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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, ***Secretary***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

Abstract

A methodology was developed to estimate the thermal performance of existing low-sloped roof systems. The methodology was based on a review of available information and experience. Roof system thermal resistance is used as the thermal performance characterization parameter. The procedure for determining total roof thermal resistance is described, including measurement and calculation methods, and adjustments for moisture intrusion, insulation gaps and fasteners.

Keywords: energy conservation, heat flow; low-sloped roofing; moisture intrusion; roofs; thermal resistance

Executive Summary

A methodology was developed to estimate the thermal performance of existing low-sloped roofing systems. The methodology was based on a review of available information and experience. The roofing systems for which the thermal resistance is to be determined include the components from the bottom of the roof deck to the top of the roof surfacing.

The thermal performance of existing roofs was estimated based on the roof thermal resistance (R-value) as the performance characterization parameter. The thermal performance of a roof was determined based on its steady-state thermal resistance, which is the ratio of the surface-to-surface temperature difference across the roof to the heat flow through the roof. Under actual dynamic temperature conditions the instantaneous heat flow is seldom inversely proportional to the R-value due to transient heat flow and heat storage within the roof, however, the R-value is an appropriate indicator of the relative thermal performance of a roof.

The steps to follow for determining the roof thermal performance using the methodology are given in a flow-chart and discussed in the report. The thermal resistance can be calculated or determined from measurement depending on the information available regarding the types of materials in the roof system, their thermal properties, the moisture content of the roofing materials, types and widths of gaps in the thermal insulation, and number and spacing of fasteners used to attach insulation. The thermal resistance of an existing roof can be reliabily calculated if the roof construction is known. The roof construction may be determined from construction information (if reliably known) or core samples. The calculated R-value must be adjusted for moisture in the insulation, gaps between insulation panels, and fasteners. It will most likely be necessary to divide the roof into sections which have similar conditions, such as types of roof materials or moisture content, in order to calculate or measure the thermal resistance.

Measurement of thermal resistance is necessary when information about the roof construction is not available and it is not possible to take core samples. A determination must be made regarding where to make thermal measurements using heat flux transducer, hot plate, or calorimeter techniques. Adjustment of the measured R-value must be made because of gaps between insulation and for fasteners, when thermal measurements are made using heat flux transducers or hot plates.

The final step in the methodology is to combine the thermal resistance for the roof sections used in the calculations or measurements into an R-value for the total roofing system.

A method is presented for estimating the thermal performance of the nation's inventory of roofing. It is based on statistical considerations, in which the characteristics of a large population (i.e., number of roofs) are determined by a smaller sampling of a portion of the population.

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1. INTRODUCTION

1.1 BACKGROUND

Low-sloped roofs of industrial and commercial buildings can be a large source of energy loss. The nation's inventory of low-sloped roofing systems is of the order of 25 x 10^9 ft^2 (2.3 x 10^9 m^2) [1]*. For many buildings having low-sloped roofs, the roofing system represents a substantial portion of the building thermal envelope [2]. For example, as pointed out by the National Roofing Contractors Association about a decade ago, a commercial building, with dimensions 100 x 150 ft by 10 ft in height (30 x 46 m by 3 m) has 5000 ft^2 (465 m^2) of wall area, and 15,000 ft^2 (1400 m^2) of roof. Thus, for many types of industrial and commercial buildings, the roof is a key building envelope component offering significant opportunity for reducing the energy used in heating and cooling. A recent estimate by Chang and Busching [3] indicates that approximately 730,000 billion Btu (770,000 x 10^{12} J) of the energy consumed in operating commercial and industrial buildings could be saved if the R-value of the roofs were improved from 5 to 25 $h \cdot ft^2 \cdot °F/Btu$. This amounts to about 1 percent of the total annual U.S. energy consumption [3].

Not only should low-sloped roofing systems be adequately designed and insulated for energy conservation, but in addition, they should maintain their designed level of performance over their intended service life. In particular, the roof membrane and associated flashings should perform satisfactorily to prevent water penetration into the roof system. Moisture accumulation in roofing systems may significantly decrease the thermal resistance (R-value) of the roofing system [4,5]. Moreover, in cases where roofs fail prematurely, the energy which was consumed in manufacturing the components and assembling them on site is effectively wasted when the failed roof is replaced. In reviewing the effect of roofing durability on energy consumption, Chang and Busching [3] concluded that about 0.06 percent of the the U.S. annual energy consumption might be saved if the service life of roofs was increased by one year. In reaching that conclusion, they assumed that average roof lifetimes range from 10 to 15 years.

At present, a methodology for the quantitative assessment of the condition of existing low-sloped roofs is not available. Roof inspections are generally subjective or include destructive measurements of the properties of the roofing membrane and other components. For example, the U.S. Air Force has developed a method for visually inspecting and rating the condition of a bituminous built-up membrane system [6]. The rating is based on reviewing the surface condition of the roofing with regard to typical built-up roofing problems and estimating the extent of the problems over the surface-area of the roof. In the case of low-sloped roofing in general, nondestructive evaluation (NDE) techniques have only been applied to the detection of moisture in roof insulation. NDE techniques have not been used for the measurement of component properties.

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* Figures in brackets refer to references given in section 6.

A methodology for quantitatively assessing the condition of existing roofing should consider four main areas:

1. the determination of thermal performance;
2. the nondestructive evaluation of properties of roof components in the field, particularly the waterproofing membrane;
3. the destructive evaluation of the properties of roof components using laboratory and field tests; and
4. visual observation of the roof condition.

Such a methodology should be applicable to roofs having a wide range of U-values and moisture contents. It should also consider the wide variety of materials (for example, single-ply and bituminous membranes), systems, and designs which comprise the nation's inventory of low-sloped roofs.

The development of a methodology for the quantitative assessment of the condition of existing low-sloped roofing would be beneficial in many ways. In particular, guidelines would be provided to assist in making decisions regarding the need for repair, the type and extent of needed repairs, and whether the roof should be replaced [7]. The needless replacement of acceptable existing systems, as well as the wasteful recovering of unacceptable membranes and systems with new membranes, might then be avoided. Moreover, since the methodology would include a quantitative estimate of thermal performance, decisions regarding repair and replacement could also consider the need and opportunity to improve the thermal performance of the roof system, and its impact on the energy consumption of the building.

Because of the benefits to be gained from the availability of a methodology for assessing the condition of existing low-sloped roofing, the U.S. Department of Energy (DoE) requested the National Bureau of Standards (NBS) to undertake a study to develop one of the four main areas; namely, the estimation of thermal performance. This report presents the results of the study.

1.2 OBJECTIVE

The objective of the study was to develop a methodology to estimate the thermal performance of existing low-sloped roofing systems.

1.3 SCOPE OF THE STUDY

The development of the methodology to estimate the thermal performance of low-sloped roofing systems was based on a review of existing information and experience. The major topics included in the review were: techniques for determining the profile or description of roofing systems; methods for detection of moisture in roofing; methods for in-situ thermal measurements; standard procedures for calculating thermal resistance of building envelope components and estimating the effect of moisture on that resistance; and techniques for estimating the effect of thermal bridges such as gaps between insulation boards and mechanical fasteners. No testing of roofing thermal resistance was conducted during the study, nor was any preliminary field validation of the proposed methodology carried out.

For purposes of this study, the roofing system includes all components from the bottom of the roof deck to the top of the roof surfacing. The typical components of low-sloped roofing systems, as listed in most part by the National Roofing Contractors Association (NRCA) [8], are given in Appendix A along with handbook values of the thermal properties of these components. Some additional materials, for example, phenolic foam insulation and concrete paver block surfacings, have been added to the NRCA list of roofing components.

The thermal resistance of the roofing system is based on a typical cross section of the roof which includes deck, insulation, and membrane. Plenum or air spaces below the deck, such as those created by the installation of a dropped accoustical ceiling, are not considered as part of the roof. The effects of flashing systems at roof edges and penetrations are also not considered within the scope of the study. Thermal losses due to heat transfer at the edges of the roof are not given separate, detailed treatment because general techniques for conducting the thermal analysis of the edge effect are not available for use in the methodology. The thermal analysis of the edge effect would be a complex procedure requiring detailed information concerning the construction of the roof/wall interface. For many buildings with low-slope roofs, the thermal losses at the edge of the building is not considered to be a significant effect, since the total roof surface area is usually much greater than the perimeter area.

The effects of roof top equipment such as fans, vents, and ventilators, and constructions such as penthouses and equipment rooms are not included in the methodology. While large energy flows can be associated with roof penetrations such as fans and ventilators, this heat loss is not directly influenced by roof thermal performance. Rather, heat loss through such service system penetrations is associated with air flow through them and is a by-product of providing ventilation and other services for the building. The number and nature of such penetrations is strongly a function of building type and occupant requirements. Energy loss through penetrations should be minimized by their proper operation.

Significant thermal losses may also result from roof penetrations that have little or no air flow associated with their use. Examples of such penetrations are vent stacks, pipe columns, and structural members used as equipment supports. These penetrations may have high thermal conductance, and are thermal bridges by-passing the roof insulation. As in the case of edge effects, the thermal analysis of the effect of these penetrations would be complex. Detailed analysis have not been conducted, and consequently sufficient data are not available for incorporation of these penetration effects in the methodology*.

* To illustrate the potential adverse effect of conductive penetrations, an example can be given based on a preliminary, unpublished analysis conducted at the Oak Ridge National Laboratory. In this example, the effect of a 3-inch pipe column on the R-value of a 4x4 ft section of insulated roofing was calculated. The R-value of the section without the penetration was 25.5; whereas the R-value with the pipe column was 14.4. This represents a reduction of about 40 percent. Boundary conditions for the analysis are not known.

When data become available, the methodology may be revised for inclusion of the effects of roof penetrations.

Finally, although an inspection of the roof may be conducted under some circumstances within the framework of the methodology, an assessment of the remaining service-life of the roofing lies beyond the scope of the methodology.

2. DESCRIPTION OF METHODOLOGY

2.1 MAJOR ELEMENTS OF THE METHODOLOGY

The roof thermal performance methodology in this study is based on roof thermal resistance (R-value) as the performance characterization parameter. That is, the thermal performance of a roof is evaluated based on its steady-state thermal resistance, which is the ratio of the surface-to-surface temperature difference across the roof to the heat flow through the roof. While under actual dynamic environmental conditions heat flow is not generally inversely proportional to the R-value due to transient heat flow and heat storage within the roof, R-value may be used as an indicator of the relative thermal performance of a roof.

