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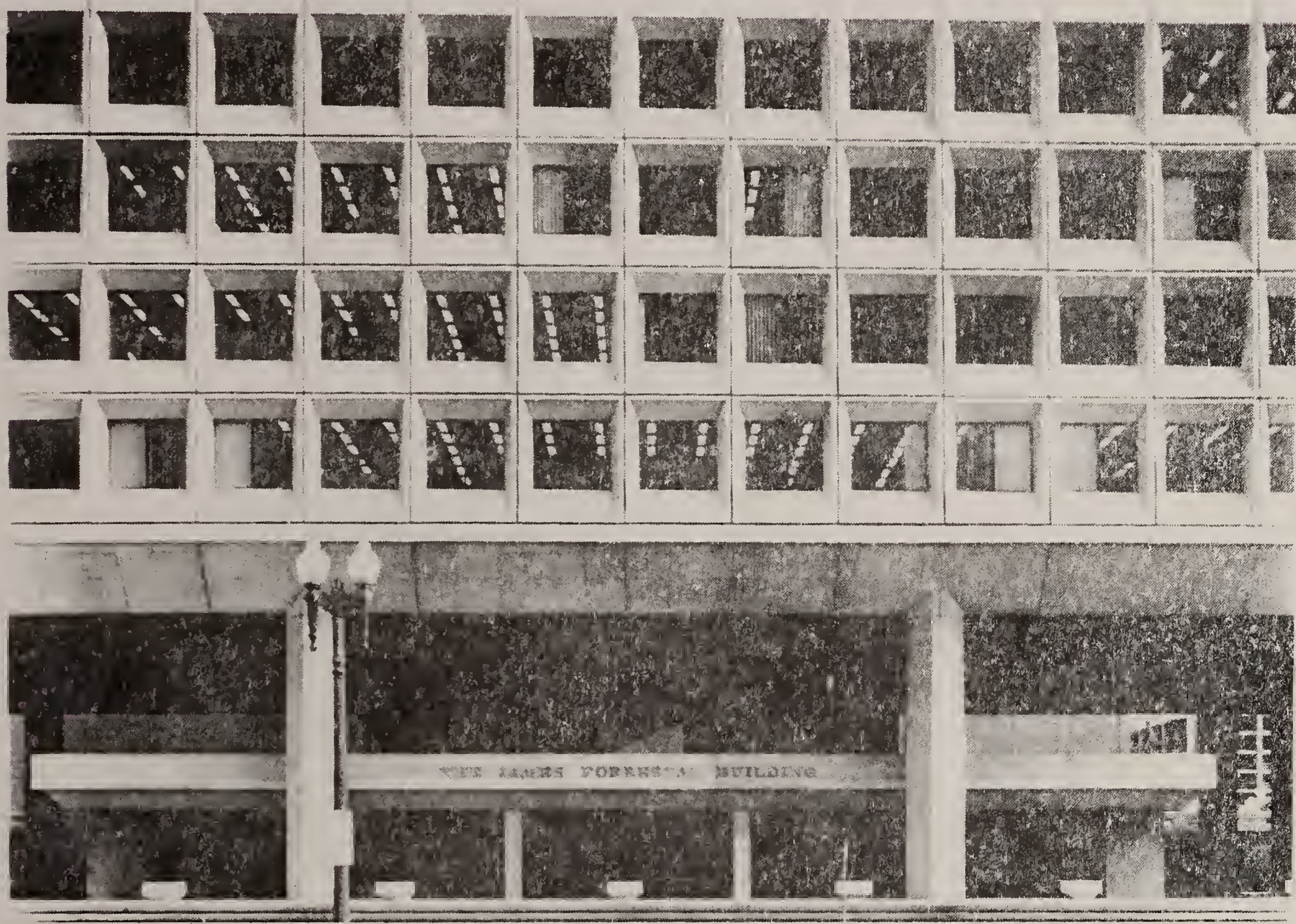
Measurement Methods for Evaluation of Thermal Integrity of Building Envelopes



by

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NOVEMBER 1982

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MEASUREMENT METHODS FOR EVALUATION OF THERMAL INTEGRITY OF BUILDING ENVELOPES

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November 1982

Prepared for
Public Buildings Service
General Services Administration
Washington, DC 20405

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

ABSTRACT

This report presents various measurement and inspection techniques for assessing the thermal performance of the exterior envelopes of buildings. The inspection techniques include the use of ground-based infrared thermographic surveys, aerial infrared surveys, tracer gas air infiltration measurements, pressurization tests for measuring the tightness of the building envelope, and spot radiometer surveys for detecting gross defects. Heat flow meters, a portable calorimeter, and a microprocessor-driven envelope testing unit are also considered. For each technique, recommended procedures are provided; they include equipment requirements, conditions under which the techniques can be carried out, calibration, accuracy, and limitations.

An Executive Summary provides an overview of the Building Diagnostic Program of which Phase 1 is covered in this report. Field test evaluations will be carried out in Phase 2.

Key Words: Air infiltration rates; envelope thermal performance; infrared imaging; radiometers; thermographic surveys; tracer gas techniques.

EXECUTIVE SUMMARY

BACKGROUND

The Federal government presently owns and leases thousands of buildings throughout the United States. Also, the General Services Administration (GSA) and other federal agencies construct new buildings each year. Many of the new and existing buildings have thermal defects in their envelopes as a result of poor workmanship, a misunderstanding of the construction specifications and aging of materials. Many of the older buildings were also compromised in their thermal performance through their design emphasis on first cost, disregarding energy efficient components or systems because fuel and power were plentiful and inexpensive. Consequently, buildings frequently use excessive amounts of energy due to envelope thermal defects.

Several diagnostic techniques have evolved which can be applied to locate and identify defects in building envelope in new and existing buildings. Through exacting problem identification remedial or retrofit actions can be carried out which result in cost effective energy savings.

The availability of these new techniques prompted the General Service Administration to work through the National Bureau of Standards (NBS) to develop a multi-phased research effort to implement a diagnostics program for the federal government. The first phase was devoted to the development of procedures that GSA could use to evaluate the thermal integrity of the building envelopes. To improve the capability of this project to meet the needs of other agencies, the Phase I effort was developed under the guidance of a peer review group consisting of representatives from the General Services Administration, the Department of Defense, the Department of Housing and Urban Development, the Department of Energy and the Public Works of Canada.

Phase I: Development of Recommended Procedures for Evaluating Thermal Integrity of Building Envelopes

This Phase I report addresses the measurement techniques, inspection procedures and data analysis procedures required to assess various aspects of the integrity of the envelope of buildings. The eight generic methods of building diagnostics that are described include: (1) ground infrared thermographic surveys for locating sources of air leakage, missing insulation, defective or damaged insulation, thermal bridges and bypasses, and moisture damage; (2) aerial infrared thermographic surveys for assessing roof damage; (3) air infiltration measurement of the building under natural conditions; (4) induced pressurization techniques of measuring the tightness of the building envelope and major components of the building envelope; (5) spot radiometers, both temperature and energy flow types, for estimating the heat loss from major building components during an energy audit; (6) heat flow meters for measuring the thermal conductance and heat loss from small sections of the building envelope; (7) portable calorimeter boxes for measuring the thermal conductance of large areas of the building envelope; (8) envelope thermal testing units for the determination, in situ, of the heat transmission of building elements.

For each of these methods there is a description of: the technique; the equipment used; the theory underlining the measurement; the interpretation methods and assessment of the anticipated accuracy; the availability of equipment and of firms offering the service; the training requirements for users of the equipment; and the potential restrictions to the application of the method. Whereas building equipment interactions with the envelope are usually important to building energy use, they are not covered in this report.

<u>Phase II</u>: Application and Evaluation of Recommended Procedures

In Phase II, the methods described in the Phase I Report are being applied and evaluated in a sample of 4 large federal buildings (over 100,000 square feet) and 4 small federal buildings (less than 100,000 square feet). Each building category represents a significant fraction of the gross area of federal buildings. Also the size of 100,000 square feet is about where different applications of the proposed inspection procedures are expected to be required (due to economic factors of application and scale). The collection and interpretation of data will indicate whether modifications to the diagnostic procedures will be required for broad practical implementation in a cost-effective manner. Techniques being evaluated by NBS include:

a. Measurement of air infiltration using tracer gas technique. Up to ten readings will be taken for each building over a period of time to reflect varying weather conditions and with the building in a normal operating mode. An additional set of readings will be taken with the inlet and outlet dampers closed (following coordination with GSA operating personnel).

b. Measurement of building tightness using fan pressurization tests. For small buildings, an external fan will be used. For large buildings, the building system fans and dampers will be used (following proper coordination with GSA operating personnel). During tests, observations will be made of typical building elements such as doors, windows and joints to determine if air leakage sites can be identified and evaluated.

c. Measurement of thermal conductance of major building components using heat flow meters, calorimeters, or envelope thermal testing units (whichever are appropriate) in areas representative of the total building envelope.

d. Interior and exterior thermographic surveys under suitable winter conditions.

e. Aerial infrared roof inspections of the four large buildings.

f. Energy audits of the four small buildings using spot radiometers to cover the same surfaces as surveyed by thermographic techniques.

Considerations used in the selection of the test sites included building size, climate, travel time and distance, building design and operating characteristics. The buildings under evaluation include:

Large (>100,000 ft^2)	Small (<100,000 ft^2)
Anchorage, AL	Ann Arbor, MI
Columbia, SC	Fayetteville, AR
Norfolk, VA	Huron, SD
Springfield, MA	Pittsfield, MA

When the evaluations are completed NBS will prepare case study reports for each building describing: the results of the tests; the interpretation of the results with use of the data for developing building retrofit options; estimates of the costs of the recommended retrofits; cost estimates for performing the test procedures; projected estimates of the energy savings from retrofits. In addition procedures will be developed for the economic evaluation of the benefits of the diagnostic techniques as applied to each category of building.

Impacts of this Research Effort

The diagnostics program will provide GSA/PBS with methods to improve the energy performance of federal buildings. In both existing and new buildings several methods can be used to locate and identify defects in the building envelope. In existing buildings, deterioration will often produce thermal anomolies long before serious damage has occurred. The detection of the anomolies can lead to corrective action before more costly repairs are required. In new construction, in situ nondestructive methods can be used to verify the thermal integrity of the envelope systems as the construction proceeds.

Significant and wide ranging contributions for improving building performance and for new building design can be derived from the results obtained in the field site demonstrations. The economic evaluation criteria will establish a basis for cost effective decisions on the use of diagnostics and for determining efficient retrofit packages for allocation of limited PBS resources.

In addition, costs determined by performing the test procedures will be directly applicable for PBS planning purposes. The development of comprehensive technical requirements for inclusion in PBS procurement specifications will assure that both new buildings and retrofits realize their anticipated savings and attain desired level of quality in federal buildings, designed, constructed or rehabilitated by PBS.

ACKNOWLEDGMENTS

The authors of this report appreciate the assistance and guidance given by David Dibner, Erma Striner, David Eakin and John Holton of Public Buildings Service of the General Services Administration. It was at their initiative that this work was started. Assistance was also given by Preston E. McNall, Noel Raufaste, Mary Reppert, Robert R. Jones, and Yui-May Chang of the National Bureau of Standards during various stages of preparation of the report. Special recognition is given to the peer group review panel: Millard Carr, Department of Defense; Richard Munis, U.S. Army Cold Region Research and Engineering Laboratory; George Courville, Oakridge National Laboratory; Dan Kluckhuhn, Department of Housing and Urban Development; and Peter Mill of Public Works Canada and to his staff of the Architectural Sciences Division, Audrey Kaplan, Gregory McIntosh, and Robert Hawley, for the exchange of information and sharing Canadian experiences on the diagnostic program. The discussions on developments in measurement methods with John Shaw and Bill Brown, National Research Council of Canada, with David Harrje, Princeton University, and with Robert Sonderegger, Lawrence Berkeley Laboratory are also acknowledged.

Special requests for accelerated support services of Ulesia Gray and Brenda Thompson of the CBT Word Processing Center and the Graphics Department of NEL are acklowledged.

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1. INTRODUCTION

1.1 BACKGROUND

The Federal government presently owns and leases thousands of buildings throughout the United States. The General Services Administration (GSA) constructs new buildings each year some of which have thermal defects in the building envelopes due to either poor workmanship or a misunderstanding of the construction specification. A strong need exists for viable, in situ and nondestructive survey techniques to verify the thermal integrity of the envelope systems of office buldings under construction. In this way, thermal defects can be identified and located, and the contractor can carry out remedial action prior to departure from the construction site. All existing buildings degrade with age and require periodic maintenance. The potential for serious deterioration in the building will often produce thermal anomalies long before serious damage has occurred. The detection of these anomalies can lead to corrective action before more costly repairs are required. To assure the quality of remedial actions taken to improve existing federal buildings, inspection techniques are also required.

A majority of federal buildings are not energy efficient because they were designed at a time when energy was plentiful and inexpensive. Economic circumstances dictated the first costs as more important than future energy costs. As a result, these buildings often use excessive energy. In the case of both new and existing buildings, several diagnostic techniques can be applied to locate and identify defects in building envelopes, thereby permitting selection of cost effective remedial or retrofit actions to be carried out in order to achieve energy savings.

This report presents reviews of the technical methods for inspections with measurement methods to provide the data, procedures to conduct analyses and apply interpretation techniques for assessing the integrity of the exterior envelopes of federal buildings. The inspection techniques considered are: ground-based infrared thermographic surveys, aerial infrared surveys; tracer gas air infiltration measurement; pressurization tests for measuring the tightness of the building envelope; and spot radiometer measurements (both the temperature measuring type and radiosity-measuring type) for detecting gross defects. Heat flow meters, a portable calorimeter and an envelope thermal testing unit developed by Lawrence Berkeley Laboratories are also considered for determining the thermal characteristics of the envelope. Applications of the instrumentation and test methods are based upon previous usage experience* and indications are provided concerning availability of equipment and services, user training requirements, and restrictions.

The techniques described in this report can be used to find, locate and assess the heat loss resulting from the following deficiencies:

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* Information from cited references, specifications, brochures and illustrative examples, have been retained in the units presented by the authors or manufacturers.

