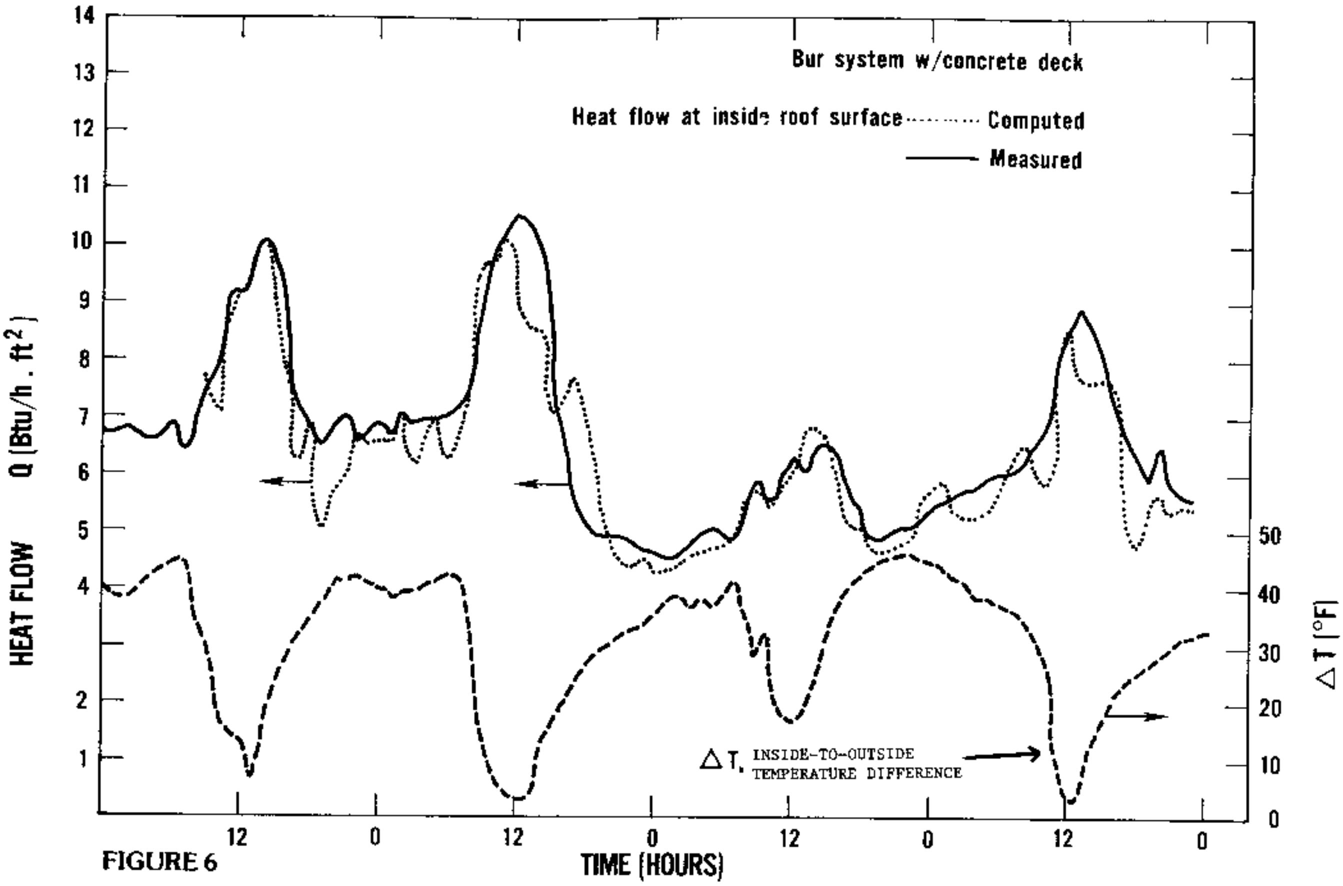

FIGURE 6

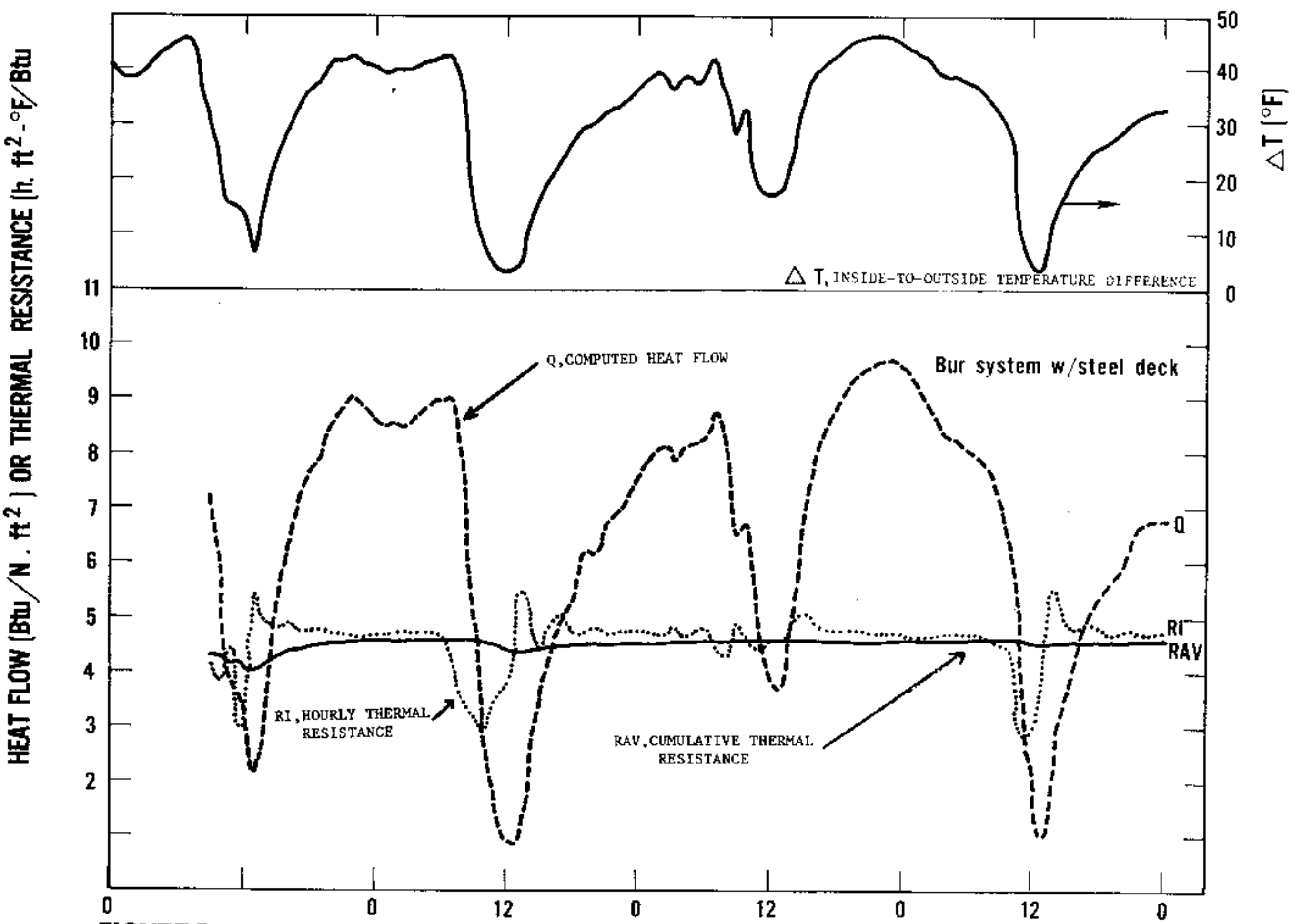

FIGURE 7

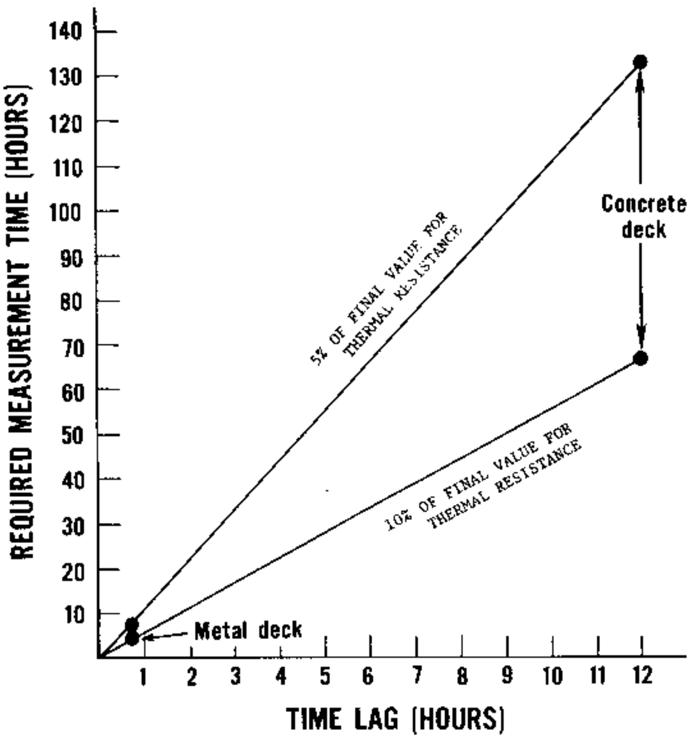

FIGURE 8

PHYSICAL QUANTITY	FROM	TO	MULTIPLY BY
Area	ft^2	m^2	9.29 (10^{-2})
Thermal Resistance	$h.ft^2.F/Btu$	$K.m^2/W$	1.76 (10^{-1})
Temperature	F	C	$t_c = (T_F - 32)\ 1.8$
Length	in	m	2.54 (10^{-2})
Length	ft	m	3.05 (10^{-1})
Heat or Energy Flow	$Btu/h.ft^2$	W/m^2	3.15
Thermal Conductance	$Btu/h.ft^2.F$	$W/m^2.K$	5.68

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