The R-value of the roofing system may either be estimated using design R-values of the individual components, or measured directly using techniques developed for in-place measurement of heat flow through roofs. The methodology includes determination of R-value by either means. However, it is emphasized that the methodology provides an estimate of R-value, due to the assumptions included in it. Roof thermal resistance measurements and calculations have an uncertainty of 10 percent or more, due to measurement error or use of handbook heat-tranfer properties. Because of constraints related to the time and expense of conducting in-place heat flow measurements, it is anticipated that for most roofs a measurement of R-value would not be practical. In most cases, the R-value would be estimated through calculation.

If the roof construction is known, its design thermal resistance can be calculated. However, due to construction variables and the potential for moisture penetration into low-sloped roofing systems, the R-value of the roofing system in service may be less than its calculated design value. For a thermally efficient roof, the major component affecting thermal performance is the insulation. Three key factors which may result in a decreased thermal resistance of the roof (as compared to its design value) are moisture in the insulation, fasteners for attaching the insulation to the deck, and gaps between insulation boards. Thus, in estimating the thermal performance of the roof, adjustments must be made to the design R-value to account for these factors.

An advantage of conducting an in-place measurement of R-value is that the effect of moisture present in the system will be included in the result of the measurement. Also, it is not necessary, in principal, to know the roof construction to carry out an in-place measurement of R-value. However, in-place R-value measurements are carried out on an extremely limited area of the roofing systems. Thus, it is necessary to know that measurements which are conducted provide results which may be extrapolated to and are indicative of the R-value of the entire roof.

The methodology for estimating the thermal performance of low-sloped roofing systems either through calculation or in-place measurement consists of the following elements:

A. Compile the information needed to describe the roof
B. Divide the roof into areas of apparently identical construction
C. Note construction components in each area, and the thermal properties of each layer (if known)
D. Determine if moisture conditions or other anomalies exist which might cause thermal resistance to vary across each area; if so, subdivide area into sub-areas, each with comparable moisture conditions or anomalies
E. Complete initial estimate of overall roof thermal resistance for each uniform sub-area
F. Determine moisture content for each uniform sub-area
or
Measure thermal resistance for each uniform sub-area
G. Adjust insulation thermal resistance to account for moisture, if necessary
H. Recompute overall roof thermal resistance including the effect of moisture in the insulation
I. Adjust overall roof thermal resistance for the effects of fasteners and gaps, if necessary
J. Compute overall roof thermal resistance for the total building, using the adjusted overall thermal resistances of each of the sub-areas

Each of these elements of the methodology are described in section 3 of the report. A flowchart for the methodology is given in figure 1. Steps in the methodology subdividing a roof into uniform sub-areas are implicite in the flow chart.

An initial value for the thermal resistance of the roof is calculated based on the determination of the roof construction. In those cases where the roof construction may vary for different sections of the building, each sub-area must be separately considered.

Figure 2 presents a typical roof cross section, consisting of a deck, insulation, membrane and surfacing. While the materials may vary, most roofs have a similar layered construction. The overall thermal resistance of the roof, in the absence of gaps or fasteners, is equal to the sum of the thermal resistances of the individual layers. Thus, the overall thermal resistance (R_o) for the roof cross section in figure 2 would be:

$$R_o = R_S + R_M + R_I + R_D \quad (1)$$

where: R_S = thermal resistance of surfacing materal
R_M = thermal resistance of membrane
R_I = thermal resistance of insulation
R_D = thermal resistance of deck

If moisture intrusion into the insulation has occured, the R-value of the insulation will decrease. If the decrease in R-value is known as a function of moisture content, the actual R-value of the insulation (R_{Ia}) can be expressed as:

$$R_{Ia} = N_m R_I \quad (2)$$

where: N_m = moisture adjustment factor (function of moisture content)

The adjustment of the insulation R-value for moisture effects results in a new value for the overall thermal resistance. For convenience, let the moisture adjusted overall R-value be represented by R_A, such that:

$$R_A = R_M + R_{Ia} + R_D \qquad (3)$$

If fasteners were used to attach the roof insulation, a second adjustment must be made to the overall R-value. Figure 3a presents a roof cross section containing a fastener extending through a single layer of insulation, and figure 3b shows a fastener in a typical double layer configuration in which the fastener only penetrates the lower layer. The presence of the fasteners will reduce the effective R-value of the roof due to thermal bridging. The effect of the fasteners can be approximated using an adjustment factor based upon fastener area. The details of the use of this factor are explained later in this report.

The effects of insulation gaps are handled in a similar manner. Figure 4a shows a roof cross section including a typical through gap, and figure 4b presents a typical lapped gap. The thermal resistance of the roof is decreased due to the presence of the gaps. The effect of the gaps is estimated using an adjustment factor based on gap area percentage.

As an alternative to computing the adjusted overall roof thermal resistance, the thermal resistance can be directly measured in-situ. Details regarding measurement procedures are described later in this report.

The foregoing procedures hold for a uniformly constructed roof of homogeneous condition. If the roof construction of a single building varies, each uniquely constructed region must be evaluated separately. If the moisture content varies across each uniquely constructed portion of the roof, separate sub-areas must be used. The final adjusted R-value for the total building (R_{TB}) is computed from:

$$R_{TB} = \frac{A_{TBn}}{\sum_{i=1}^{N} \frac{A_{ni}}{R_{Ci}}} \qquad (4)$$

where: A_{TBn} = total building net roof area
A_{ni} = net area of ith portion of roof
R_{Ci} = adjusted R-value of ith portion of roof
n = number of unique portions of roof

The adjustment factors are obtained from tables and methods given in this report, on the basis of insulation type and size, moisture content, penetration area and insulation gap size. The gap adjustment factor is derived from work by Lewis [9], and the penetration adjustment factor is adapted from Burch [10] and from Chang and Busching [3], the moisture adjustment factor is based on work by Knab et al. [5], Tobiasson and Ricard [4], and Powell and Robinson [11].

After adjustments for moisture, fasteners, and gaps, the estimated in-service R-value of the roof system may be compared to its design R-value. This comparison provides a rating of how the roof is thermally performing versus its design value. Similarly, the estimated in-service R-value may be compared to an R-value for the roof which was optimally designed according to current recommendations to obtain maximum benefits for energy conservation. This comparison provides a rating of how the roof is thermally performing versus an optimally designed roof.

The methodology may be used for any building for which there is interest in estimating the in-service thermal performance. However, it is believed that the major utility of the methodology would be in its application to roofing systems which are being investigated or surveyed for other reasons such as to determine the need for repairs or renovation, on the presence of water in the system. The reason is that the methodology includes steps normally conducted during roof investigations such as non-destructive evaluation (NDE) of moisture in the system and the taking of core samples. Thus, it would be most practical to conduct the methodology in conjuction with such roof investigations.

3. DETAILS OF THE METHODOLOGY

3.1 THE ROOF PROFILE

The first step of the methodology is to assemble a profile of the roof for which the thermal performance (R-value) is to be determined. The major characteristics of the roof profile are:

(1) description of the roof system components.

(2) identification of the construction details of the roof system.

(3) identification of the moisture condition of the roof system.

These characteristics are described in the steps taken to assemble the roof profile.

Step 1.1 Determine candidate roof

In principle, any existing low-sloped roof could be a candidate for evaluation of R-value according to the procedure described in the methodology. However, some practical considerations may preclude or reduce the possibility that a given roof is a candidate for R-value determination. Such considerations include:

- a roof which is planned for replacement,
- a roof in which cuts or core samples cannot be taken,
- a roof for which the construction cannot be readily verified (for example, a sloped fill system containing insulating form boards).

In order to complete one pathway through the methodology, at least one of the following must be true (see figure 1):

1) the roof construction and moisture condition must be known
2) the taking of core samples must be possible
3) the thermal resistance of the roof system must be obtainable by direct measurement

Once determining that the roof in question is a candidate, information regarding the building identification should be compiled, including its name or number, its location, and owner. It may be also useful to identify the use of the building (e.g., school, hospital, office building, shopping center).

Step 1.2 Assemble the available roof information

Existing information which may assist in the determination of the roof construction and moisture condition is assembled. In the ideal case, such information would be in a "roof file" for the building in question. The information to be assembled includes: the "as built" drawings and specifications; records describing the performance history including maintenance inspections, leaks, and repairs; and results of tests and NDE inspections conducted on the roof.

Experience has often shown that in many cases accurate information on the "as built" condition and present moisture condition of an existing roof are only partially available or not available at all. In some cases, records concerning the roof may be scattered. However, the lack of availability of information concerning the roof and its past performance is not a detriment to conducting the methodology. The information needed concerning the roof construction and moisture condition can be assembled in subsequent steps of the methodology.

Step 1.3 Decide whether the roof construction and moisture condition are known

The intent of the methodology is to provide an estimation of the in-service R-value of the roof in as straightforward a manner and to the best extent possible. A review the information assembled in step 1.2. must be conducted to see whether it is sufficient and accurate for determining the profile of the roof. A summary of the needed information is given in table 1. If a complete, accurate, and up-to-date file is available, then it may be used to assemble the roof profile before proceeding. It is emphasized that the information must be known with sufficient confidence. If there is any doubt concerning the reliability or completeness of the information gathered in step 1.2, additional information must be obtained in steps 1.4 and 1.5.

Step 1.4 Decide whether core sampling is possible

Core sampling plays an integral role in the determination of the roof construction and moisture condition. If the roof components and moisture conditions are not known, and core sampling is not possible, then the R-value of the roofing system can not be estimated by calculation but must be determined through measurement (figure 1). Although it is considered that for most roofs core sampling would be possible, in some cases that it may not be possible.

If core sampling is possible, proceed to either step 1.5 or step 1.6. If core sampling is not possible, proceed to step 1.6.