1) uninsulated walls
2) uninsulated ceilings/roofs
3) partially insulated areas
4) air leakage
5) heat loss at joints
6) thermal by-passes
7) below-grade heat loss
8) thermal bridges
9) wet insulation
10) shrinkage in foam insulation
11) settlement of loose-fill insulation
12) air movement around vapor barriers

In addition to locating deficiencies, the techniques can be used to quantify heat losses, to determine the extent of deterioration, and to suggest remedial action. They are applicable to both new and existing buildings, although the manner in which they are applied will differ (see 1.2 below).

A common presentation format was adopted to describe the required method, equipment and instrumentation; where ever applicable the information was organized as follows:

Summary
Description of Equipment
Theory
Guidelines for Conducting Measurements
Interpretation of Results
Accuracy of Techniques
Availability of Equipment and Services
Previous Usage
Personnel Training Requirements
Program Application Restrictions

Cited references for each test procedure are listed at the end of each chapter.

1.2 POTENTIAL DIAGNOSTIC PROCEDURES APPLICATIONS

The diagnostic procedures described in this report are broadly applicable to development of cost effective reductions in the energy usage of buildings. The appropriate methods are summarized below for use in different stages of new construction and for existing building improvement retrofits. For new buildings the process of construction is divided into six steps: design, prototype evaluation, construction, pre-occupancy acceptance, first year occupancy and post occupancy evaluation. For existing buildings, the process of retrofitting the building is divided into the following stages: diagnosis of deficiencies, quantification of thermal deficiencies, prototype retrofit evaluation, retrofit quality control, post retrofit evaluation, and end of warranty evaluation.

1.2.1 Application to New Construction

The application of the diagnostic procedures to the construction of new buildings would occur in 6 stages of construction: 1) the design stage during which planning of the tests are included in the traditional design methodology of buildings; 2) a prototype evaluation of the proposed construction practices and materials; 3) during-construction quality control; 4) preoccupancy testing; 5) during-the-first-year-of-occupancy evaluation of the building; and 6) post occupancy evaluation. The tests applicable to each of these stages are summarized in table 1.2.1.

Design of the Building

During the design of the building, plans should be made for incorporating the test procedures into the construction process and to assure that the building specifications are written in such a way that the results of the test can be used to verify that the specifications are met. Building specifications must be determined for: thermal conductances of major building sections; acceptable air infiltration rates; the extent of tightness of building components, joints and the total envelope.

The construction methods to be used should be analyzed in order to identify potential areas where deficiencies in workmanship may occur and potential areas for the existance of thermal bridges and by-passes. A time schedule for applying the tests should be developed and interfaced with the construction schedule for the building.

Building Prototype Evaluation

If innovative construction procedures or materials are to be used in the construction of the building, an evaluation of prototypes of the section or components of the building should be undertaken.

The prototypes should be tested for air leakage using fan pressurization tests for components. If possible, thermography should be used to determine abnormal temperature patterns in the prototypes. The thermal characteristics of the prototype should be determined using the ETTU, calorimeter or heat flow meters.

In order to ensure that the building will meet the specifications and to allow for timely correction of poor quality workmanship which will decrease the energy performance of the building, tests would be performed during construction to assess the quality of the workmanship. The test procedures appropriate for quality control are: thermographic inspection of typical finished walls and joints, fan pressurization testing of finished components and sections and quantitative determination of the thermal characteristics of finished building sections using heat flow meters, the ETTU or calorimeters. The testing should be the responsibility of the building contractor and should be performed by his personnel or by a private inspector, under contract to him.

Preoccupancy Testing

In order to determine that the specifications for the building were met, preoccupancy testing should be carried out. The tests for this stage are those which could not be performed during the quality control inspection stage; those include air infiltration testing using tracer gas methods, total building fan

Table 1.2.1 Phasing of Test Procedures for New Construction

Stage		Activity or Test Procedures Appropriate
I.	Design of the building	1) develop building specifications which tests must verify a) thermal conductance b) air infiltration rates c) tightness of building components, joints and total envelope. 2) identify potential areas of deficiencies in workmanship 3) identify potential areas of thermal bridges and by-passes 4) develop time schedule for applying tests
II.	Building prototype evaluation (if appropriate)	1) fan pressurization testing of components 2) thermographic inspection of prototype section 3) quantitative U-value of prototype section with ETTU or calorimeter 4) quantification of effect of thermal bridges with heat flow meters
III.	During-construction quality control	1) fan pressurization of finished components and sections 2) thermographic inspection of typical finished walls and joints 3) quantitative U-value of typical finished wall section (ETTU or calorimeter)
IV.	Pre-Occupancy Testing	1) complete tests of stage II which could not be finished 2) air infiltration by tracer gas 3) total building pressurization test 4) complete thermographic inspection
V.	First Year of Occupancy	1) air infiltration measurements by tracer gas
VI.	Post Occupancy Evaluation (or after 1st year)	1) thermographic inspection 2) total building fan pressurization 3) fan pressurization of components if total building fan pressurization is different.

pressurization testing and a complete thermographic inspection. Data from these tests should be represented in such a way that the observed deficiencies can be corrected before occupancy of the building.

First Year Occupancy Testing (Warranty Period)

During the first year of occupancy the air infiltration rate of the building under normal usage conditions should be measured using the air sample bag method. The results of this test should be compared with the anticipated air infiltration rates for the building.

Post Occupancy Evaluation

At the end of the shakedown period for the building, tests should be performed to determine whether deterioration in the building envelope has occurred as a means of recognizing latent (hidden) defects and to note degradation rate of materials and performance. Such information will enable criteria to be evaluated and improved. This effort can be associated with a formal Post Occupancy Evaluation program. The tests appropriate for the evaluation are: thermographic inspection of the building in order to detect abnormal thermal patterns in the envelope, total building fan pressurization testing and if necessary an evaluation of the air leakage of defective components using fan pressurization techniques for air leakage deterioration or quantitative thermal tests by heat flow meters, ETTU or calorimeters for thermal conductance defects.

1.2.2 Applications to Existing Buildings

The application of the diagnostic procedures to existing buildings would occur in six stages: 1) a diagnostic stage in which the deficiencies in the building are identified; 2) a quantification stage in which the energy losses and the potential for physical building deterioration are determined where there is some doubt as to the cost/benefit of correcting the observed deficiency; 3) the testing of prototype retrofit measures if there exists some uncertainty in the effectiveness of proposed corrections to the observed deficiencies; 4) during-retrofit, quality control of the retrofit work; 5) post retrofit evaluation of the workmanship; and 6) testing of the building during post occupancy evaluation. Table 1.2.2 presents a summary of the applicable test procedures at each of these stages. It is not proposed that all the tests listed in table 1.2.2 be applied to every retrofitted building. Stages 1, 4, and 5 should be applied to most retrofitted buildings. Stages 2, 3, and 6 should be used only as required or as means to provide data for future evaluation in which the stages are not utilized.

Diagnostic Stage

The purpose of the diagnostic stage inspection of an existing building is to identify the existing thermal deficiencies in the building envelope. For large buildings the appropriate test procedures for diagnosing the building thermal deficiencies are: 1) air infiltration tests using the air sample bag technique of the tracer cleaning method; 2) ground thermographic inspection of the building's envelope from both the exterior and interior; and 3) aerial infrared

Table 1.2.2 Phasing of Test Procedures for Existing Buildings

Stage	Activity or Test Procedure Appropriate
I. Diagnosis Stage	1) Air infiltration by tracer gas 2) Complete exterior and interior thermographic inspection (or for small buildings, energy audit with spot radiometer) 3) Aerial roof survey (large building)
II. Quantification of Deficiencies	1) Fan pressurization tests a) whole building b) components 2) Heat loss from thermal bridges with heat flow meters 3) U-values of major components if uncertainty exists
III. Prototype Retrofit Testing	1) Fan presurization of prototype solutions to leakage of components 2) Thermographic inspection of prototype 3) Quantification of U-value if necessary
IV. During Retrofit Quality Control	1) Fan pressurization of components for quality control 2) Thermographic inspection of quality control
V. Post Retrofit Evaluation	1) Whole building fan pressurization 2) Air infiltration by tracer gas 3) Complete thermographic inspection 4) Quantification of U-value if necessary
VI. End of Retrofit Warranty Evaluation (or after one year)	1) Fan pressurization of whole building and/or tracer gas tests 2) Component testing if necessary 3) Thermographic inspection

inspection of the roof. For small buildings the tests applied would be: 1) air infiltration tests using the air sample bag techniques; and 2) either a ground thermographic inspection of the building's envelope or an energy audit of the building using spot radiometer, if the testing proves this technique viable. The air infiltration tests will determine if the buildings are experiencing high air exchange rates. This test should be done between 5 to 10 times under typical weather conditions with the inlet and exhaust dampers both open and closed. The thermographic inspection (or the energy audit using spot radiometer) should be of such nature that the major thermal deficiencies are identified in the thermal envelope. In other words, identification should be made of areas of missing insulation, areas of improving installed insulation, existence of thermal bridges, existence of heat bypasses, location of major sources of air leakage, and areas of moisture damage. Inspections should be made in such a way that the tests required in the quantification stage can be undertaken and specific information can be given to the retrofit contractors. The data gathered in this stage should be analyzed in such a way that the extent of the thermal deficiencies can be determined, the cause identified, and corrective action proposed.

Quantification of Thermal Deficiencies

After the diagnosis of the thermal deficiencies in the building, a judgment should be made to determine whether quantitative data are required to evaluate the effectiveness and benefits of the retrofit measure proposed to eliminate the thermal deficiencies. The appropriate diagnostic test for this quantification are: fan pressurization tests of the whole building, using either the HVAC system fans for large buildings or an external pressurization fan for small buildings and the pressurization tests of typical joints and components of the building, the measurement of the heat loss from thermal bridges with heat flow meters; the measurement of the thermal characteristics (U-values) of major components, if they cannot be accurately determined from building material and construction data. In addition to determining the energy losses due to the thermal defect, the data gathered by these tests should be used to assess the potential for further physical building deterioration which could result from the thermal deficiency if left uncorrected.

The tracer gas measurements of the air exchange rate of the building in the diagnosis stage provides for an estimate of the total energy loss due to air leakage in the building. The thermographic inspection identifies the sources of the leakage. The fan pressurization testing of this stage will allow estimation of the energy loss due to these leakages and allow the assessment of specific retrofit measures. Similarly, the measurement of heat flow on typical thermal bridges and the measurement of the thermal characteristics (U-value and dynamic response if thermal mass effects are to be assessed) will provide data for estimating the energy losses due to the defects observed in the diagnosis stage.

Prototype Retrofit Testing

In large buildings, or in complexes of similarly constructed buildings, the same retrofit action may be repeated many times. In such a situation, it is prudent to evaluate proposed retrofit measures in a small number of applications before applying them to the complete building or complex. The test procedures appropriate for the evaluation of prototype retrofit measures are: fan pressurization testing of prototype solution to the air leakage of components; thermographic inspection of prototype installations; and quantification of the heat losses using heat flow meters, the ETTU, or calorimeters.

Quality Control During Retrofit

The quality of the retrofit installation can be assessed by performing fan pressurization tests of the leakage of retrofitted components and by thermographic inspections. The results of these tests can be compared to the results of the prototype stage tests to determine if deviations are occurring due to poor quality workmanship. In this type of testing, thermographic inspections with low-resolution imaging systems should be adequate and provide the most cost effective procedure. This testing should be the responsibility of the installation contractor and could be performed by his personnel or by private inspectors under contract to him.

Post Retrofit Evaluation

The post retrofit evaluation will determine whether the applied retrofit measures achieved the expected results in improving the energy performance of the buiding and preventing continued deterioration of the building envelope. The test procedures which can be used at this stage are: a complete thermographic inspection (or for small buildings an energy audit using spot radiometers); air infiltration measurements using the air sample bag technique; whole building pressurization tests; and quantification of the heat losses from retrofitted sections of the building using heat flow meters, the ETTU, or calorimeter.

End-of-Retrofit Warranty Evaluation

There is the potential that the applied retrofits will deteriorate with time and lose their effectiveness. This is especially true of many solutions to air leakage problems. At the end of the retrofit period or during post occupancy evaluation (or after one year) tests may be applied to the building to determine whether deterioration in the retrofit measures has occured. The appropriate tests for this evaluation are thermographic inspection of the building and air infiltration tests using either the tracer gas technique or fan pressurization of the building. If these tests show signs of deterioration in the retrofit measures, component testing using fan pressurization or quantification heat loss measurements using heat flow meters, the ETTU, or calorimeter may be required to assess the magnitude of the deterioration.

2. GROUND INFRARED THERMOGRAPHIC SURVEYS

2.1 SUMMARY

Infrared thermography is a qualitative technique for locating and identifying thermal defects in a building envelope [1-6]*. For a thermographic survey an infrared imaging system (see fig. 2.1) is used to provide an image of a surface in which the variations in intensity of each point (usually referred to as the gray tone) correspond to variations of the apparent radiance temperature along the surface. Variations in the gray tone of a thermal image produced by a thermographic imaging system correspond to variations in the heat flow along the surface and to variations in the thermal resistance along the building envelope. A copy of the thermal image produced by a thermographic system is called a thermogram. The most common means of producing thermograms are to photograph the display of the thermographic system or to directly record the video output of the system for subsequent reproduction. The thermal picture is a hard copy which documents the type of defect to a trained investigator (i.e., missing insulation, air infiltration, thermal bridges, etc.) and the extent of the defect (i.e., the percent of the building component which is uninsulated, the length of the crack producing the air infiltration, etc.). When the thermogram is accompanied with information specifying the range in apparent radiance temperatures included in the display and the inside-to-outside temperature difference across the envelope, the thermal pattern can be interpreted by trained personnel for use in energy audits, as a regulatory tool for the enforcement of codes, for the certification of a building's thermal integrity, for the quality control of weatherization retrofits, for the detection of moisture damage to roofing systems, and for the detection of deficiencies in mechanical heating systems and solar systems.

2.2 DESCRIPTION OF INFRARED IMAGING SYSTEMS

There are several types of infrared devices used in the United States to inspect buildings. These devices include: [6-9]

a) infrared thermometers (spot radiometers)
b) thermal line scanners
c) single-element raster scanners
d) multiple-element raster scanners
e) pyroelectric vidicon instruments
f) forward looking infrared (FLIR) instruments
g) Schotsky infrared diode arrays (future).

Infrared thermometers (see fig. 2.2) have been in use for building inspections and also for the measurement of thermal conductivities of building elements. Tests at the National Bureau of Standards and the U.S. Army Cold Regions Laboratory [10-12] have shown that these devices do not give accurate thermal resistance values and that operators of these devices would have difficulty assessing the extent of most defects. However, these devices do have a useful

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* References listed at end of each chapter.

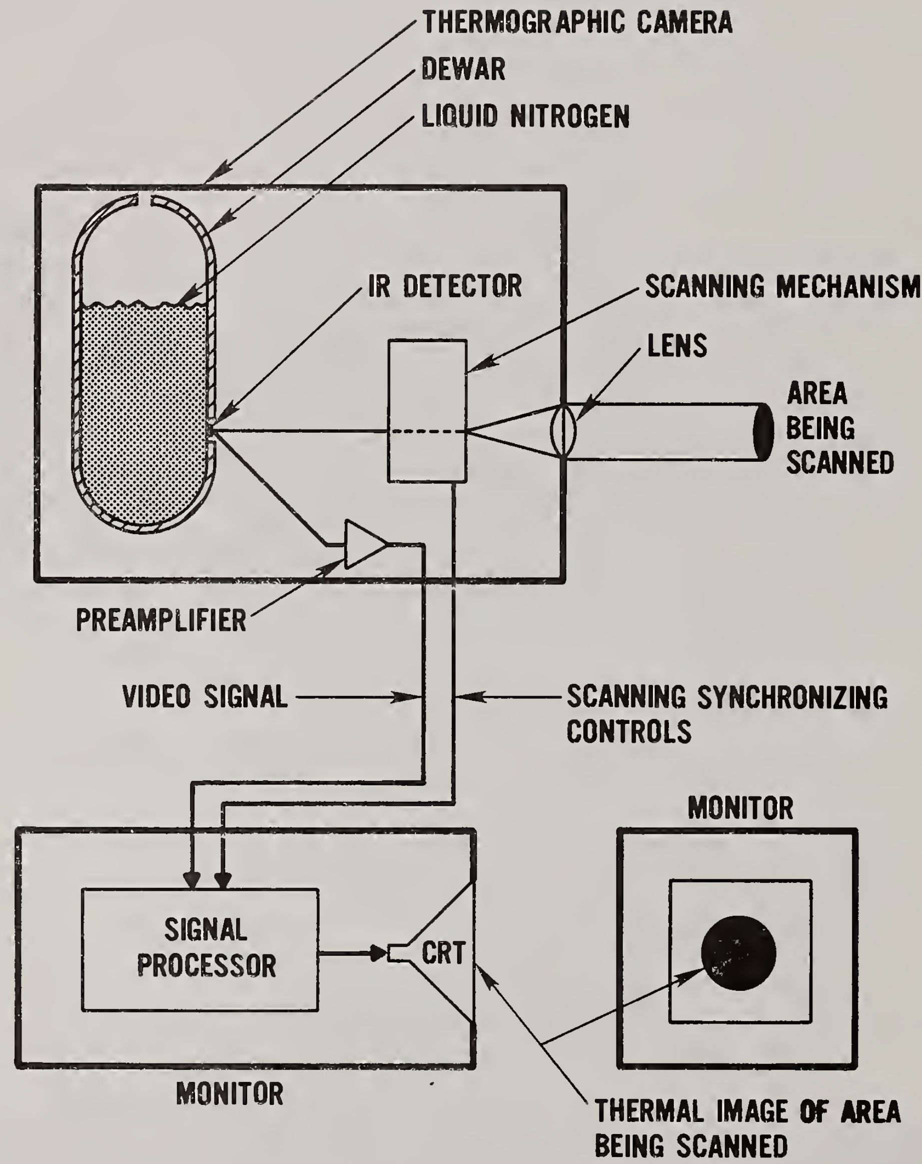

Figure 2.1 Block diagram of thermographic system [13]

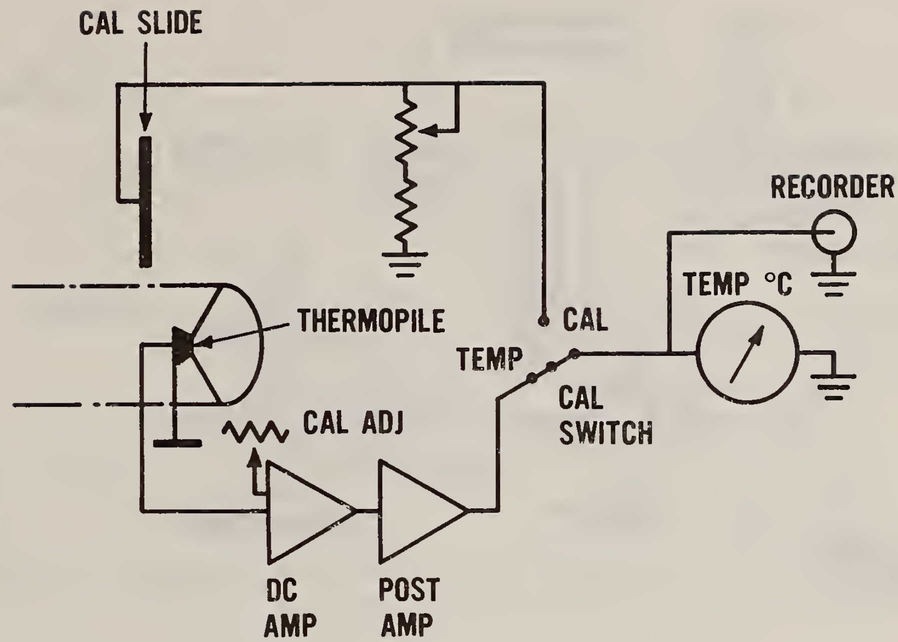

Figure 2.2 Schematic of basic spot radiometer [6]

function in thermographic inspections of buildings for measurement of the absolute temperature at a location within a thermogram. The application of spot radiometers for the determination of thermal conductivities is discussed in section C, chapters 6 and 7, of this document.

Two types of thermal line scanners have been used for building inspections [6]. Each of these systems produces a single straight-line scan of a target along which the emitted and reflected radiant energy from the target along this line is displayed. The hand-held version of this system (fig. 2.3) superimposes the thermal trace over a visual picture of the target. The other class of line scanners used is of the aerial-type mapper where the instrument is mounted in a moving vehicle, either a van or an aircraft. Single-element raster scanners used in the United States operate in both the 3-5 micron and 8-14 micron range, and use both refractive (fig. 2.4) and reflective (fig. 2.5) scanning systems to produce a two-dimensional thermal image of the target. These systems have a temperature resolution of about 0.2 degrees Celsius and produce between 128 to 256 lines and 128 to 256 pixels per image at scan rates up to 30 frames per second. Low-cost multiple-element raster scanners (fig. 2.6) have been developed which use multi-detector arrays [6,14] in order to reduce the constraint imposed by single-element scanners due to the trade-off between the speed of response and the signal-to-noise characteristics of the detector. Scanning improvements allow a faster frame rate with no reduction in signal-to-noise ratio, or improved signal-to-noise performance without decrease in frame rate. However, multiple-array detectors do have uniformity limitations due to the difficulty in matching the detectors in the array. Pyroelectric vidicon systems (fig. 2.7) are television camera tubes in which the target is made up of a thin layer of pyroelectric material which is sensitive to infrared radiation

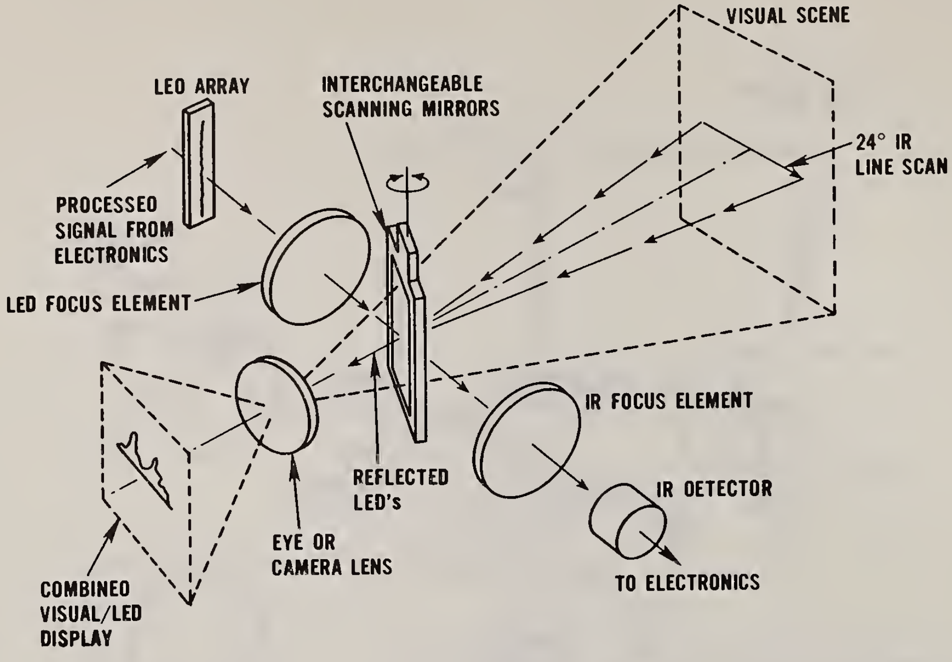

Figure 2.3 Schematic of portable line-scanner [6]

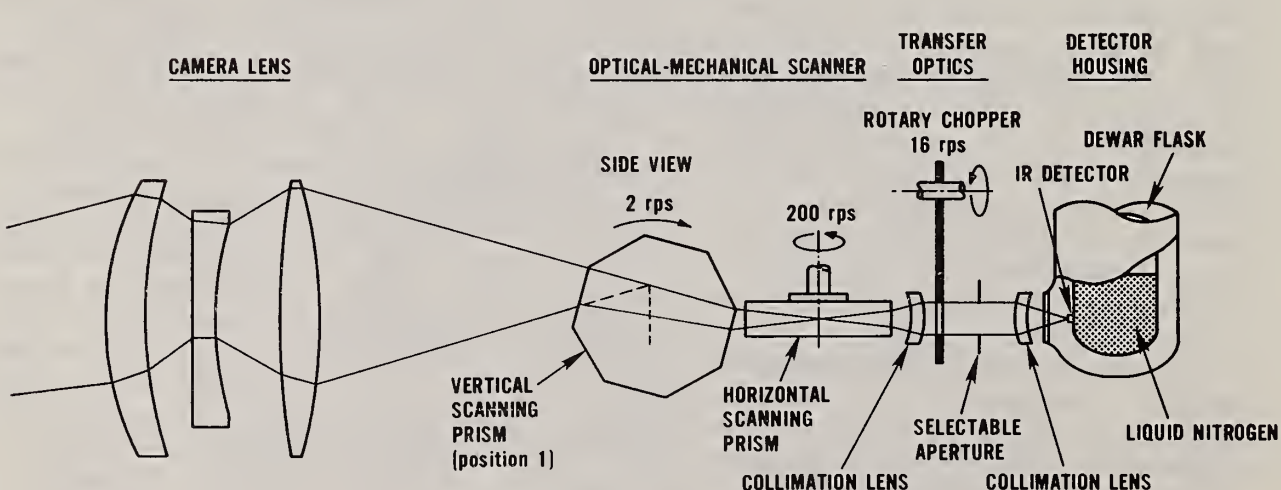

Figure 2.4 Schematic of prism-scanning imaging system [6]

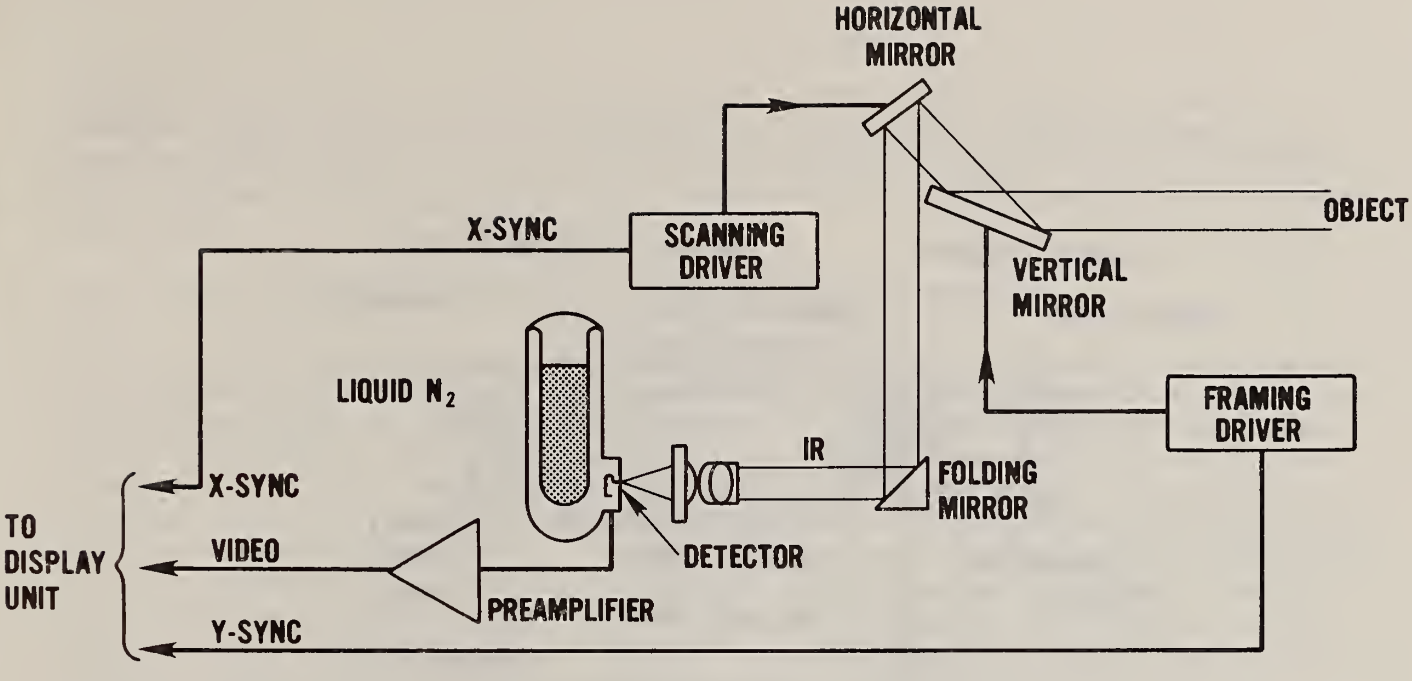

Figure 2.5 Schematic of rotating mirror scanning infrared imaging system [6]