Step 1.5 Identify roof construction and moisture condition

This step provides needed verification and additional information concerning the roof construction and moisture condition through firsthand experience on

Table 1. Summary of Information Concerning Roof Construction and Condition

The Roof	Details
1) Construction	
Surfacing	Type Thickness
Membrane	Type Thickness
Insulation	Number of Layers Type of each layer Thickness of layer (including composite boards) Joints Staggered (if two or more layers) Method of attachment Number of metallic fasteners per board (If mechanically fastened); area of fasteners
Vapor Retarder	Type
Deck	Type Thickness
2) Condition	
Leaks	Any suspected or known leaks and area where occurring
Moisture	Areas where the roofing systems has moisture in the insulation, percent of the roof area which contains moisture
Defects	Any known defects which could have resulted in water penetration since last evaluation.

the roof including test cuts or core samples. It is a key step in the methodology, since it allows an estimation of the R-value of the roof through calculation. It must be determined whether the roof construction is the same for the entire building or if differences in construction exist for some sections. A determination must also be made of those areas of the roof system which contain moisture beyond the normally accepted ambient moisture levels. Erroneous information concerning the roof construction and moisture condition will result in an inaccurate estimation of the roof's R-value. The identification of the roof construction and moisture condition involves three main activities:

1. visual inspection of the roof

2. nondestructive evaluation (NDE) of moisture condition of the roof system

3. removal of core samples of the roof system and determination of moisture content of the insulation

Each area of the roof which is identified as having different construction or moisture condition should be treated as a distinct sub-area of the roof. The R-value of each sub-area is to be estimated and used in the calculation of the R-value of the entire roof.

The visual inspection of the roof, nondestructive evaluation (NDE) of moisture, and the removal of core samples may be carried out together or as separate steps. It is generally desirable to perform the NDE moisture condition surveys prior to obtaining core samples, since the moisture distribution information will aid in the determination of the appropriate locations to take core samples. However, core samples can be obtained before any NDE surveys, if convenient, to assist in the identification of roof system components.

The visual inspection is intended to provide information concerning factors affecting the thermal performance of the roof. Moisture intrusion into the roofing system is obviously the key factor and areas where moisture has penetrated should be noted. The details of such inspections have been given by a number of organizations including the National Roofing Contractors Association and the Asphalt Roofing Manufacturers Association [11], the Roofing Industry Educational Institute [12], the U.S. Air Force [6], and the U.S. Department of Defense [14].

The NDE evaluation of the roof is the primary method used in the methodology to detect areas of the roof system where water has penetrated and wetted the insulation. Three nondestructive methods of moisture detection are currently being used: infrared thermography, nuclear backscatter, and electrical capacitance. Descriptions and use of these methods have been reported in the literature [15-18]. They detect changes in properties of the roofing system due to moisture and do not directly detect water. Thus, the reliability of the results depends upon factors such as instrument response, interpretation of instrument response, and knowledge of the construction of the roofing system. The selection of an NDE method should be carefully considered, and the results verified by sampling cores of the roofing system. Core samples should be taken from each section of the roof where the NDE survey indicated unique moisture conditions or other thermal anomalies. For each area, the moisture content of the insulation should be determined. Knab et al [16] have described a procedure for this. Upon completion of the NDE survey, areas of wet roofing should be marked on a roof plan and the percent of wet areas as related to the total roof area should be calculated. Where the measurements of moisture content of the core samples and results of the NDE survey indicate varying degrees of moisture in different sections of the roof, then each area should be treated separately and their percent areas calculated individually. It is realized that this procedure gives only an estimate of varying moisture content within the roof and that considerable judgment must be exercised in approximating those areas of varying moisture content.

In addition to verifying the results of the NDE tests, the core samples may be used to determine the construction of the roofing system. Tobiasson and Korhonen [18] have described a core sampling device which has been found effective in taking 2 in. (50 mm) core-samples. Core-samples should be taken down to the deck so that the type of deck may be noted.

Examination of the core samples provides information concerning the type of membrane, insulation, and vapor retarder. The insulation thickness and number of layers can also be ascertained. Sections of the roof system from which core samples have been removed must be sealed using repair methods appropriate to the type of membrane and insulation in the system.

In identifying the roof construction, it is also necessary to know the type of gaps between insulation boards, the gap spacing, and the method of attachment of the boards to the roof deck. The type of gap may be classified as follows: no gap, lapped gap, and through gap. Single-layered insulation board applications obviously have through gaps. Two or more layers of insulation boards may have through gaps or lapped gaps depending upon whether the layers of boards have staggered joints. An example of no gaps would be spray-in-place polyurethane foam. It is difficult at best to determine the gap spacing after the roof is in place. In these cases, a spacing of 3/16 in. (4.8 mm) should be assumed for the entire roof [9].

Insulation boards may be adhered, mechanically fastened or loose-laid depending upon the type of deck and method of membrane attachment. For some roofs, combinations of these techniques may be used. Where mechanically fastening is used, it is necessary to know if the type of fasteners (i.e., metallic, plastic, or composite), the size of the head on the fastener, and the number of fasteners per board.

Step 1.6 Determine where to make in-situ thermal measurements

This step is included when in-situ thermal measurements are to be made to determine the R-value of the roof. Since an in-place measurement of R-value is only made on a limited section of the total roof area, the location where measurements are to be made must be selected judiciously to be indicative of the general thermal performance of the entire roof system. If the roof contains areas which are performing different thermally (for example, due to moisture in the insulation), then a number of measurements representative of the different areas of the roof would be needed to describe the total thermal performance.

Non-destructive methods for evaluation of moisture content in the roof may be used to indicate the areas where in-place measurement of R-value should be taken. However, since infrared thermography primarily responds to differences in heat flow through the roof, it is suggested that thermography be used to indicate where the in-place thermal measurements should be made. Thermography also offers the advantage that the technique inspects the entire roof surface, while alternate NDE methods make evaluation at specific points. Based on a thermographic survey, areas of suspected high heat flow can be isolated from areas of low heat flow, regardless of whether these differences are caused by the presence of moisture or anomolies in the roof construction.

Upon determination of the areas where the heat flow measurements are to be made, proceed to step 2.2 or 2.3.

3.2 DETERMINATION OF INITIAL ROOF THERMAL RESISTANCE

Roof thermal resistance is a measure of the ability of a roofing system to retard heat flow due to a temperature difference between the top and bottom roof surfaces. Each of the roof layers contributes to the thermal resistance of the system as a function of its thickness, conductivity and condition.

For an n-layer roof construction, the total thermal resistanc (R_n) is the sum of the individual thermal resistances of each of the layers:

$$R_n = \sum_{i=1}^{n} R_i \qquad (5)$$

where R_i denotes the thermal resistance of the i-th layer.

The thermal resistance of the i-th layer can be determined from the thermal conductance (C), or the thermal conductivity (k) and thickness (L), according to:

$$R_i = \frac{1}{C_i} = \frac{L_i}{k_i} \qquad (6)$$

The appropriate values for C, k and L can be determined from specifications, measurement, manufacturers literature, or table A1, which lists typical thermal properties of roof components.

As an alternative to roof R-value calculation, roof thermal resistance can be determined by direct measurement, using either heat flux transducers and thermopiles, or roof calorimeter techniques. These procedures are described in Appendix B.

Step <u>2.1 Compute initial R-value</u>

This step, and those following, must be completed for each unique roof sub-area. First, the net area of the particular section of the roof is computed by subtracting the area of any penthouses, skylights or vents from the gross roof area. Next, the initial estimate of the overall roof R-value is made by summing the resistances of individual layers. For example, the overall roof R-value is typically given by:

$$R_{oi} = R_M + R_I + R_D \tag{7}$$

where: R_M = R-value of membrane
R_I = R-value of insulation
R_D = R-value of deck
R_{oi} = initial overall R-value

Judgement must be exercised in properly applying equation 5 and 6 when a roof section is composed of multiple layers of insulation, and in accounting for variable insulation thickness. In general, each roof sub-area should have nearly uniform insulation thickness. If insulation thickness varies considerably, e.g., tapered insulation systems, separate sub-areas should be defined for each area of relatively uniform insulation thickness. An equation for computing the thermal resistance of linearly tapered insulation is given in Appendix B.

Step <u>2.2 Measure R-value, heat flux transducer or hot plate</u>

The sub-area R-value can also be measured using a heat flux transducer or hot plate (see details in appendix sections B.1 and B.3). The measured R-value should be labeled R_B, which includes the effects of fasteners and moisture. After completing this step, proceed to step 4.2. Step 4.1 is <u>not</u> used, since these measurement methods include the effects of moisture, and fasteners.

Step <u>2.3 Measure R-Value, calorimeter</u>

The sub-area R-value can also be measured using a portable calorimeter, if a suitable measurement area is available (see details in appendix C.2). The measured R-value should be labeled R_B. After completing this step proceed to step 5.1. Steps 4.1 and 4.2 are <u>not</u> used, since the calorimeter measurement includes the effects of moisture, fasteners, and gaps.

3.3 <u>MOISTURE INTRUSION</u>

The moisture content of insulation materials can exert a strong influence on heat flow-through a roofing system. As the amount of moisture in the insulation increases, the R-value decreases. This section of the methodology adjusts the previously calculated R-value for moisture effects.

Step 3.1 Adjustment for moisture intrusion

Laboratory research [4,5,11] has enabled estimation of the effect of moisture content on the thermal resistance of the roof insulation for different insulating materials and thickness. These results have been incorporated into table 2, which provides coefficients for computing moisture adjustment factors, N_m, which are tabulated on the basis of total moisture content. The relations between the reduction in R-value and moisture content of the insulations were based on measurements under simulated use conditions where moisture distribution occurred naturally. At this time, data required to provide adjustments based on moisture distribution are lacking.

The moisture adjustment factor is multiplied by the initial thermal resistance of the insulation, R_I, to account for the derating effects of moisture intrusion. The variation of thermal resistance with moisture content is not, in general, linear. However, the moisture adjustment factor N_m can be determined from the coefficients listed in table 2, according to:

$$N_m = \frac{1}{K} \quad \text{or} \quad N_m = J \qquad (8)$$

$$K = b_o + b_1 V_p + b_2 V_p^2 \qquad J = 1 + a_1 V_p + a_2 V_p^2 \qquad (9)\ (10)$$

where b_o, b_1, b_2, a_1, a_2 = coefficients from table

V_p = percent moisture content by volume of insulation

$$V_p = \frac{\text{Volume of water}}{\text{Volume of insulation}} \times 100 \qquad (11)$$

Either factor, K or J, can be used to determine N_m, depending upon the type of material and the type of insulation as listed in table 2. This distinction between K or J is artificial and is strictly due to differences in the reference sources from which the coefficients were obtained.