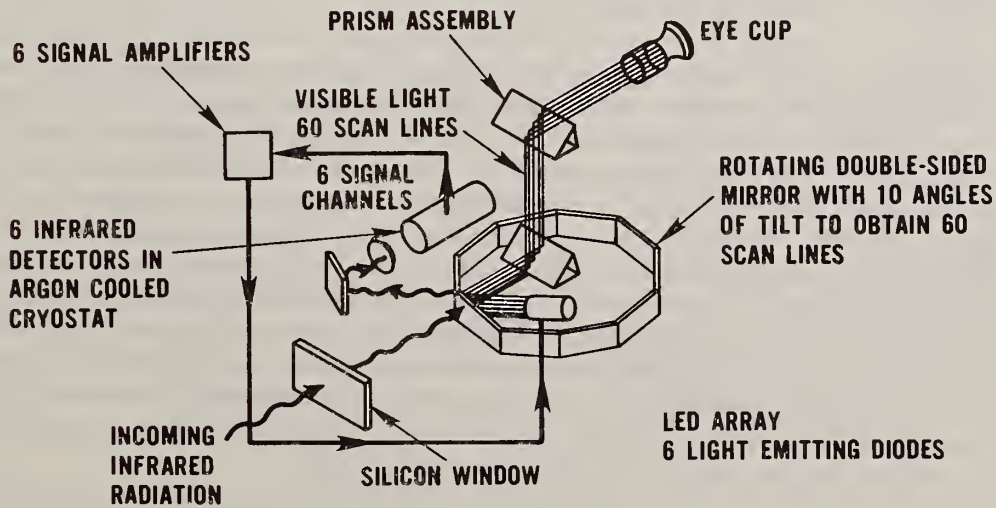

Figure 2.6 Schematic of low-cost multiple-raster infrared imaging system [6]

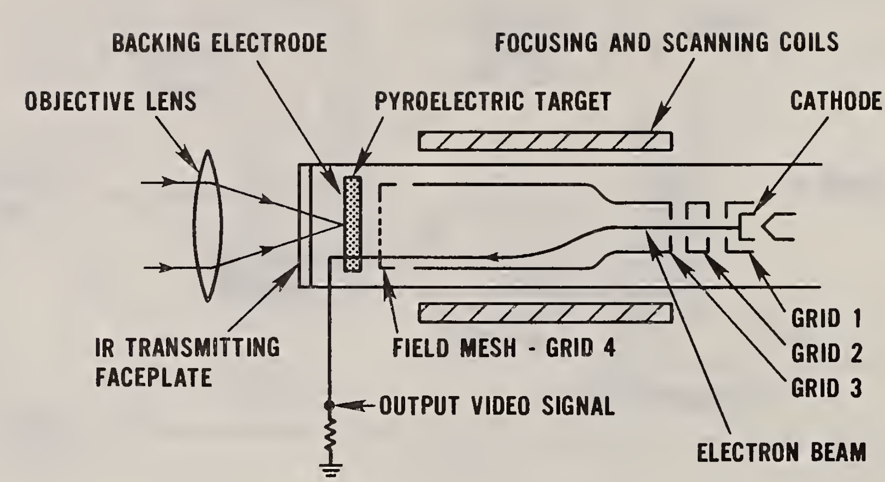

Figure 2.7 Schematic of pyroelectric vidicon

[6,15]. The target is scanned by a controlled electron beam and the image is reconstructed electronically. These systems have been used in the past mainly for surveillance and general purpose thermal viewing. The major limitations for their acceptance as a practical tool for inspecting buildings have been the requirement for panning or chopping (the pyroelectric target responds only to temperature changes) and the lack of uniformity in the pyroelectric layer which leads to a non-uniform spatial response of the equipment. However, progress is being made in the development of this type of equipment, especially with the addition of digital electronic image processing, which could alleviate both of these limitations in the near future.

Forward-Looking Infrared Instruments (FLIR) are high-performance real-time scanning instruments which have excellent spatial and thermal resolution. They have been used primarily for military and surveillance purposes. They are capable of producing thermal images with a temperature resolution better than 0.5 degrees Celsius, with images containing 525 lines with 525 pixels per line at 60 frames a second. These units are fully television-compatible. The Schotsky infrared diode arrays (probably to become available in the future) consist of two-dimensional infrared diode arrays which were developed by several manufacturers for military applications. Commercial systems of this type are not yet available for building inspections. These arrays do offer the potential for the development of a low-cost thermal viewer. However, the problem of matching detectors in the array may lead to spatial uniformity deficiencies which could restrict their applications.

The cost of infrared equipment varies depending on the type: infrared spot radiometers cost from $300 to $1500; hand-held line scanners are approximately

$8000; low-resolution imaging systems cost $1400; high-resolution imaging systems range from $27,000 to $70,000; and pyroelectric vidicon systems cost approximately $20,000. The services of infrared inspectors using high resolution equipment may be contracted for between $600 to $1000 per day plus travel expenses.

2.2.1 Thermographic Equipment Specifications and Evaluation

From the wide range of equipment available in the United States it is difficult to determine which equipment characteristics are primarily important for building inspections. In general, thermographic hardware is characterized in manufacturer brochures with a variety of descriptions and non-standard specifications [10,17]. For example, thermal sensitivity is described in many cases as minimum detectable temperature difference (MDTD) with no indication given of the spatial extent of the target. In other cases, thermal sensitivity is described as noise-equivalent temperature difference (NEΔT), minimum resolvable temperature difference (MRTD) at some unknown spatial frequency, or simply as "thermal sensitivity." ASHRAE Standard 101 [18] has emphasized the need for more standardized specifications of the sensors used for various applications. The parameters which are meaningful for equipment specification fall into five categories:

1. spatial resolution
2. noise characteristics
3. signal transfer properties
4. geometric properties
5. summary measures.

The first four of the above categories are objective laboratory measurements. The fifth category is the most critical for qualitative use of infrared imaging equipment, since it involves imagery interpretation by human observers at the sensor display and incorporates the other four parameters. The performance parameter, summary measures, is based on the observer's ability to see a standardized bar pattern when the temperature difference between the pattern and its background is varied (see fig. 2.8). When the type of the anomaly to be detected is specified in terms of its spatial and temperature characteristics under given environmental conditions, it is then possible to specify the MRTD requirement of any sensor, which might be used to conduct a particular type of inspection, in order to detect or recognize the defect. American test standards specify the spatial frequency for the MRTD at 0.5 cycles/cm and 0.13 cycles/cm. The MRTD requirement is usually then specified as the temperature difference produced by insulation levels of R-5 to R-15 (void to fully insulated wall area) or R-10 to R-15 (partially insulated to fully insulated wall area) for a given inside-outside temperature difference across the building. The methodology for relating the MRTD to the ability of the infrared imaging system to detect a defect is shown in figure 2.9.

The required instrument sensitivities for interior and exterior surveys are presented below:

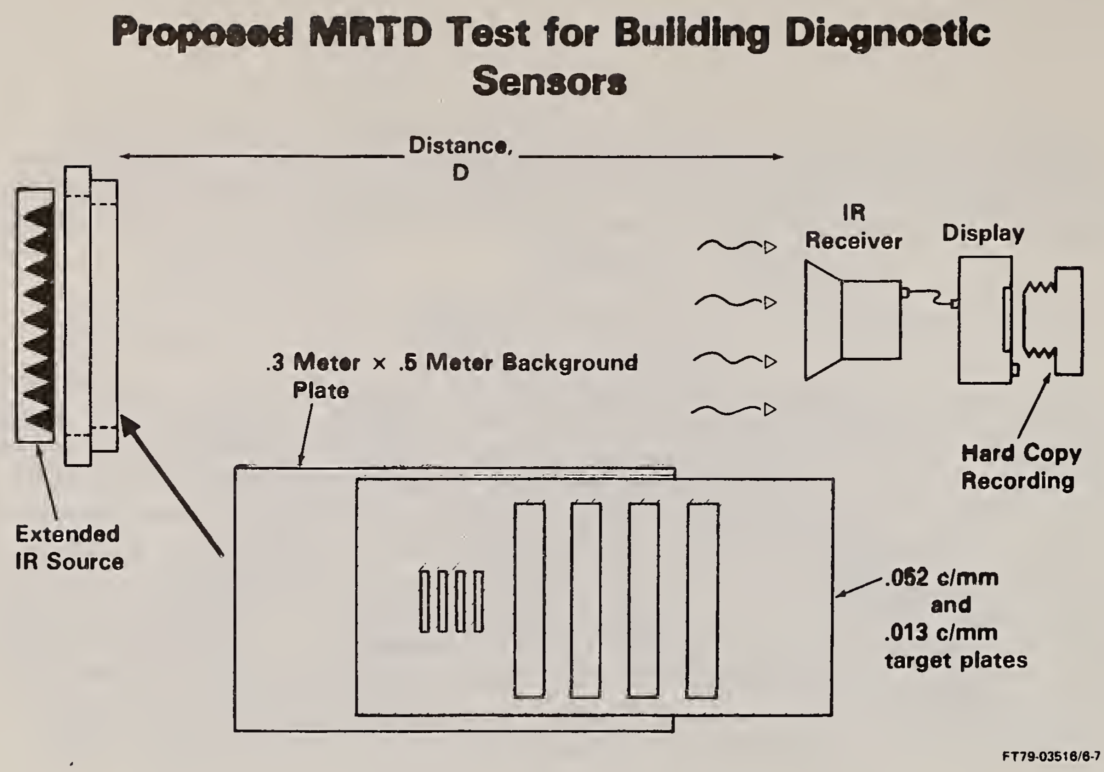

Figure 2.8 Schematic of MRTD test for infrared imaging systems [16]

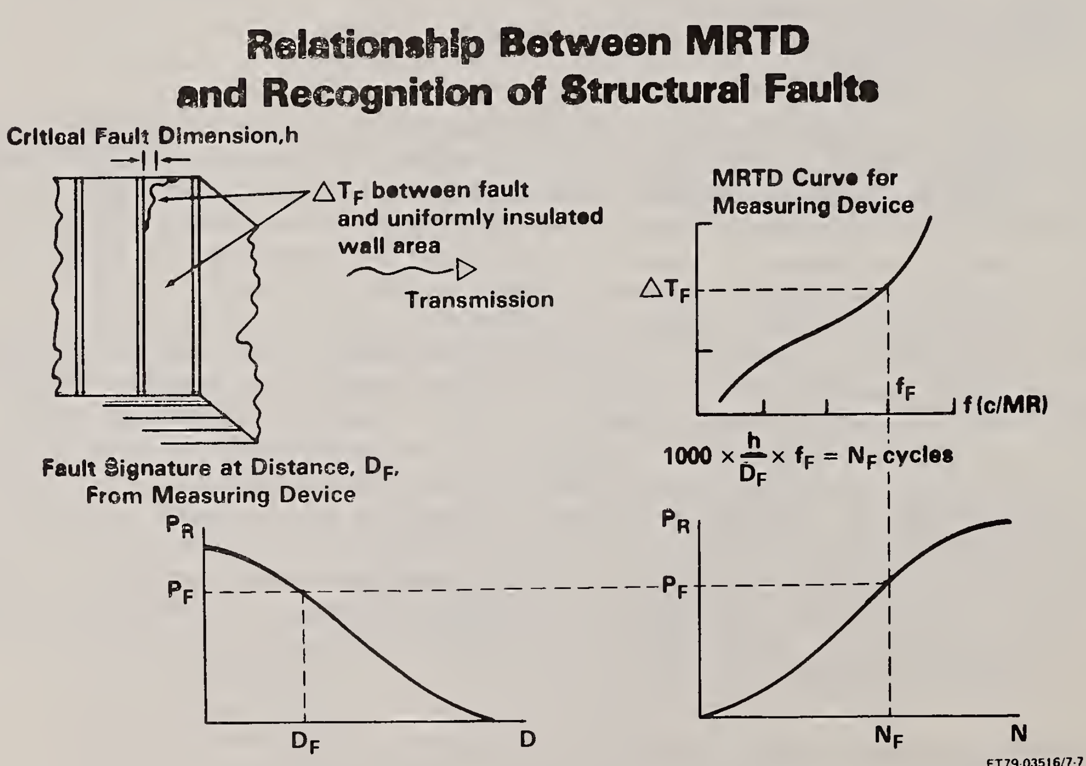

Figure 2.9 Relation between MRTD and building defects [16]

Interior Surveys

Required instrument sensitivities for interior surveys are given in table 2.1.

Table 2.1 Required Instrument Sensitivities for Interior Surveys (MRTD)

T_I-T_O	MRTD °F	
°F	R5/R15	R10/R15
10	0.5	0.125
20	1.0	0.250
30	1.5	0.375
40	2.0	0.500
50	2.5	0.625

The first column of the minimum resolvable temperature differences are those required to distinguish an R5 region from an R15 region; the second column are the differences required to distinguish an R10 region from an R15 region.

T_I - inside air temperature, T_O - outside air temperature.

Consider a situation in which it is desired to determine the location of a partial void which has a thermal resistance of R-10 compared to the wall around it whose thermal resistance is R-15. In this case, it is essential that the infrared device have sufficient sensitivity to enable distinguishing between R-10 and R-15. For an outdoor air temperature 20°F lower than the inside air temperature, use of table 2.1 indicates that a system having an MRTD of 0.25°F or less is required. Similarly, for a greater indoor/outdoor temperature difference, an infrared device having a larger MRTD is permissible (i.e., for a temperature difference of 40°F, table 2.1 indicates an MRTD of 0.5°F).

Exterior Surveys

When the purpose of an exterior infrared survey is to distinguish an uninsulated region of a building envelope (R-5) from an insulated region (R-15), the instrument sensitivity, expressed in terms of MRTD at 30°F, must be less than the value given in figure 2.10 for an infrared scanning system operating in the 8-14 micron wavelength band and less than the values given in figure 2.11 for an infrared imaging scanning system operating in the 3-5 micron wavelength band. Here the wind speed is the local wind speed moving past the exterior surface being examined. A considerably lower MRTD is required for an infrared scanning device operating in the 3-5 micron wavelength band than one operating in the 8-14 micron wavelength band, due to the much greater effect of object temperature on instrument sensitivity for the 3-5 micron wavelength band. Consider the following example:

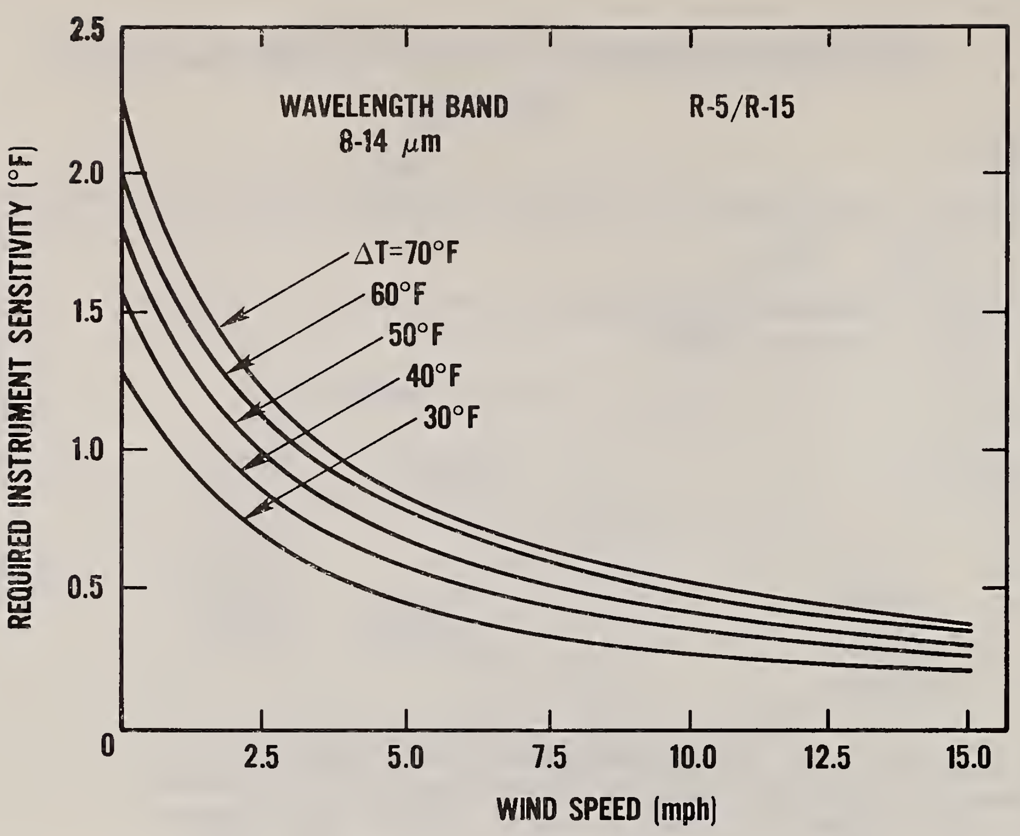

Figure 2.10 Instrument sensitivity requirement R5/R15 for recognition @ 8-14 microns-exterior survey [18]

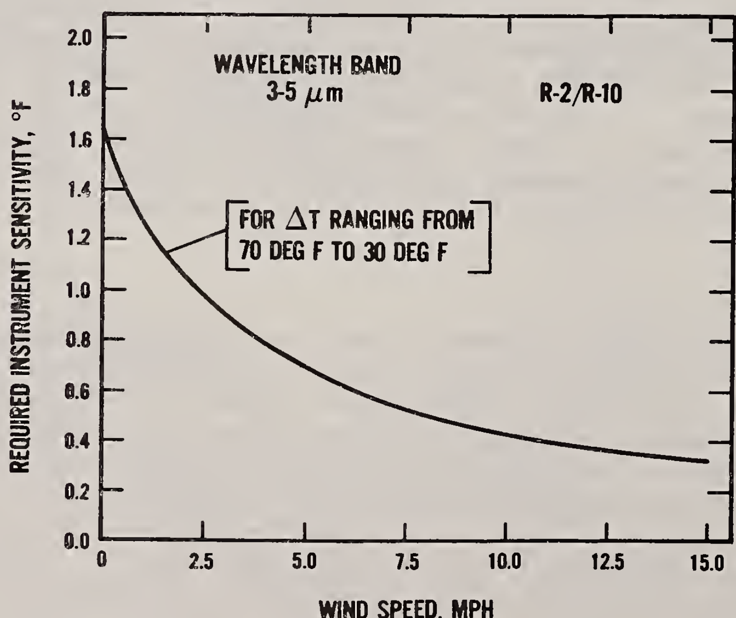

Figure 2.11 Instrument sensitivity requirements R5/R15 for recognition @ 3-5 microns [18]

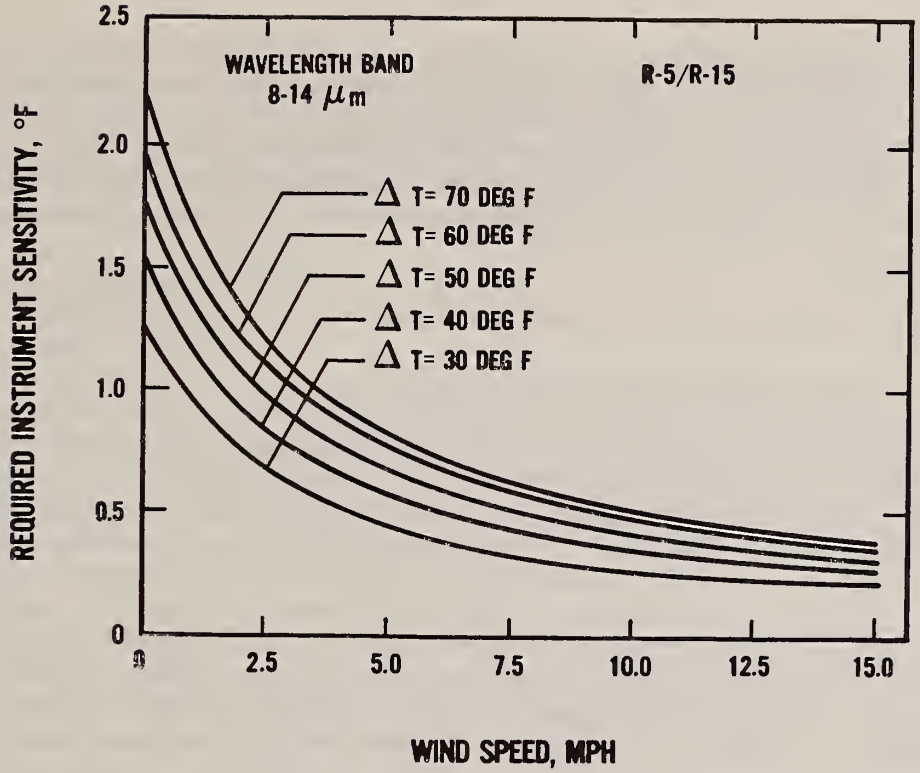

Figure 2.12 Instrument sensitivity requirement R2/R10 for recognition @ 8-14 microns [18]

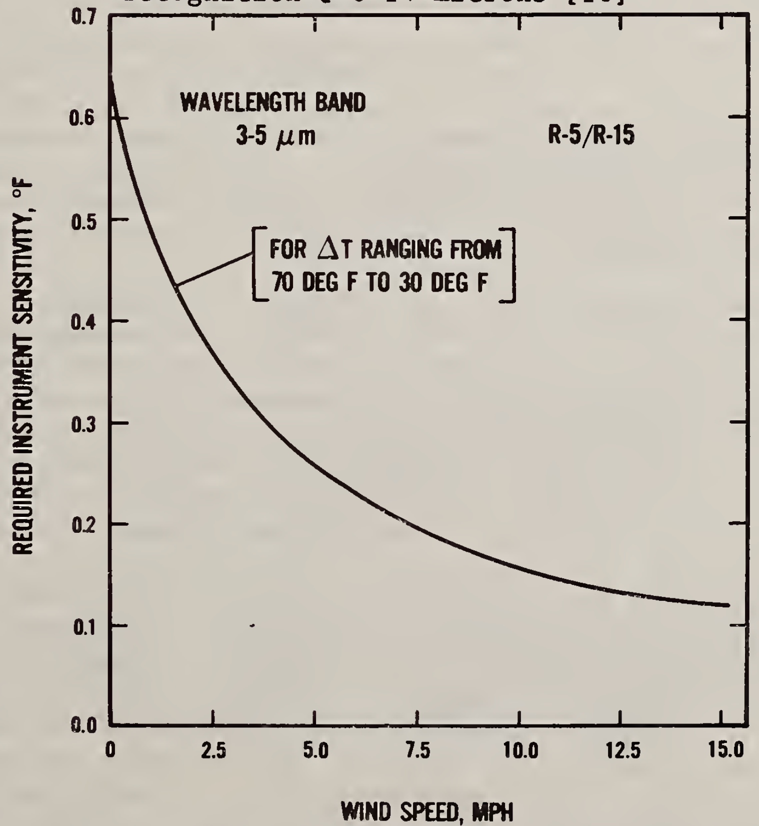

Figure 2.13 Instrument sensitivity requirement R2/R10 for recognition @ 3-5 microns - exterior survey [18]

A thermographic imaging system is used to locate insulation voids of an exterior wall of a building. At the time of the survey, the local wind speed moving past the surface is 7.6 mph and the indoor-outdoor temperature difference is 50°F. The required MRTD referenced to 86°F is 0.54°F for an infrared imaging device operating in the 8-14 micron wavelength band (see fig. 2.10) and 0.22°F for an infrared imaging system operating in the 3-5 micron wavelength band (see fig. 2.11).

2.2.2 Conditions Under Which Thermographic Surveys Can Be Performed

The conditions under which thermographic data can be obtained depend upon both the types of defects which are to be detected and the type of infrared imaging systems employed [20-21]. For high resolution imaging systems (systems with a minimum resolvable temperature difference less than 0.54°F with a spatial frequency of 0.52 cycles/cm), it suffices that a) the minimum temperature difference across the building envelope is greater than 18°F for a period of at least 8 hours prior to inspection, b) the transient conditions are such that there is no more than a 30-percent variation in the temperature across the surface for a period of 24 hours prior to the inspection, and c) that there is no direct solar radiation on the inspected surface for a period of 3 hours for light construction and 8 hours for masonry and masonry veneer construction. During exterior inspections the wind should be less than 15 mph and the surfaces should be dry.

It is recognized that both exterior and interior thermographic surveys are technically possible. If it is possible to observe a class of defects from the interior, it is generally preferable to obtain data from the inside; greater temperature variations exist on interior surfaces than on exterior surfaces and the sensitivity of infrared equipment is greater at interior ambient conditions than it is under normally encountered exterior ambient temperatures. However, certain practical considerations, such as the ease of performing the survey and the accessibility, often dictate the type of survey. Also, certain classes of defects such as heat bypasses into attics, excessive basement losses, and roof inspections for moisture damage, are best observed from the exterior.

The above conditions guarantee that the building is sufficiently close to steady state so that the anticipated thermal patterns of the defects are those produced in steady state. Although it is preferred that steady state conditions exist at the time of inspection thermographic inspections can be undertaken under other conditions if sufficient knowledge is used in taking and interpreting the thermographic data. Under different conditions, other classes of thermal patterns will exist. For example, a wall exposed to direct solar radiation will, after a sufficient time, experience a temperature reversal -- studs and voids will appear warm and the insulated section cold on interior inspection. An exterior inspection about an hour after sunset will show the studs warmer than the insulated section on both interior and exterior surveys due to the differences in the thermal capacities of the two sections. On many veneer surfaces, interior surveys are technically possible an hour or two after the sun has been shining on them. In southern climates, roofs suspected of moisture damage can be inspected in the evenings after being exposed to solar radiation. In such cases, the interpretation of the thermograms is not based on differences in the thermal conductance between the damaged and undamaged sections but on the differences in their heat storage.

In using thermographic systems operating in the 8-12 micron range, care should be taken to ascertain that none of the apparent image is caused by the reflection of thermal radiation from extraneous heat sources. An extraneous heat source can be an adjacent hot object such as a radiator, a chimney, the operator himself or the night sky.

2.3 CONDUCTING INTERIOR SURVEYS

2.3.1 Measurement Technique

For an interior survey, a thermographic imaging system is used inside a building. A series of thermal images is obtained for all portions of the interior envelope of the building. For each measurement, the infrared camera is placed sufficiently far from the subject surface that the field of view of the infrared camera will subtend as much of the interior surface as is possible without loss of thermal and spatial resolution.

The sensitivity setting of the equipment is adjusted at the highest possible setting (lowest minimum resolvable temperature difference) which will prevent all portions of the subject surface from being displayed at a saturated level (either white or black). If prominent thermal defects are displayed in the thermal picture, the oscilloscope screens of the television monitor are photographed, using a conventional camera. To assist in the interpretation of results it is desirable to obtain a visible-spectrum photograph of the same scene displayed in the infrared picture.