The moisture content must be determined using one of the methods described in appendix B. Once the moisture adjustment factor has been determined, the moisture adjusted insulation thermal resistance (R_{Ia}) is determined from:

$$R_{Ia} = N_m R_I \qquad (12)$$

and the moisture adjusted overall roof thermal resistance (R_A) is recomputed according to:

$$R_A = R_M + R_{Ia} + R_D \qquad (13)$$

Table 2. Coefficients to Compute Moisture Adjustment Factors, N_m

Insulation Type	Thickness	$K = (b_o + b_1 V_p + b_2 V_p^2)$ Curve Coefficients b_o	b_1	b_2
Glass fiber	1 in	.99	-.00463	.00565
Glass fiber	2 in	1.069	-.0025	.00554
Perlite	1 in	1.107	.0554	-.000259
Perlite	2 in	1.187	.0701	-.000372
Fiberboard	1 in	1.096	.0359	-.000181
Fiberboard	2 in	1.111	0.571	-.00187
Expanded Polystyrene	1 in	1.056	.0436	--
Expanded Polystyrene	2 in	.987	.0188	.000466
Polyurethane	1 in	1.018	.0457	.00104
Polyurethane	2 in	.918	-.00606	.00631

Insulation or Deck Type	Thickness	$J = 1 + a_1 V_p + a_2 V_p^2$ Curve Coefficients a_1	a_2
Wood fiber cement board	3 in	-0.0174	-0.00567
Perlite concrete	3 in	-0.0520	-0.00122
Perlite concrete	6 in	-0.0532	-0.00110
Vermiculite concrete	7 in	-0.0554	-0.00105
Extruded Polystyrene	2 in	-0.171	-0.0816
Cellular glass	1.5 in	-0.0694	-0.00607

** Vp = moisture content, percent by volume of insulation

$$V_p = \frac{\text{Volume of water}}{\text{Volume of insulation}} \times 100$$

$$N_m = \frac{1}{K} \text{ or } N_m = J$$

3.4 ADJUSTMENT FOR FASTENERS AND GAPS

A significant amount of heat flow through roof systems can occur through thermal bridges created by fasteners and gaps between insulation boards. This section treats the effect of these thermal bridges.

It should be noted that in some cases a design R-value for a roof may already include the effects of gaps or fasteners. In those cases, the adjustment for those effects should not be implemented.

Step 4.1 - Adjustment for fasteners

Some mechanical fasteners are more conductive than the roof insulation, and may act as thermal bridges. A typical mechanical fastener consists of a metal or plastic disk or plate pierced by a metal nail or screw. When installed, the disk or plate is flush with the top of the insulation, and the fastener extends through the insulation and is imbedded in the roof deck (See figures 3a and b). More fasteners ensure better attachment but increase the number of thermal bridges. The thermal resistance of the roof is less in the vicinity of a fastener. Theoretical analysis of this effect has shown that the change in overall roof R-value due to fasteners is a function of the fastener area percentage, insulation thickness, and whether the insulation is single or double-layered [3,10].

The fastener area is determined as the product of the top surface area of a single fastener (i.e., disk or plate area) and the number of fasteners in the roof. The fastener area percentage is determined as the ratio of fastener area to net roof area. Once the fastener area percentage is determined, the fastener adjustment factor, a scaling factor to account for the change in roof thermal resistance due to the fasteners, can be determined as follows. The fastener adjustment factor will depend upon whether the fastener cap or disk is metal or plastic due to the differences in conductivity [10].

While the actual heat flow near a fastener will include some heat transfer in a radial, or horizontal direction, acceptable analytical results can be obtained by assuming that heat flow occurs through parallel paths, one path through the fastener area, and a second path through the remainder of the roof, and subsequently adjusting the results to account for the radial heat flow. The adjustment for radial heat flow was determined by comparing the results of the parallel path to the results of a detailed finite-difference model [10]. The assumption of parallel heat flow overestimates the effect of metal fasteners, as a nearly linear function of insulation thickness for metal and wood decks. The correction factor (CF) for the two types of decks is given by:

$$\text{for metal deck} \quad CF = 0.989 + 0.022 \times \text{insulation thickness (inches)} \qquad (14)$$
$$\text{for wood deck} \quad CF = 1.001 + 0.018 \times \text{insulation thickness (inches)}$$

In the case of a metal disk on the fastener, the fastener adjustment factor (N_f) is given by:

$$N_f = \frac{CF}{1 + \frac{A_f}{A_{Tn}} \left(\frac{R_x}{R_y} - 1\right)} \qquad (15)$$

where: A_f = total fastener surface area
A_{Tn} = total net roof area
R_x = overall R-value without fastener
R_y = overall R-value with fastener
CF = correction factor for radial heat flow

R_x and R_y must be calculated including air film coefficients, so that the same temperature difference can be applied across both areas. Thus:

$$R_x = R_M + R_I + R_D + 1.1 \quad \frac{(h.ft^2.{}^oF)}{Btu} \qquad (16)$$

$$R_y = R_M + R_D + 1.1 \quad \frac{(h.ft^2.{}^oF)}{Btu} \qquad (17)$$

If the fasteners extend only through one layer of a double layer of insulation, the insulation should be divided into two layers, with one of the layers being by passed by the fastener in series with the second layer.

In the case of a plastic disk on the fastener, the fastener adjustment factor (N_f) is again calculated using equation (15) and modified as follows:

$$N_f' = 0.6\ N_f + 0.4 \qquad (18)$$

where: N_f' is the fastener adjustment factor for the case of a plastic disc on the fastener.

The overall R-value (R_B) adjusted for moisture and fasteners is given by:

$$R_B = N_f\ (R_A + 1.1) - 1.1 \quad \text{for metal disks} \qquad (19)$$
$$R_B = N_f'\ (R_A + 1.1) - 1.1 \quad \text{for plastic disks}$$

Step <u>4.2 Adjustment for Gaps</u>

Rigid insulation boards are commonly used as insulation in low-sloped roofing systems and are normally applied to the surface of the structural deck. The installation of the insulation boards result in gaps or joints between adjacent boards. Even carefully placed boards can have gaps of 1/16 to 1/8 of an inch. Larger gaps are common, and dimensional changes of the insulation boards can lead to even wider joints.

Heat losses due to the effect of insulation gaps have been studied by Lewis [9] using a finite element technique. Based on this work, roof thermal resistance adjustment factors due to insulation gaps (N_g) were determined and are presented in table 3. The effect of insulation gaps is dependent on the

Table 3. Gap Adjustment Factors, N_g

For through gaps:

Insulation Thickness in. (mm)	< 1	Gap Area Percentage* 1 to 1.5	1.5 to 2	> 2
2 (50)	0.98	0.96	0.93	0.91
3 (75)	0.97	0.93	0.89	0.86
4 (100)	0.95	0.91	0.86	0.81

For lapped gaps:

Insulation Thickness in. (mm)	< 1	Gap Area Percentage* 1 to 1.5	1.5 to 2	> 2
2 (50)	1.00	0.99	0.99	0.98
3 (75)	0.99	0.99	0.98	0.97
4 (100)	0.99	0.98	0.97	0.96

*Ratio of gap area to roof area

insulation thickness, type of gap, and gap area percentage. The gap adjustment factor is used to scale the R-value, previously adjusted for moisture and fasteners, to account for the derating effects of gaps between insulation.

Gap area percentage is determined by the ratio of gap area to roof area, where gap area is equal to gap width times total gap length (i.e., length of all the insulation joints). The two general types of gaps are (see figures 4a and 4b) through gaps, which result when two boards are placed end-to-end in a butt joint, and lapped gaps, which result from staggering double-layer insulation so no single gap extends entirely through the insulation.

Since the finite element model used to generate the gap adjustment factor included surface air film coefficients, these must be added to R_B and subtracted from the gap-adjusted thermal resistance. The overall roof thermal resistance (R_C) adjusted for moisture, fasteners and gaps is given by:

$$R_C = N_g\,(R_B + 1.22) - 1.22 \qquad (20)$$

Thus, R_C is the final value for the overall, surface-to-surface thermal resistance for the particular roof sub-area.

3.5 FINAL ADJUSTED THERMAL RESISTANCE

Step 5.1 Determination of Final Adjusted Thermal Resistance

The thermal resistance values previously obtained for each of the roof sub-areas must be combined to determine the R-value for the entire roof. The final adjusted R-value (R_{TB}) for the total building consisting of N unique roof subareas is equal to:

$$R_{TB} = \frac{A_{Tn}}{\sum_{i=1}^{N} \frac{A_{ni}}{R_{Ci}}} = \frac{A_{Tn}}{\frac{A_{ni}}{R_{Ci}} + \frac{A_{n2}}{R_{C2}} + \frac{A_{nN}}{R_{CN}}} \qquad (21)$$

where: A_{Tn} = total net building roof area
A_{ni} = net area of sub-area i
R_{Ci} = thermal resistance of sub-area i
N = number of sub-areas

If it is desired to compute the effective average thermal resistance for a group of buildings, equation 21 applies using the net areas and thermal resistances of each building roof.

4. PROCEDURE FOR STATISTICAL ANALYSIS AND INFERENCE

This section of the report is not part of the methodology, but given as an example of the methodology's use.

While the methodology is intended to provide a means for assessing the thermal performance of the roof of a single building, application of the methodology to a small sample of roofs can be used to extrapolate towards an assessment of the thermal performance of a large inventory of low-sloped roofs. This type of extrapolation is based on statistical considerations, in which the characteristics of a large population (i.e., large number of roofs) are determined by observations of a smaller sampling of a portion of the population. Such generalization about the characteristics of a population from a study of one or more samples from the population are termed statistical inferences [19]. Statistical inferences are predictions of what would be found for the case if the parent populations could be fully analyzed with respect to the relevant characteristic, in this case thermal resistance.

In order to obtain a valid statistical inference, the sampled population (i.e., roofs assessed using the methodology) must be essentially similar to the target population (i.e., the class of roofs which is being evaluated). Thus, if it is desired to estimate the average thermal resistance of all low-sloped roofs in the United States, the number and type of roofs evaluated using the methodology should be similar to those found in the general population of roofs. However, if it is desired to evaluate only low-sloped roofs with concrete decks and glass fiber insulation, the sampled population should be limited to roofs of that type.

Information regarding the breakdown of existing low-sloped roof system types is difficult to obtain, particularly since different roofs can vary in many ways. Roof system components, dimensions, age and weathering can vary substantially from building to building. Until this survey information is more readily available, it will be difficult to estimate the average roof thermal resistance for the entire country. However, it should be possible to determine the average thermal performance of each class of roofing systems assessed. This could be accomplished by computing the mean thermal resistance for each sampling of roof types. As more buildings are included in each sample, the confidence interval will become narrower and the sample population mean will approach the target population mean. Once additional information is available concerning the percentage of the nation's roofs which are of each type, the mean thermal performances of each roof type can be combined using weighting factors based on these percentages.

Two parameters are useful for characterizing the performance of a low-sloped roofing system. These are:

1) nominal performance rating, NPR

where:

$$NPR = \frac{\text{final roof thermal resistance}}{\text{initial roof thermal resistance}} = \frac{R_{TB}}{R_{TBd}} \qquad (22)$$

where:

$$R_{TBd} = \frac{A_{TB}}{\sum_{j=1}^{n} \frac{A_{ni}}{R_{oij}}} \qquad (23)$$

R_{oij} = initial R-value for sub-area j

and 2) optimal performance rating, OPR

where:

$$OPR = \frac{\text{final roof thermal resistance}}{\text{optimal overall roof thermal resistance}} = \frac{R_{TB}}{R_{TBO}} \qquad (24)$$

The nominal performance rating is a measure of the actual roof thermal performance compared to the nominal design specifications, and incorporates the derating effects of moisture intrusion, insulation gaps, and fasteners.

The optimal performance rating compares the actual roof thermal performance to a baseline, energy efficient roof, designed according to current energy-conscious practices. The choice of a value for optimal roof thermal resistance is left up to the user of the methodology. However, for the purposes of normalizing the roof R-values for statistical analysis, any reasonable value can be chosen, since all results will be simply scaled.

Once NPR and OPR have been computed for a building roof, the data can be used to update cumulative histograms of frequency of occurance of the two parameters. Such histograms display the percentage of values falling into different ranges, graphically illustrating the total range and distribution of the parameters.

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6. REFERENCES

1. Busching, Herbert W., Mathey, Robert G., Rossiter, Walter J., Jr., and Cullen, William C., "Effects of Moisture in Built-Up Roofing - A State-of-the-Art Literature Survey," National Bureau of Standards (U.S.), Technical Note 965 (July 1978), 78 pages.

2. "Good Roofs Save Energy," National Roofing Contractors Association, Chicago, IL, 52 pages.

3. Chang, Te-chuan and Busching, Herbert W., "Energy Savings Potential of Roofing Research," Clemson University, Report prepared for Oak Ridge National Laboratory (U.S.), ORNL/Sub/82-22293/1 (December 1983), 204 pages.

4. Tobiasson, Wayne and Ricard, John, "Moisture Gain and Its Thermal Consequence for Common Roof Insulations," Proceedings 5th Conference on Roofing Technology, NBS/NRCA, Gaithersburg, MD (19-20 April, 1979), pp. 4-16.

5. Knab, Lawrence I., Jenkins, David R., and Mathey, Robert G., "The Effect of Moisture on the Thermal Conductance of Roofing Systems," National Bureau of Standards (U.S.), Building Science Series 123 (April 1980), 46 pages.

6. "Built-Up Roof Managment Program," AFM 91-36, Chapter 3, Department of the Air Force (U.S.), Washington, DC (3 September 1980), pp. 3-1 - 3-46.

7. Cullen, William C., Rossiter, Walter J., Jr., Mathey, Robert G., and Clifton, James R., "Low-Sloped Roofing Research Plan," National Bureau of Standards (U.S.), Special Publication 659 (July 1983), p. 26.

8. "The NRCA Roofing + Waterproofing Manual," National Roofing Contractors Association, Chicago, IL (January, 1981).

9. Lewis, James E., "Thermal Evaluation of the Effects of Gaps Between Adjacent Roof Insulation Panels," J. of Thermal Insulation, Vol. 3, (October 1979), pp. 80-102.

10. Burch, D. M., Shoback, P., and Cavanaugh K., "A Heat Transfer Analysis of Cylindrical Metal Fasteners in Built-Up Roofs," National Bureau of Standards (U.S.), Report in Preparation.

11. Powell, Frank J. and Robinson, Henry E., "The Effect of Moisture on the Heat Transfer Performance of Insulated Flat Roof Constructions," National Bureau of Standards (U.S.), Building Science Series 37, (October 1971), 81 pages.

12. "Manual of Roof Maintenance and Roof Repair," National Roofing Contractors Association, Chicago, Illinois, and Asphalt Roofing Manufacturers Association, Rockville, Maryland, (January 1981).

13. "Roof Maintenance," Roofing Industry Educational Institute, Englewood, Colorado, R-102, (February 1981).

14. "Maintenance and Repair of Roofs," Department of Army, the Navy, the Air Force, and the Marine Corps, TM 5-167, NAVFAC MO-113, AFM 91-31, MCO P11014.9, Washington, D.C. (January 1974) 116 pages.

15. Tobiasson, Wayne, Korhonen, Charles, and Van den Berg, Alan, "Hand-Held Infrared Systems for Detecting Roof Moisture," Proceedings, Symposium on Roofing Technology, Paper No. 31, National Bureau of Standards/National Roofing Contractors Association, Gaithersburg, Maryland (September 21-23, 1977), pp. 261-271.

16. Knab, Lawrence, Mathey, Robert, and Jenkins, David, "Laboratory Evaluation of Nondestructive Methods to Measure Moisture in Built-Up Roofing Systems," National Bureau of Standards (U.S.), Building Science Series 131 (January 1981), 173 pages.

17. Jenkins, David R., Mathey, Robert G., and Knab, Lawrence I., "Moisture Detection in Roofing by Nondestructive Means - A State-of-the-Art Survey," National Bureau of Standards (U.S.), Technical Note 1146 (July 198), 82 pages.

18. Tobiasson, Wayne and Korhonen, Charles, "Roof Moisture Surveys: Yesterday, Today, and Tomorrow," Proceedings of the Second International Symposium on Roofing Technology, 18-20 September 1985, Available from National Roofing Contractors Association (U.S.), Chicago, IL, pp. 438-443.