2.3.2 Guidelines for Conducting Surveys*

Preferably, thermographic surveys are performed within a building rather than from the exterior in order to avoid the problem of wind "scrubbing away" surface temperature differences depicting thermal anomalies in the building envelope and degrading instrument sensitivity due to reduced object temperature. It is recommended that at least an inside-to-outside temperature difference of 20 °F exist at the time of a survey, so that sufficiently large temperature differences will occur to permit thermal anomalies in the building envelope to be readily distinguished. Surveys may be carried out during either the day or night. For day surveys it is important that solar loading not negate inside-to-outside temperature differences, thereby causing thermal anomalies to become indistinguishable. Night surveys are preferred because more stable heat transfer conditions will usually prevail; meaningful survey results will be obtained by the elimination of interference from solar loading and reflections.

Preparation for the survey may include elimination, to the extent practical, of thermal artifacts such as furniture located near exterior walls. During the survey, a thermogram shall be taken of each surface of the building where anomalies may exist and which are regarded as significant (i.e. major air infiltration paths, large uninsulated regions of a wall or ceiling, etc.).

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* Mostly from ref. [18].

Data should be recorded with each thermogram to proivde reference to a calibrated gray scale for the purpose of indicating the relationship between contrast and temperature difference. Often, the reference requirement can be accomplished by simply recording the instrument sensitivity setting, which is the range of radiance temperature displayed in the thermal picture. That information, along with the inside-to-outside temperature difference, will permit a thermal anomaly to be interpreted correctly by a third party. During the survey, the following data should be recorded:

1. date of survey
2. time of survey
3. indoor temperature
4. outdoor temperature
5. general wind condition (i.e., calm, moderate wind, etc.)
6. unusual surface finish (i.e., low emittance surface)
7. building construction
8. data for calibrating gray-tone scale

2.4 CONDUCTING EXTERIOR SURVEYS

2.4.1 Measurement Technique

For an exterior survey, a thermographic imaging system is used to obtain a series of thermal images of the exterior envelope of a building. For each measurement, the infrared camera is placed sufficiently far from the subject surface so as to provide the maximum field of view for the infrared camera without loss of thermal and spatial resolutions. The sensitivity setting of the equipment is adjusted at the highest possible setting (lowest minimum resolvable temperature differences) which will prevent all portions of the subject surface from being displayed at a saturated level (either white or black). If conspicuous thermal defects are displayed in the thermal picture, then the oscilloscope screens of the television monitor are photographed, using a conventional camera. It is desirable to obtain a visible-spectrum photograph of the same scene displayed in the infrared picture to assist in the interpretation of results.

2.4.2 Guidelines for Conducting Surveys

In 2.3.2 it was noted that thermographic surveys are preferably performed from within a building rather than from the exterior. However, exterior surveys are frequently more readily accomplished.

The infrared imaging system used for the survey may be portable, cart-mounted, ground-vehicle-mounted, or mounted on an aerial platform. The field of view of the infrared imaging system should be at least 18 degrees. In carrying out the survey, an attempt should be made to include as much of the exterior surface, as possible, of the building without causing its horizontal field of view to subtend more than 10 meters and its vertical field of view to exceed 6 meters. Surveys should not be carried out with larger fields of view unless it can be shown that the MRTD of the instrument meets the requirement of figures 2.10, 2.11, 2.12 and 2.13 at the particular field of view. Surveys should be carried out at least 3 hours after sunset and before sunrise to avoid surface temperature differences from variations in solar absorptance which could be incorrectly interpreted as thermal anomalies. The minimum inside-to-outside temperature difference at the time of survey, and for a minimum of 4 hours prior to the survey, should not be less than 18°F. Exterior surveys should not be carried out during periods when the wind speed exceeds 15 mph, in order to avoid the problem of the wind completely scrubbing away temperature differences depicting thermal anomalies.

Exterior surveys should proceed to the extent practical only when the view of building surfaces is substantially clear of water, snow, and/or ice, and when no fog is present. Data should be recorded with each thermogram to allow reference to a calibrated grey scale, or two reference temperatures, for the purposes of indicating the relationship between contrast and temperature difference. Often this may be accomplished by simply recording the instrument sensitivity setting which is the range in radiance temperature displayed in the thermal picture. This information, along with the inside-to-outside temperature difference, will permit a thermal anomaly to be interpreted correctly by other investigators. For the purposes of carrying out exterior surveys of buildings, infrared cameras operating on the 8-14 micron region are preferred over those operating in the 3-5 micron region, in order to obtain much greater instrument sensitivity. Consider the following example:

Both 8-14 micron and 3-5 micron infrared detectors have an MRTD of 0.36°F at 86°F. When these detectors view an object at 68°F, the MRTD for the 8-14 micron detector is degraded to 0.5°F whereas the MRTD for the 3-5 micron detector is degraded to 1.2°F.

During the survey, the following data should be recorded:

1. date of survey
2. time of survey
3. indoor temperature
4. outdoor temperature
5. data for calibrating gray-tone scale
6. wind speed at each surface measured
7. unusual surface finish (i.e., low-emittance surface)
8. building construction

As a final note, when conventional photographic equipment is used outdoors, the required exposure times for films may be substantially altered at temperatures below normal (room) temperature. Guidelines for compensating for this effect can be obtained from photographic film manufacturers.

2.5 INTERPRETATION OF THERMOGRAPHIC DATA

The interpretation of thermographic data [20-21] is a process which consists of comparing the thermal patterns of a building with previously observed and cataloged thermal patterns for various types of thermal defects. The major steps in this process are: 1) determination of anticipated thermal patterns, given physical building data and the environmental conditions to which the building was subjected, 2) acquisition of actual thermal patterns under environmental conditions which will produce thermal irregularities identifiable by the infrared system employed and for the defects which one desires to observe, 3) deduction of the temperature distribution on the inspected surface, correcting for emissivity changes, and eliminating apparent temperature patterns produced by the reflection of radiation from extraneous sources, 4) comparison of the observed temperature patterns with the anticipated thermal patterns, 5) deduction of the types of defects in the structure which could produce the observed irregularities in the thermal patterns, and 6) verification of the conclusions, using ancillary measurements, if reasonable uncertainty remains, as to the cause of the thermal irregularities.

The inspection of buildings using infrared scanning systems can produce information which is useful for locating and assessing heat losses from buildings, such as: 1) areas of the exterior wall which were not insulated; 2) areas of the roof not properly insulated; 3) shrinkage or fissures in fully insulated wall areas; 4) air leakages around doors and windows; 5) excessive heat loss around door and window frames; 6) excessive heat loss in the joints between walls, ceilings, and floors; 7) excessive heat loss in unconditioned spaces, 8) air penetration into interior cavities; and 9) moisture damage to insulation.

Each of the above defects produces thermal patterns which have distinct pattern characteristics. In the evaluation of thermographic data one should assess: 1) the lack of uniformity of the observed radiation intensity in the image; 2) the coincidence of changes in radiation intensity with structural features; 3) the sharpness and nature of the contours separating areas with different thermal characteristics; and 4) the changes in thermal patterns caused by equipment positioning and adjustment.

Some typical defects observed in single-family dwellings [20] are shown in figures 2.14 to 2.19. Missing insulation in two cavity-filled walls is detected in the thermal images taken from the interior of the dwellings in figures 2.14 and 2.15. Missing insulation usually produces regular and well-defined shapes not associated with structural features; the contour of the boundary between the void and the insulated sections is usually sharp. In frame construction, voids usually appear colder than the framing members. Two levels are observed in the thermal pattern in figure 2.16. That both of these levels are insulated can be ascertained by noting that the studs are colder than the area between them in both regions. Figures 2.17 and 2.18 show examples of air leakage. Air leakage usually appears at joints and junctions in the building envelope, and often produces thermal patterns with irregular variations. In the interpretation of thermograms for the purpose of locating voids or missing insulation, some care should be exercised to ensure that the thermal patterns observed are not due to air leakage around improperly installed insulation. Information on the condition of the wall before the application of the insulation, the type of insulation installed, and the location of possible sources of air penetration, helps in correctly interpreting thermal patterns.

The thermogram in figure 2.19 shows the type of information which can be observed during exterior surveys. Figures 2.20 and 2.21 show some examples of thermal reflections observed during surveys using 8-14 micron systems.

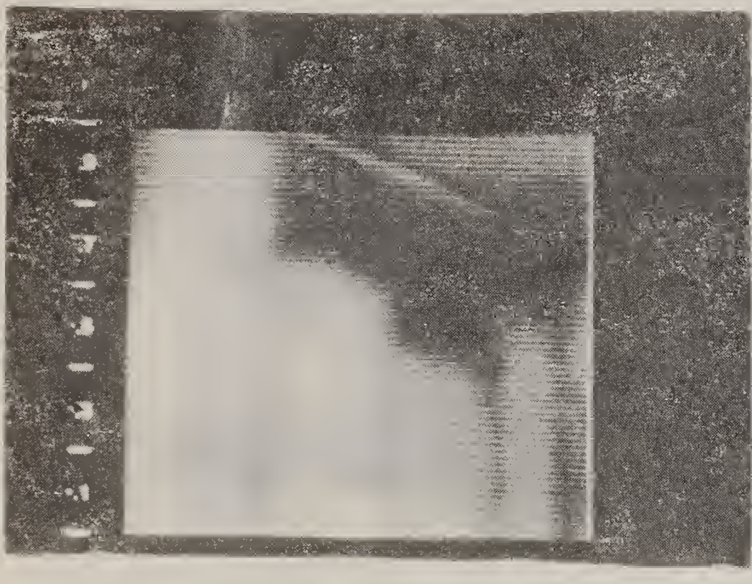

Figure 2.14 Example of thermogram voids in a cavity wall retrofitted with foam insulation.

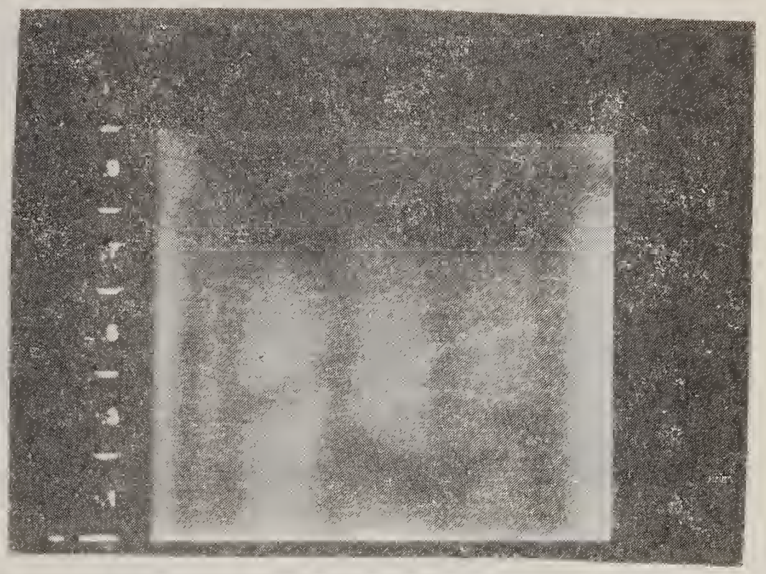

Figure 2.15 Example of thermogram of voids in a cavity wall retrofitted with cellulose insulation.

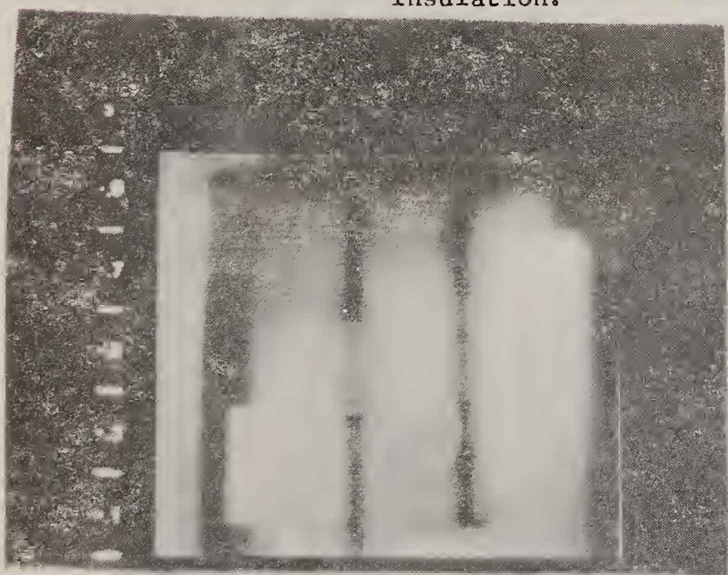

Figure 2.16 Example of thermogram showing two levels of insulation in a cavity wall initially insulated with 3-1/2" glass fiber batts over which foam is installed as a retrofit.

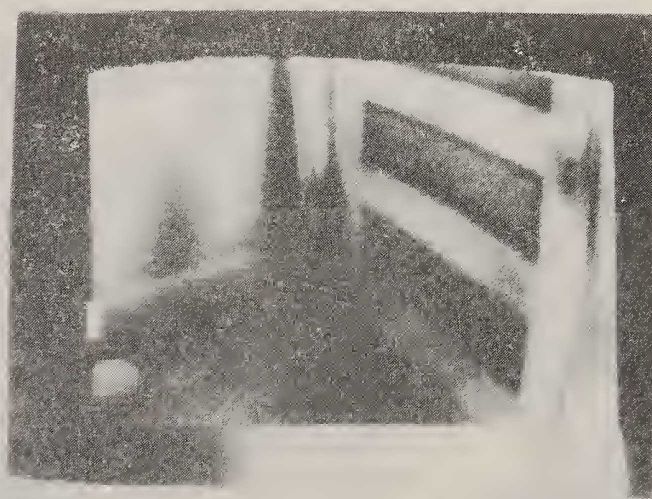

Figure 2.17 Thermogram showing air infiltration around an improperly weather-stripped door.