19. Natrella, Mary G., "Experimental Statistical," National Bureau of Standards (U.S.), Handbook 91, (August 1, 1963).

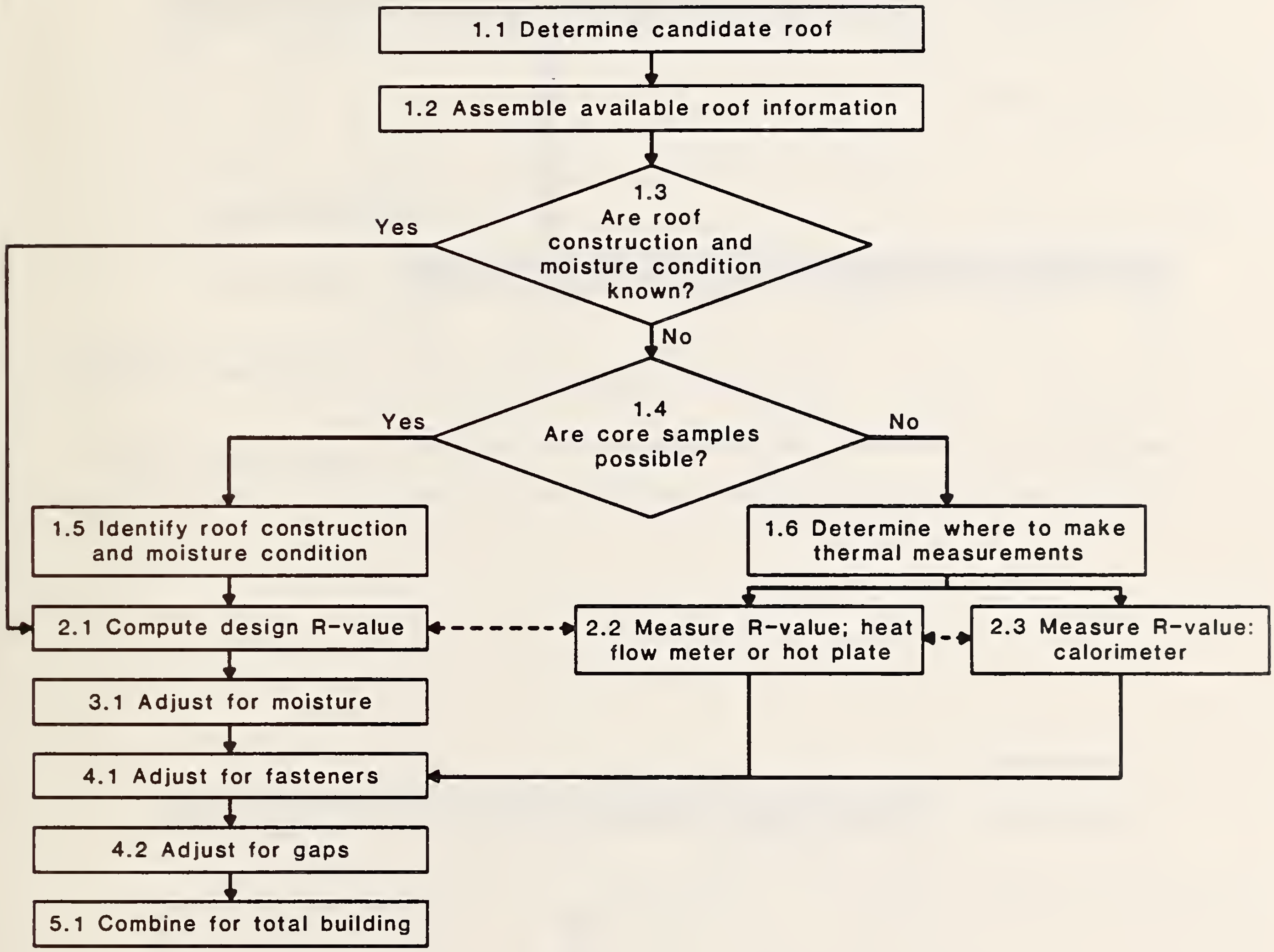


Figure 1. Flowchart for methodology

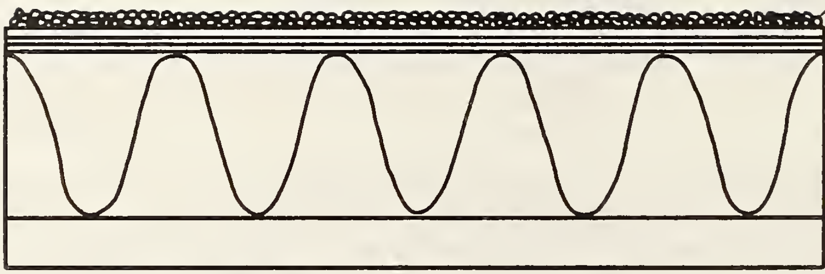
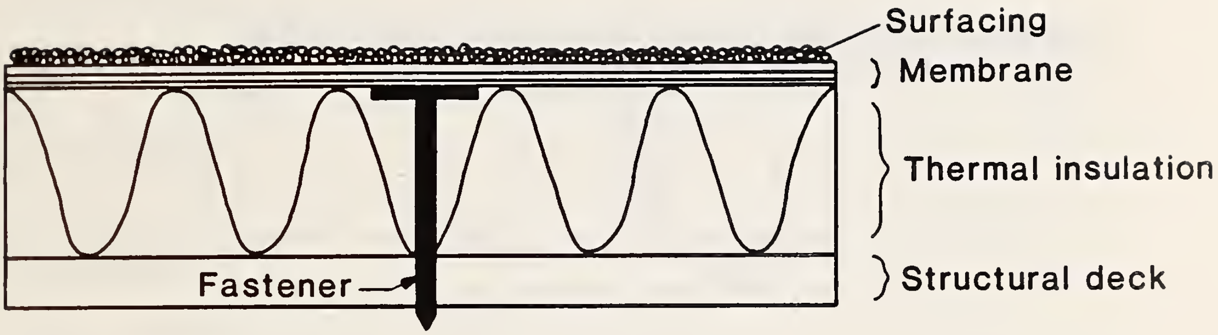
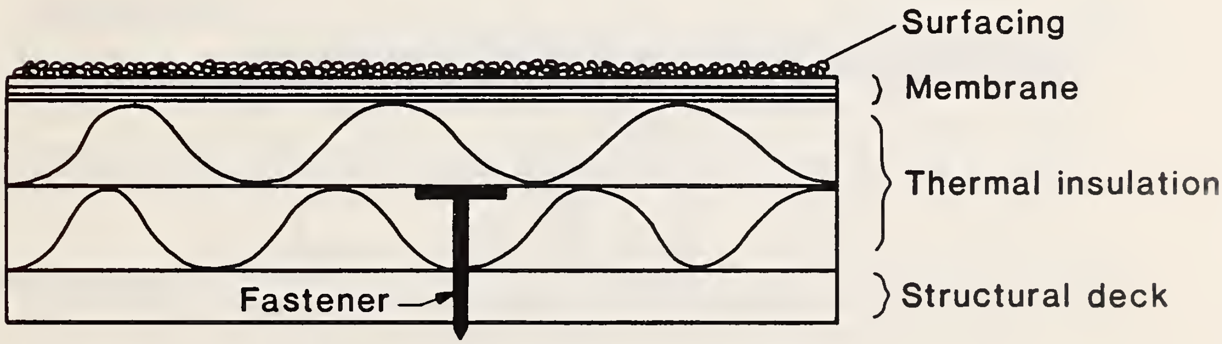


Figure 2. Typical roof cross section

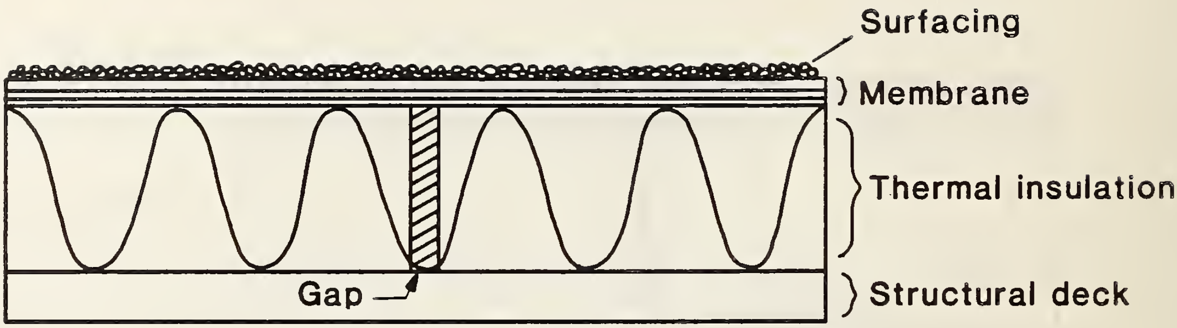


a) single-layer insulation

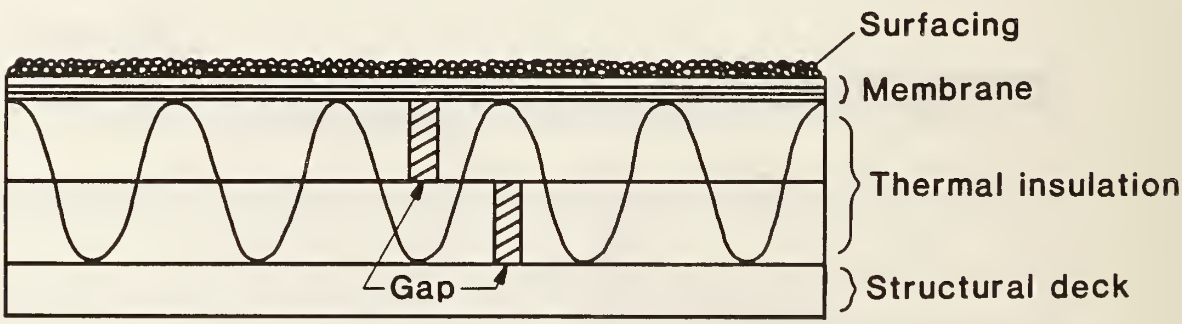


b) double-layer insulation

Figure 3. Typical fastener usage



a) through gap



b) lapped gap

Figure 4. Types of insulation gaps

Appendix A. Low-Sloped Roofing Components and Thermal Properties

Low-sloped roofing systems generally consist of the following major components: structural deck, vapor retarder (when used), thermal insulation, waterproofing membrane, and surfacing. Roofing flashings, which have been historically a failure point for water penetration into the system, must also be considered in evaluating the system as a whole. Figure 2 shows a schematic whereby the components are assembled in a conventional manner with the insulation situated below the membrane on the deck (or vapor barrier). Less often, the insulation may be above the membrane in the so-called protected membrane assembly, or in some cases, below the deck. In the assembly of components, the membrane may be secured to its substrate (i.e., the component directly below) by one or more of three major techniques: fully-adhered, partially-attached, and loose-laid. Griffin [A1] has provided a review of the function of each of the major components in roofing systems. In brief, their functions may be summarized as follows:

A. Decks - The deck provides the structural base for the waterproofing membrane and thermal insulation roofing system. Live and dead loads applied to the roof are transfered through the deck to the structural framework of the building.

B. Vapor Retarders - The vapor retarder is intended to reduce the flow of water vapor into the roofing system. It is primarily used when the climate conditions are relatively cold outside the building and the interior environment is humid. In many climates in the United States (particularly cold northern), in the winter the flow of water vapor is from the warm humid interior of the building upward through the roof towards the colder dry outside atmosphere. To reduce the risk of moisture accumulation within the roofing system, a vapor retarder is at times used on the warm side of the thermal insulation. Not all roof systems contain vapor retarders.

C. Thermal Insulation - Thermal insulation is used to provide increased resistance to heat flow across the roof, thereby providing reductions in heating and cooling fuel costs and also improvements in the interior comfort level for the building occupants. A secondary function of insulation is to provide for a smooth, level substrate on which the waterproofing membrane may be installed. Slope may be added to the roofing system for drainage through the use of tapered insulation boards.

D. Membranes - The membrane provides the waterproofing component of the roof system. For low-sloped roofs, the membrane is continuous without holes, punctures, tears, rips, splits or other defects through which water may enter into the roofing system and building.

E. Surfacing - Surfacing on membranes provide for a number of functions including: weather (UV) resistance, fire resistance, puncture and hail resistance, and ballast for wind uplift resistance. Included among the types of surfacings are mineral aggregates, granules, and concrete paver blocks. Mineral aggregates on built-up roofs are normally set in a layer ("flood coat") of bitumen. In some cases, coatings to reflect solar radiation and minimize solar heating of the membrane are used. In constrast, in some cases, surfacings are not used as part of the low-sloped roofing system.

There are a number of generic types of materials which can serve as the major components of a low-sloped roofing system. The most common of these materials have been listed by the National Roofing Contractors Association (NRCA) in the 1981 edition of the Roofing and Waterproofing Manual [A2]. The listing below is based on the NRCA Manual with some other materials added, for example, phenolic foam insulation.

A. Decks - Generic types of roof decks include:

Cement-Wood Fiber Panel
- Lightweight Insulating Concrete
- Poured Gypsum
- Precast Concrete
- Prestressed Concrete
- Reinforced Concrete
- Steel
- Thermosetting Insulating Fill
- Wood Plank or Plywood

B. Vapor Retarders - Generic types of vapor retarders include:

- Bituminous membranes
- Laminated kraft paper
- Vinyl film

C. Thermal Insulations - Generic types of roof insulations include:

- Cellular Glass
- Composite (whereby one or more layers of an inorganic insulation board are laminated as a facing to an organic cellular insulation.)
- Glass Fiber
- Perlite
- Phenolic
- Polystrene (Extruded and Expanded)
- Polyurethane and Polyisocyanurate
- Wood Fiber

D. Membranes - Generic types of waterproofing membranes include:

- Built-up Bituminous
- Non-bituminous Organic Single-Ply (including rubber and plastic sheets)
- Polymer-Modified Bituminous (including APP and SBS modified materials)

E. Surfacings - Generic types of membrane surfacings include:

- Concrete Paver Blocks
- Granules
- Gravel
- Slag
- Coatings (Non-Reflective and Reflective)

Table A1 lists handbook values of the heat transfer properties (thermal conductivity and thermal resistance) of the typical components used in low-sloped roofing systems. The values given in the table may be used to estimate the design thermal resistance of the roofing system. Actual values of the thermal properties of roofing system components in service may vary from those listed in table A1 depending upon variables such as material structure and density, moisture content, and material age.

REFERENCES FOR APPENDIX A

A1. Griffin, C. W., "Manual of Built-Up Roof Systems," 2nd Edition, McGraw-Hill, New York (1982).

A2. "The NRCA Roofing and Waterproofing Manual," National Roofing Contractors Association, Chicago, IL (January, 1981).

A3. ASHRAE 1981 Fundamentals Handbook, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Ga., Chapter 23, Table 3A (1981), pp. 23.14-23.17.

A4. Griffin, C. W., "Manual of Built-Up Roof Systems," 2nd edition, McGraw-Hill, New York (1982), pp. 58, 59.

A5. Wood, L. A., "Physical Constants of Different Rubbers," Rubber Chemistry and Technology, Volume 49, No. 2 (May-June 1976), pp. 189-199.

A6. Modern Plastics Encyclopedia, Properties of Resins and Compounds, (1983-1984), p. 501.

A7. Courville, G. E. and Kolb, J. O., "Economic Analysis of Insulation Materials Used in Low-Sloped, Built-Up Roof Systems," Oak Ridge National Laboratory, ORNL/TM-9004 (June 1984), p. A-15.

Table A1. Heat Transfer Properties of Materials Used As Components of Low-Sloped Roofing Systems [a]

Component	Component Material	Thermal Conductivity, k		Thermal Resistance, R Per Unit Thickness (1/k)		Data Source
		Btu·in/h·ft²·°F	W/m·K	h·ft²·°F/Btu·in	m·K/W	
Deck	Cement-Wood Fiber Panel	0.5	0.072	2.0	13.9	[A3]
	Concrete (Precast or Cast-in-place)	12.0	1.73	.083	0.58	[A3]
	Concrete (Cellular)	0.70	0.10	1.43	10.0	[A4]
	Concrete (Lightweight, Perlite Aggregate)	0.64	0.092	1.67	10.9	[A4]
	Concrete (Lightweight, Vermiculite Aggregete)	0.80	0.12	1.25	8.33	[A4]
	Gypsum (Poured)	1.66	0.24	0.60	4.17	[A3]
	Steel	-	-	Negligible	Negligible	-
	Thermosetting Fill (Perlite-asphalt)	0.40	0.058	2.50	17.24	[A4]
	Wood Plank or Plywood	0.80	0.12	1.25	8.33	[A3]
Vapor Reterder	Bituminous Membrane	1.13	0.16	-	-	[A3]
	Laminated Kraft Paper	-	-	Negligible	Negligible	-
	Vinyl Film	-	-	Negligible	Negligible	[A3]
Thermal Insuletion	Cellular Glass	0.038	0.055	2.63	18.18	[A4]
	Composite Board [c]	-	-	-	-	-
	Glass Fiber	0.24	0.035	4.17	28.57	[A4]
	Perlite	0.36	0.052	2.78	19.23	[A4]
	Phenolic [d]	0.21	0.030	4.76	33.33	[A4]
	Polyisocyanurate	0.16	0.023	6.25	43.48	[A4]
	Polystyrene (Expanded)	0.26	0.037	3.85	27.03	[A4]
	Polystyrene (Extruded)	0.20	0.029	5.00	34.48	[A4]
	Polyurethane	0.16	0.023	6.25	43.48	[A4]
	Wood Fiber	0.36	0.052	2.78	19.23	[A4]
Membranes	Bituminous Built-up [e]	1.13	0.16	0.88	6.25	[A3]
	Rubber (Single-Ply)	1.4	0.2	0.71	5.0	[A5]
	Polymer-Modified Bituminous [f]	1.13	0.16	-	-	-
	Poly (Vinyl Chloride)	1.0	0.15	1.0	6.7	[A6]
Surfacings	Aggregate (Including Granules, Gravel and Slag [g]	10.0	1.44	0.10	0.69	[A7]
	Concrete Paver Blocks	12.0	1.73	0.83	0.58	[A3]
	Coatings	-	-	Negligible	Negligible	-
	Foil	-	-	Negligible	Negligible	-

a| This table lists typical handbook values. Actual values may very from those listed in the table depending upon variables including structure and density of the material, moisture content, and material age.

b| The R-factor is based on conductance value for a bituminous built-up membrane given in ASHRAE [A3].

c| Composite insulation boards generally consist of a cellular plastic (foam) insulation laminated to an inorganic insulation. The thermal resistance of a composite board may be taken as the sum of the resistances of the individual components.

d| The k-value may vary depending upon the blowing agent used in foam production.

e| The R-factor for a bituminous membrane is based on the conductance value given in ASHRAE [A3] for a membrane having 3/8 in (10 mm) thickness.

f| The thermal properties of a polymer-modified bituminous membrane are taken to be the same as those of a conventional built-up bituminous membrane.

g| Little data have been published on the thermal properties of aggregate surfacing materials. For purposes of this report, values of thermal properties for all mineral aggregates have been taken to be the same.

Appendix B. Thermal Resistance Measurements

This information is largely taken from reference B1.

B.1 HEAT FLUX TRANSDUCERS

In this technique a heat flux transducer is spot-glued to a representative location on the interior surface of a building component, and temperature-sensing probes are attached to the inside and outside surfaces at the same location. The measured thermal resistance of the component is determined by dividing the average surface-to-surface temperature difference (for a sufficient period of time) by the average heat flow measured (during the same time interval).

This technique has been shown to be accurate to within 6 percent when the flux transducers meters are accurately calibrated. The thermal resistance measurement is applicable only to the local spot where the heat flow meter is mounted onto the component. However, coupled with a thermographic survey, this technique becomes an extremely viable tool for assessing the thermal performance of building components.

A heat flux transducer consists of thin flat wafer (comprised of a series of pairs of thermocouple junctions) either circular, square, or rectangular in shape. The wafer contains an embedded thermopile which produces a voltage (millivolt) signal proportional to the rate of heat flow passing through the wafer.

The constant of porportionality relating the millivolt output of the sensed heat flow rate is called the sensitivity of the device. It is expressed in millivolts per Btu/(h•ft^2). The sensitivity of a heat flux transducers is a function of its average temperature. In selecting a heat flux transducers, the output a signal must be sufficiently large for measurement and resolution by the readout device at the lowest expected heat flow rate. Heat flux transducers cost approximately \$100 to \$200 each.

Consider the example where it is desired to measure the thermal resistance of a heavily insulated roof (R = 13). The expected temperature difference is 10°F, giving a heat flow rate of 0.77 Btu/(h•ft^2). If the read-out device has a resolution of $\pm$ 5 microvolts, then the heat flux transducers must produce a signal of 20 times this level or 0.100 millivolts in order to provide a 5 percent resolution. The required sensitivity is determined by taking the ratio of the millivolt output to the heat flow rate at the lowest heat flow condition, or 0.10/0.77 = 0.14 mv/Btu/(h•ft^2).

Another important characteristic of a heat flux transducers is the time required for the device to respond to changes in heat flow rate. It is desirable for the heat flow meter to respond to fluctuations in heat flow caused by diurnal variations in the outdoor air temperature; but it is not desirable for it to respond to high frequency fluctuations at the inside surface due to small-scale convection and cyclic operation of the building heating/cooling plant. Good results are obtained by using heat flux transducers having a thickness of about 1/8 inch. Heat flux transducers having extremely small thicknesses introduce the problem of responding to high frequency fluctuations in heat flow.

Temperature Sensors

It is recommended that the inside and outside surface temperatures be monitored with premium grade 24-gage or thinner copper-constantan thermocouple wire. Thermistors may also be used. Other larger temperature-sensing probes should not be used, since the temperature sensed with the larger probes may not be indicative of the actual surface temperature. An alternate approach is to locate a thermopile on the interior and exterior surfaces (across the bulding component). The thermopile consists of a series of pairs of thermocouple junctions which are 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.

Read-Out Devices

The output signals from heat flow and temperature-sensing probes can be read out at hourly intervals using data loggers, strip-chart recorders, or analog integrators. In all cases, the read-out device must have sufficient sensitivity to resolve the signal at its lowest signal level. Analog integrators have the advantage of averaging out fluctuations in signals due to the cyclic operation of the heating plant. When monitoring signals from thermocouples, an ice-point reference must be provided external to the read-out device, or internally, using an electronic ice-point referencing system.

The total cost of an instrument system suitable for measuring the heat flow and temperature differences at ten locations in a building wil cost approximately $7000 to $10,000.

A problem that has contributed to a poor reputation for heat flow measurement methods has been the lack of accuracy in the calibration of commercially manufactured components. Precision laboratory assemblies, however, have provided precisely calibrated heat flux transducers. The accuracy of data reported in this section is limited to the accuracy to which the heat flux transducers are calibrated and does not include errors associated with the installed performance. The following procedure should be utilized to calibrate heat flux transducers: The heat flux transducers to be calibrated are first sandwiched into a composite assembly having heat transfer properties comparable to those of the heat flux transducers. This composite assemble is subsequently sandwiched between two insulating boards and inserted into a thermal conductivity measuring device capable of receiving large specimens. Inside this apparatus, the embedded heat flux transducers are exposed to a uniform heat flux at the desired mean temperature. After a 24-hour conditioning period, the sensitivity of each of the heat flux transducers is determined by taking the ratio of millivolt output to the heat flux rate.

When heat flux transducers are calibrated, calibration must be at a temperature very close to the of the intended application. The sensitivity of heat flux transducers is temperature dependent. If the heat flux transducers are intended for exterior applications, the above calibration must be repeated at mean temperatures corresponding to those experienced during the test.

The accuracy of the temperature sensors can be verified by inserting the sensors into known temperature baths. Often the read-out device has adjustments for nulling out temperature errors.