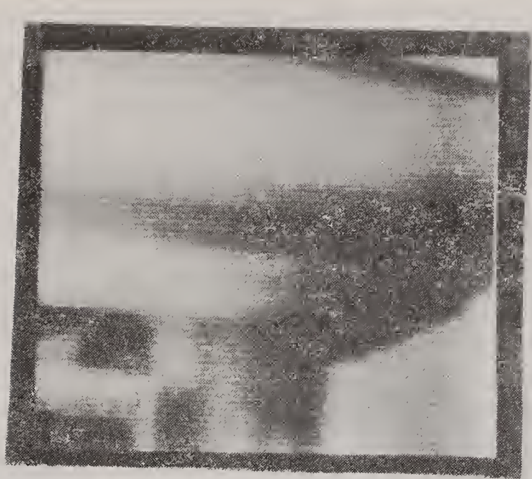

Figure 2.18 Thermogram showing air penetration under ceiling insulation.

Figure 2.19 Example of an exterior thermogram of a retro-fitted dwelling. Notice the missing insulation in a bay cavity and the abnormally warm roof.

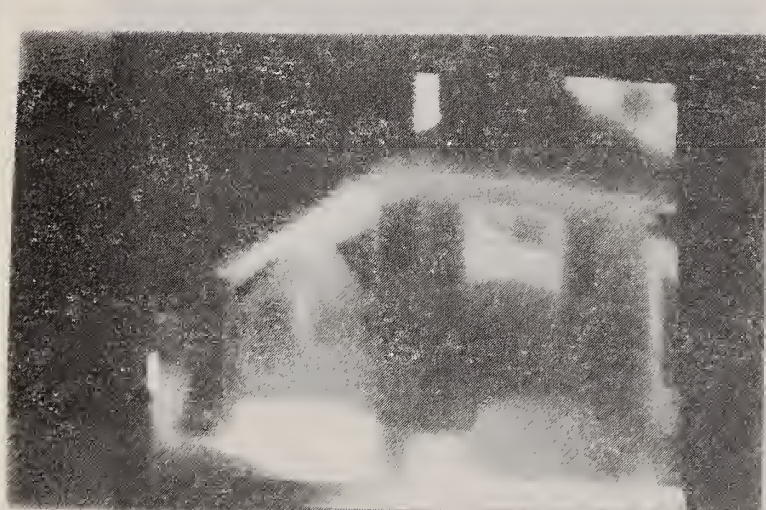

Figure 2.20 Example of thermal reflection recorded by an 8-14 micron system. Image in the side of the house is the neighboring house.

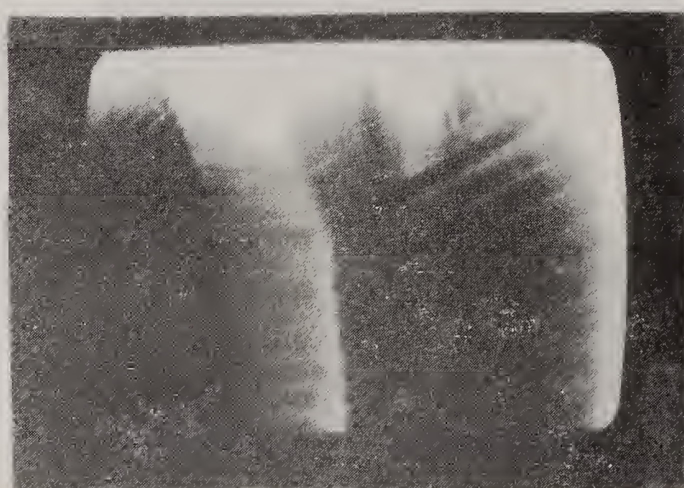

Figure 2.21 Example of thermal reflection recorded by an 8-14 micron system. Light area along the chimney is a reflection of the chimney in the siding.

Reflection can be detected by viewing the surface from different angles. If the patterns move, they probably are due to reflections from extraneous sources.

2.6 ACCURACY OF THERMOGRAPHIC SURVEYS

Thermographic surveys are qualitative at the present state of development. If the guidelines for carrying out the thermographic surveys are fulfilled, then properly trained thermographers can detect the classes of thermal deficiencies in over 90 percent of the cases [2]. However, untrained operators do not usually arrive at consistent results [28, 45, 46].

The difficulties seem to arise from: 1) performing inspections under unsuitable conditions; 2) not understanding fully the principles of heat transfer in buildings; 3) not understanding the characteristics of the infrared equipment; 4) not performing simple additional measurements to verify the conclusions drawn from the infrared inspections; and 5) attempting to perform infrared inspections with a minimum of effort.

If there are doubts as to the results of a thermographic survey, ancillary measurements should be made.

2.7 AVAILABILITY OF THERMOGRAPHIC EQUIPMENT AND SERVICES

There are approximately six manufacturers of spot radiometers in the United States, two manufacturers of hand-held line scanners, two manufacturers of low-resolution imaging equipment, four manufacturers of pyroelectric vidicon and three manufacturers of high-resolution imaging systems. There are over 50 firms in the United States offering thermographic services for energy conservation assessments. A detailed description of most of the manufacturers and services can be found in ref. [9], as of December 1978. High resolution infrared cameras cost in the range of $25,000 to $500,000, low-resolution systems cost $8,000 to $14,000; thermographic survey services without analysis ranges from $500 to $700 per day.

2.8 TRAINING OF THERMOGRAPHIC OPERATORS

One of the major difficulties in successfully applying thermography to buildings has been lack of trained operators and interpreters of thermographic data. This shortcoming has been clearly recognized by Public Works Canada [20-22] who have developed a training program for the various levels of technical expertise required for performing, analyzing and interpreting thermographic surveys of buildings.

Public Works Canada has defined three levels of investigation in building thermography, each of which requires a different degree of professional expertise. The levels of investigation consist of the following.

Level I (Thermographic): Locating thermal anomalies and interpreting causal mechanisms. Both activities produce qualitative results and are performed by a thermographer (i.e., a trained IR-system operator with para-professional knowledge of building science).

Level II (Thermographic): Interpreting the significance of the problem in the construction and recommending appropriate remedial action. Both activities produce qualitative results and are performed by a thermologist (i.e., a trained IR-system operator with professional knowledge of building science).

Level III (Building Science): Interpreting the cause and effect of building problems, and detailing design recommendations to correct existing problems and prevent future ones. All activities produce qualitative results and are performed by a building scientist (i.e., a trained interpreter of IR thermal images with specialized knowledge of building science).

For each of these levels, a person must obtain an appropriate level of proficiency in:

- the fundamentals of building physics,
- infrared theory and equipment,
- building enclosure and heat transfer principles.

In implementing a diagnostic program for federal buildings, the Canadian training program provides a useful model. It will be necessary to have federal employees exposed to the basic principles put forth in the Canadian training program in order to be able to communicate effectively with the professionals who perform and interpret the results of the thermographic surveys. The professionals who undertake the surveys should be trained to the level specified in the Canadian training program.

2.9 PREVIOUS USES OF THERMOGRAPHY

Thermography has been widely used as a research tool in the United States. A summary of published work on thermography can be found in reference [23]. Applications where thermography have been shown to be effective are:

a. Quality Control of Building Retrofits [24-27]. In this application, the use of thermography seems economically viable. The retrofit of buildings is difficult under the best of circumstances, and it has been demonstrated that (although the building owner has invested a sizable amount of money to fix the building) much of the work is poorly done and that there are often serious defects remaining in the building.

b. Moisture Damage to Roofs [28-31]. In this application, thermography can be used to identify those areas which have been damaged, and also the sources of the moisture. There are good economic reasons for repairing only the damaged areas, not the whole roof.

c. The Inspection of Commercial and Institutional Buildings [32-42]. The pioneering work in the area is now being performed at Public Works Canada. They have undertaken a program to inspect 100 federal buildings in the various provinces of Canada.

d. The House-Doctor Approach to Weatherization. Princeton University has developed a method of using infrared imaging systems, along with fan depressurization of the building, to discover air leakage paths. These leakage paths are repaired at the time of inspection with the infrared system. (This may be the only viable means of being certain that a dwelling is air tightened properly.)

2.10 PROGRAM RESTRICTIONS TO THE APPLICATION OF THERMOGRAPHIC SURVEYS

There should be no serious program restrictions to the application of thermographic surveys to the diagnosis of federal buildings. However, some care should be taken in its implementation. The inspection of the buildings in warm climates, though theoretically possible, is a problem area where little practical experience exists. Thus, earlier stages of the program should be structured to emphasize colder climates, progressively moving to warmer climates as experience is gained. The number of buildings inspected should be consistent with staff capabilities to utilize the results, i.e., thermographic surveys produce large amounts of data and there is a tendency to collect these data and then not properly or completely analyze them. Emphasis should be placed on data analysis techniques and methods for presenting the data in a form useful to the building operators.

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3. AERIAL INFRARED SURVEYS

3.1 SUMMARY

Aerial infrared thermography is an imagery process utilizing an infrared line scanner generally mounted underneath an aircraft, which produces an apparent radiance temperature in a partial map of the terrain below the aircraft.

In surveying low-slope built-up roofs of commercial and industrial buildings, this technique is usually effective in identifying those roofs that are either uninsulated or have defective roof insulation. This technique has been shown to be particularly effective in locating regions on individual built-up roofs that have defective, missing, or wet insulation thereby permitting local repairs to be carried out.

With regard to surveying pitched ventilated roofs of residential buildings, variations in ceiling resistance cause differences in apparent radiance temperatures among the roofs displayed in an aerial infrared image which are smaller, by approximately a factor of three, than those for low-slope built-up roofs. Field surveys have shown that under optimum climatic conditions (i.e., clear sky and low wind), a highly sensitive infrared imaging system viewing a small cluster of residential roofs having the same roof emittance and exposed to the same microclimate will produce a thermal picture, ranking the buildings correctly according to their heat loss characteristics. Under non-optimum conditions the variations in roof emittance, local wind speed and local outdoor temperature (throughout the macroclimate) may often cause differences in apparent temperature which mask out those differences in radiance due to variations in ceiling resistance. When viewing individual pitched ventilated roofs, it is not possible to distinguish uninsulated portions of the ceiling.

3.2 CONCEPT OF AERIAL INFRARED THERMOGRAPHY

In conductng an aerial infrared survey, an infrared line-scanning system mounted in an aircraft scans the terrain, building up a thermal image as the aircraft progresses along a flight line, as shown in figure 3.1. The scanner is basically an optical telescope, with its narrow field of view continuously redirected by a spinning flat mirror. The mirror causes the system to scan in a plane perpendicular to the direction of flight of the aircraft. Such systems have one or more cryogenically cooled thermal radiation detectors in the focal plane of the telescope which convert the focused thermal energy received by the detector into an electrical signal. This electrical signal can be processed into a visual image on a cathode-ray tube (CRT) which can be photographically recorded or digitized and recorded on a magnetic tape recorder for future processing*.

An aerial infrared photograph of a large number of residential roofs is shown in figure 3.2. Variations in gray tone from light to dark correspond directly to variations in apparent radiance temperature. Parts of the thermal picture

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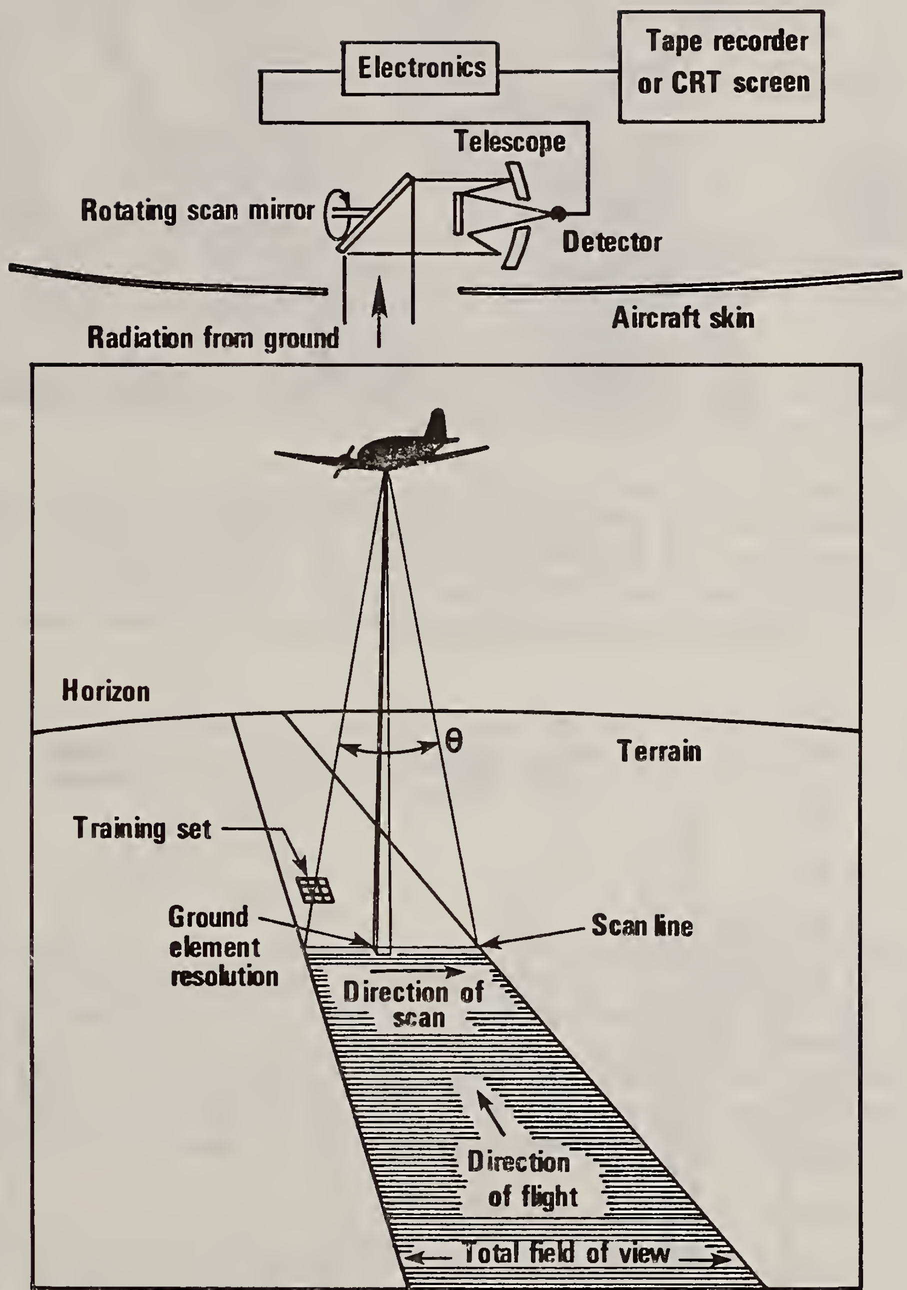
* Much of this description was taken from ref. [1]