In assessing the thermal performance of a BUR system, the measured performance at locations between structural members is probably of much greater interest than that at locations on the structural members, since the focus of an in situ measurement is often aimed at the performance of insulation placed between structural members. It may be desirable to use a spot radiometer or infrared thermographic system to select measuring locations which are representative of the bulk performance of the component. Since small defects in the roof insulation do not contribute largely to the overall performance of the roof, providing these defects are few in number, it is desireable to mount heat flux transducers at locations free of minor insulation defects. When the measuring locations is selected, attach the heat flow meter to the inside surface using industrial contact cement. It is imperative that the heat flow meter be held in intimate contact with the inside surface at all locations of the device. Substantial errors will occur if the bonding breaks loose at certain locations on the heat flow meter. After the heat flow meter is bonded to the surface, it should be covered with the same (or similar) paint system used on other parts of the surface, so that the radiative exchange between the metered location and other surfaces will be comparable to that of the subject surface. Mounting heat flux transducers onto the exterior surface of a component is poor practice because the sensitivity of the heat flow meter can no longer be treated as a constant, owing to changes in the mean temperature of the device. Heat flux transducers mounted on the underside of metal decks may produce erroneous results because metal decks act as a fin to conduct heat laterally.

Thermocouple junctions are mounted (using tape or epoxy) to the inside and outside surface of a building component. After the epoxy dries, it is a good practice to cover the dried epoxy with the same paint as used on the subject wall in order to equalize the solar absorptance and long-wave emittance of the measuring location to that of the subject surface. It is also good practice to run thermocouple leads at least two feet along the subject surface prior to departing from the surface in order to minimize heat conductance along the thermocouple wires themselves. Such heat conduction could conceivably alter the temperature at the measuring location. After the sensors are installed, they can be "hooked up" to the read out devices. The thermal resistance, R, of the component is determined by dividing the average temperature difference by the average heat flow over a sufficiently long period of time. This may be expressed mathematically by the relation:

$$R = \frac{\int_0^t \Delta T dt}{\int_0^t Q dt} \qquad \text{(B1)}$$

where Q = the heat flow rate
ΔT = the temperature difference
t = time required for the measurement

The time, t, required for the measurement will be dependent on the thermal capacity of the component. Light-weight components (i.e., wood-frame walls) require short periods, while heavy-weight components (i.e., masonry walls) require long periods of time. During the course of a measurement, the outdoor conditions must be sufficiently cold to always keep the temperature difference (ΔT) above 10°F. Required measurement times, t, are correlated to time lags for building components in table B1. Here "time lag" refers to the elapsed time (phase lag) between peak heat flow rate and the maximum temperature difference driving force when a building component is exposed to typical outdoor temperature variations.

Table B1 - Typical Phase Lags for Various Roof Constructions

Component	Phase Lag (hours)	Required Measurement Time (days)
Built-up roof, concrete deck	12	6
Built-up roof, steel deck	1	0.5

The indicated measurement times should ensure an accuracy of 10 percent. The phase lag values were taken from reference [B2].

B.2 PORTABLE CALORIMETER BOXES

A typical calorimeter box consists of a five sided insulated box, the open side of which is sealed against the subject building component. An electric heater located inside the box is thermostatically controlled so that the inside box temperature is equal to the indoor temperature of the building enclosure. Since the reverse heat loss through the box and the edge loss where the box edge contacts the metered surface are essentially nulled to zero, the metered electric energy supplied to the electric heater is essentially equal to the heat transmission through the metered area. This technique has the advantages that the measurement provides a minimum disturbance to the measured heat transmission and a sufficiently large surface area is metered to be considered representative of the bulk performance of the building component. The accuracy of the technique is reported to be about 5 percent.

The construction details for a typical portable calorimeter box are given in reference B1. The size of the metering area is over ten square feet. The walls consist of two layers of glass-fiber insulation board glued together with an exterior plywood covering to provide structural support. The edge portion of the calorimeter which contacts the surface of the building component contains a gasketing material for providing an airtight seal. A multijunction thermopile is placed across the rear surface of the calorimeter.

The controller modulates the electrical energy supplied to the heating element such that the thermopile is nulled to zero. The electric energy supplied to the box is metered with a conventional watt-hour meter. Air circulation within the calorimeter box is achieved through natural convection.

It is recommended that the inside and outside surface temperature be measured with one of the following type sensors:

i. premium-grade, 24-gauge or higher, copper-constantan thermocouples.
ii. multi-junction copper-constantan thermopiles fabricated from premium grade, 24-gauge or higher, cooper-constantan thermocouple wire.
iii. precision bead-type thermistors

The electrical energy supplied to the calorimeter box should be metered with a watt-hour meter equipped with a demand metering device such as a contact closure or pulse generating device. The generated contact enclosures or pulses should be accumulated and printed out at prescribed time intervals using commercially available pulse counting and recording systems. With regard to the electric energy measurements, a sufficient number of contacts or pulses should be developed to permit adequate resolution of the energy consumption (approximately 1 pulse per watt-hour). Thermocouple, thermopile or thermistor signals may be read out at hourly intervals using data loggers, continuous strip chart recorders, or if the signal is a linear function of temperature, averaged over hourly intervals using analog integrators. In all cases, the readout device must have sufficient sensitivity to resolve the signal at its lowest level. When monitoring signals from thermocouples, an ice-point reference must be provided either externally to the readout device, or internally using an electronic ice-point referencing system.

Prior to conducting a calorimeter box measurement of a building component, a representative measuring station should be selected. The calorimeter box is subsequently sealed to the underside of the roof. It is very important that a good seal is provided continuously, along the edge seal gasketing, in order to prevent convective air exchange between the calorimeter and the room air.

The calorimeter box is then turned on and permitted to equilibrate with respect to the interior air. An equilibrium condition is deemed to exist when the box loss measurement with the thermopile approaches zero.

After an equilbrium condition is reached, then the calorimeter box is operated over a measurement period, τ, and the thermal resistance, R, of the building component is computed using the relation:

$$R = \frac{\int_0^{\tau} \Delta T \cdot dt}{W_T} \qquad (B2)$$

where

W_T = electrical energy measured with the watt-hour meter system

Δ_T = measured surface-to-surface temperature difference across the building component.

Required measurement periods, τ, for various building compnents are summarized in table B2.

Table B2 - Required Measurement periods (τ) for Various Building Components

Component	Measurement Time (τ) Days
Built-Up Roof, Concrete Deck	6
Built-Up Roof, Steel Deck	0.6

The foregoing measurement periods should insure an accuracy of 10 percent in determining the thermal resistance, R.

Calorimeter box measurements should be carried out only during periods when the outdoor to indoor temperature difference (ΔT) is always greater than 10°F. Solar loading on walls in the winter season may frequently produce ΔT's less than 10°F. During the period of the measurement, the indoor temperature must be thermostatically controlled at a constant level in order to minimize differences in the temperature between the calorimeter box and the room. In addition, solar radiation (into the interior) and conditioned air from warm air supply registers must not be permitted to strike the calorimeter box.

In specifying a calorimeter box, it is desirable that the reverse heat loss through the box be minimized. That is accomplished by designing the thermal resistance of its walls as high as practical, minimizing the box surface area which is exposed to room air, and minimizing the temperature difference that exists across the box wall during its operation. With regard to minimizing the box surface area, it is desirable to reduce the depth of the box to the point where natural convection patterns within the box begin to depart from typical room conditions. The metering area should be as small as practical, while still measuring a representative section of the building component. For instance, for a wood-frame cavity wall the minimum interior wall surface to be metered would be a width of 3 stud spaces and height of 6 feet. The edge loss where the box is sealed to the wall is minimized by reducing the average temperature difference across the box wall around the edge perimeter. The surface emittance of the interior of the box should be selected to be comparable to that of typical indoor room surfaces, so that the radiation heat transfer coefficient at the metered surface will be comparable to its value under natural room conditions.

The pattern for the zigzag electrical heating within the calorimeter box should be designed to produce uniform temperatures within the box. For example, calorimeter boxes used to measure vertical walls should have closely spaced wires at the bottom of the box in order to offset vertical temperature gradients.

It is desirable that the exterior covering for the calorimeter box have a low emittance in order to minimize the radiation exchange between the box and other interior surfaces. This will help to maintain the exterior box temperature more closely to the room temperature.

B.3 HOT PLATE

Another method which can be used for measuring thermal resistance involves a hot plate apparatus. This measurement procedure is similar to the previously described heat flow meter method, except that a small sample of the roofing (usually about 2 ft^2) is removed from the roof and measured in a laboratory environment, rather than in place. A complete description of the method is given in ASTM C518.

The hot plate apparatus consists of two horizontal temperature controlled plates sandwiched about the roof sample. The lower (hot) plate contains a metering section with an integral heat flux transducer. A known temperature difference is established across the specimen by controlling plate temperatures, and the resulting heat flow is measured in the metering section. Thus, the steady-state thermal resistance can be determined by the ratio of temperature difference to heat flow.

REFERENCES FOR APPENDIX B

B1. Grot, R.A.; Burch, D. M.; Silberstein, S.; and Galowin, L.S.; "Measurement Methods for Evaluation of Thermal Integrity of Building Envelopes," NBSIR 82-2605, National Bureau of Standards, November, 1982.

B2. Treado, S.J., "Thermal Resistance Measurements of a Built-Up Roof System," NBSIR 78-2100, National Bureau of Standards, October, 1978.

APPENDIX C. COMPUTATION OF R-VALUE FOR TAPERED INSULATION

The average thermal resistance of a roof section composed of linearly tapered (i.e., constant slope) insulation, R_{ave}, can be determined from the following relation:

$$R_{ave} = \frac{S\,\ell}{K} \cdot \frac{1}{\ln\left(\frac{R_{max}}{R_{min}}\right)}$$

where:

S = slope of insulation
K = thermal conductivity of insulation
ℓ = length of tapered run
R_{max} = thermal resistance at maximum thickness
R_{min} = thermal resistance at minimum thickness

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A methodology was developed to determine the thermal performance of existing low-sloped roof systems. The methodology was based on a review of available information and experience. Roof system thermal resistance is used as the thermal performance characterization parameter. The procedure for determining total roof thermal resistance is described, including measurement and calculation methods, and adjustments for moisture intrusion, insulation gaps and fasteners.

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