Fiqure 3.1 Schematic illustration of the use of a line scanner to perform aerial infrared thermography [1]

Figure 3.2 An aerial infrared photograph of a large number of residential roofs (provided by Texas Instruments)

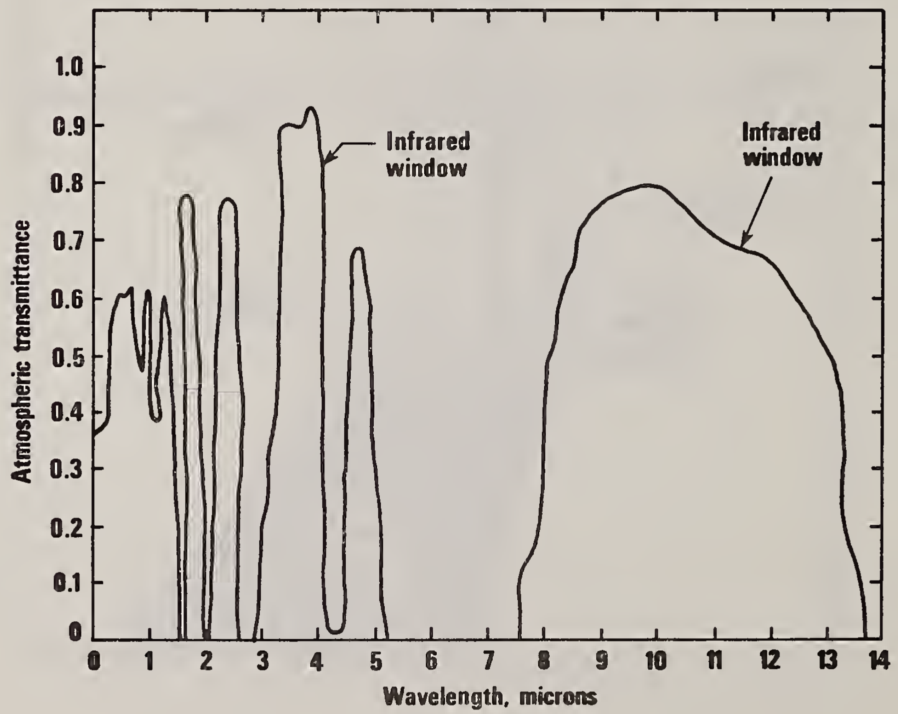


Figure 3.3 Transmittance of the whole atmosphere as a function of wavelength [2]

appearing in lighter gray tones have a higher apparent radiance temperature than other parts of the thermal picture. Infrared line-scanning systems usually have a sweep angle (θ), as depicted in figure 3.1, which does not exceed 110 degrees, in order to restrict distortion at the outer edges of the thermal picture [3]. Flights are most often conducted at altitudes between 1000 and 2000 ft. The instantaneous field of view of the infrared line scanner varies with the particular system but will generally range between 1 and 2.5 milliradians on a side. Aerial infrared thermography is usually performed in the 8 to 14 micron wavelength band because of the high atmospheric transmission over that part of the infrared spectrum (see figure 3.3). Atmospheric transmission data presented in figure 3.4 shows that the average atmospheric transmittance at a distance of 1640 ft above ground level are 0.93 and 0.97 at outdoor relative humidities of 95 and 20 percent, respectively. In addition, the same data shows that an increase in path length due to an increase in the view angle, has a very small effect on the atmospheric transmittance over this particular wavelength band.

The theoretical consideration for thermal radiation sensed from surfaces, such as roofs, by an infrared line scanner includes both self-emitted radiation and reflected radiation from the sky. The apparent radiance temperature (T_a) is defined as the temperature of a perfectly black surface which would radiate the same amount of thermal radiation as a real surface at a temperature (T_s) and having a surface emittance (ε). An equation relating the apparent radiance temperature of a surface to its actual temperature has been derived by Goldstein [5]. For the convenience of the reader, a derivation for the equation is given below.

For the 8-14 micron wavelength band, the self-emitted energy from a perfectly black surface at the apparent radiance temperature (T_a) is equal to the self-emitted and reflected sky radiation from the actual surface at a temperature (T_s), or

$$T_a^{\,n} = \varepsilon \cdot T_s^{\,n} + (1-\varepsilon)\cdot(T'_{sky})^n \qquad (3.1)$$

Here the radiant energy from the sky is based on the spectral sky temperature (T'_{sky}) instead of the calorimetric sky temperature (T_{sky}), since radiant energy is being considered only over the 8-14 micron portion of the infrared spectrum. The spectral sky temperature is lower than the calorimetric sky temperature because the atmosphere is relatively transparent over the 8-14 micron wavelength band. The exponent n is 5 instead of 4 because radiation is only being considered between 8-14 microns instead of the whole infrared spectrum.

Solving eqn. (3.1) for (T_a) gives:

$$T_a = T_s \cdot [\varepsilon + (1-\varepsilon)\cdot\beta^5]^{1/5} \qquad (3.2)$$

Here β is the ratio of the spectral sky temperature (T'_{sky}) to the surface temperature (T_s). The accuracy of equation (3.2) was investigated by numerically integrating the Planck distribution function for the self-emitted and

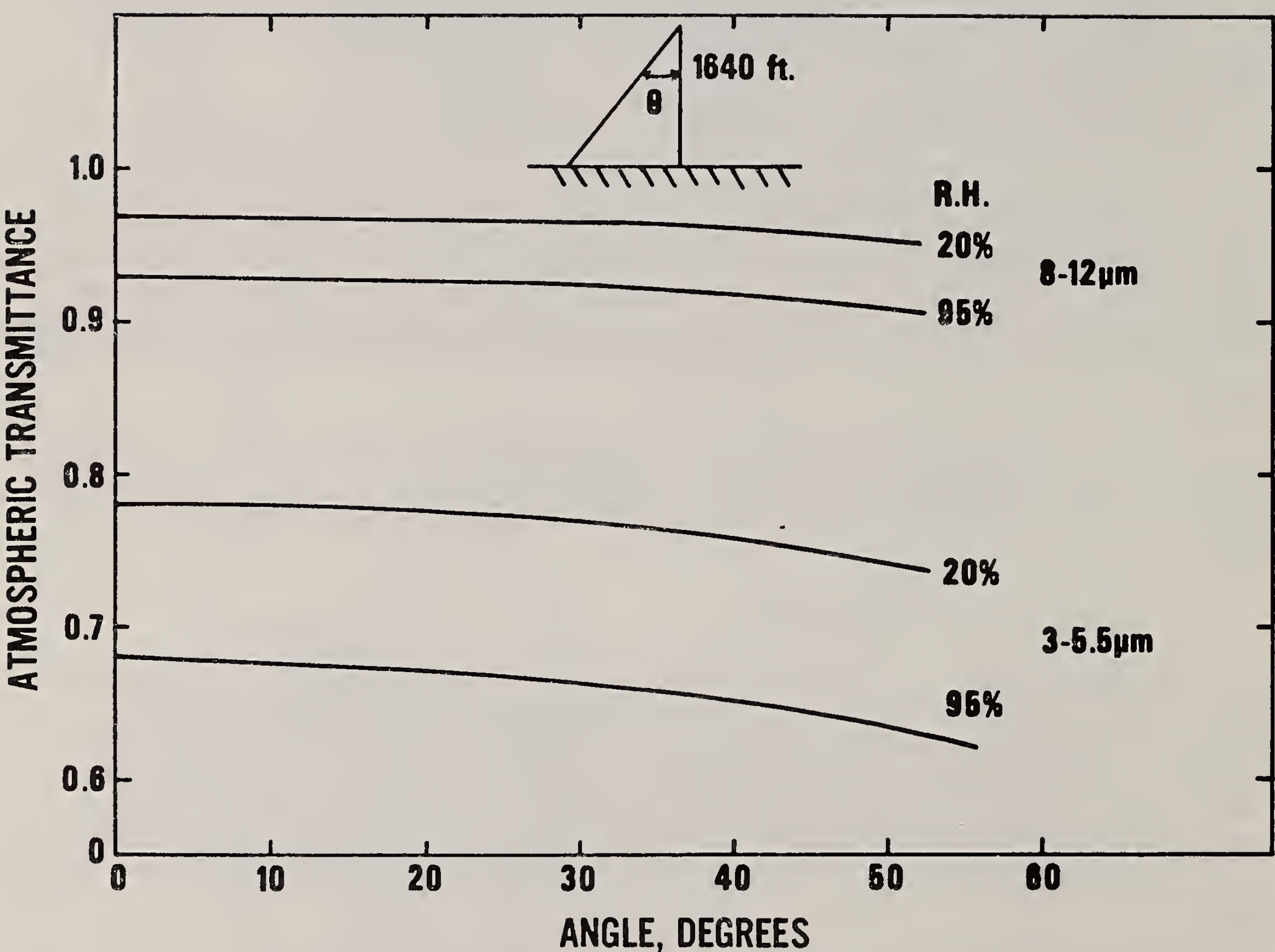


Figure 3.4 Average atmosphere transmittance as affected by incident angle and outdoor relative humidity [4]

reflected components of the roof radiance. Equation (3.2) was found to be accurate to within a fraction of a degree Fahrenheit over a representative range of surface temperatures and sky temperatures. It should be pointed out that equation (3.2) does not account for thermal reflections from nearby buildings.

3.3 ACCURACY OF TECHNIQUE

3.3.1 Pitched Ventilated Roofs

Several winters ago, the National Bureau of Standards, in cooperation with the Texas Instrument Company, carried out an aerial infrared survey of a three house cluster located in Missouri. The test houses had similar floor plans and identical roof emittances. The ceiling thermal resistance levels were as follows:

Building	Insulation Level
1	R-30
2	R-11
3	R-0

During the survey, the indoor temperatures within the three test houses were maintained at 70°F. An aerial thermogram obtained during this survey is given in figure 3.5.

When that thermogram was taken, the outdoor temperature was 20°F, the sky was clear, and the wind speed varied between 5 to 7 mph. Note that the uninsulated roof of building 3 appears lighter (depicting higher heat loss) than the other two buildings. Also, note that it is difficult to distinguish the different insulation levels in buildings 1 and 2. These results indicate that, when aerial infrared surveys are performed under optimum (clear sky and low wind) conditions, uninsulated roofs can be distinguished from insulated roofs, provided that the roofs are exposed to the same microclimate and have the same emittance. When aerial infrared surveys are carried out for a large group of houses, typical variations in roof emittances and variations in local wind speed and local outdoor temperatures throughout the macroclimate cause differences in the apparent radiance temperature of roofs, which may frequently mask out those differences due to variations in ceiling thermal resistance.

3.3.2 Low-Slope Built-Up Roofs

In the case of low-slope built-up roofs, variations in roof resistance cause differences in apparent radiance temperature among the roofs displayed in an aerial infrared photograph, which are approximately a factor of three greater than those for pitched ventilated roofs. Variations in roof emittance and variations in local wind speed and local outdoor temperature throughout the macroclimate produce differences in radiance temperature which are larger than those between built-up roofs having 2 and 4 inches of insulation. Therefore, there

Figure 3.5 Aerial thermogram of three test houses

is a good chance that built-up roofs which have little or no roof insulation will be displayed in a lighter gray tone than more insulated built-up roofs included in an aerial infrared thermogram. However, if all the built-up roofs displayed in an aerial infrared thermogram are well insulated, then variations in other parameters such as roof emittance, local wind speed, and local outdoor temperature may also cause particular roofs to appear warmer than other roofs, which may be incorrectly interpreted as the absence of roof insulation without knowledge from ground inspections. The field measurements of Goldstein [5] have shown such effects.

The aerial infrared techique has been shown to be very effective in locating regions of individual low-slope built-up roofs that have defective roof insulation [6, 7]. These regions will show up as "hot spots" in the radiance temperature map. A common problem with built-up roofs is that the exterior membrane becomes ruptured, permitting water to penetrate the roof system and wet the insulation. Regions having wet insulation will conduct more heat and will appear warmer than regions having dry insulation. The merit of such a survey technique is that defective regions can be located, permitting local repairs to be carried out instead of replacing the whole roof system.

3.4 GUIDELINES FOR CARRYING OUT SURVEYS*

Airborne thermographic surveys should be conducted when the buildings are heated. Building roof surfaces should be clear of water, dew, snow or ice. The outside ambient air temperature at ground level should be at least 40°F below the building interior air temperature, unless the survey is conducted under clear-sky conditions. In this case, a temperature difference of 30°F can be used. In all cases, however, it is preferable that the outside ambient air temperature not exceed 45°F.

The survey should be conducted at least 4 hours after sunset. The sky conditions should be homogeneous, either clear or solid overcast, to permit uniform radiation exchange to occur. The wind speed should be less than 15 mph measured at the nearest weather station. It is desirable that a conventional aerial photograph be taken during daylight hours of the same scene displayed in the thermal image. The formation of dew or frost on a roof may change its emittance, and the phase change which occurs releases latent heat to the roof which increases its surface temperature. Both of these effects may substantially change the apparent radiance temperature of a roof. Thus it is recommended that aerial infrared surveys be carried out under conditions without dew or frost formation.

The mathematical model for aerial infrared surveys was used to investigate the depression in surface temperature for a roof due to radiation exchange with a clear night sky (see figure 3.6). For the analysis, a pitched ventilated roof having R-30 ceiling insulation was used, since the depression in surface temperature would be greater for this roof than for roofs having less insulation. Dew or frost would form on this roof before it would form on roofs having less thermal insulation. A criterion for precluding the formation of dew or frost

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* Most of this information was obtained from ref. [8].

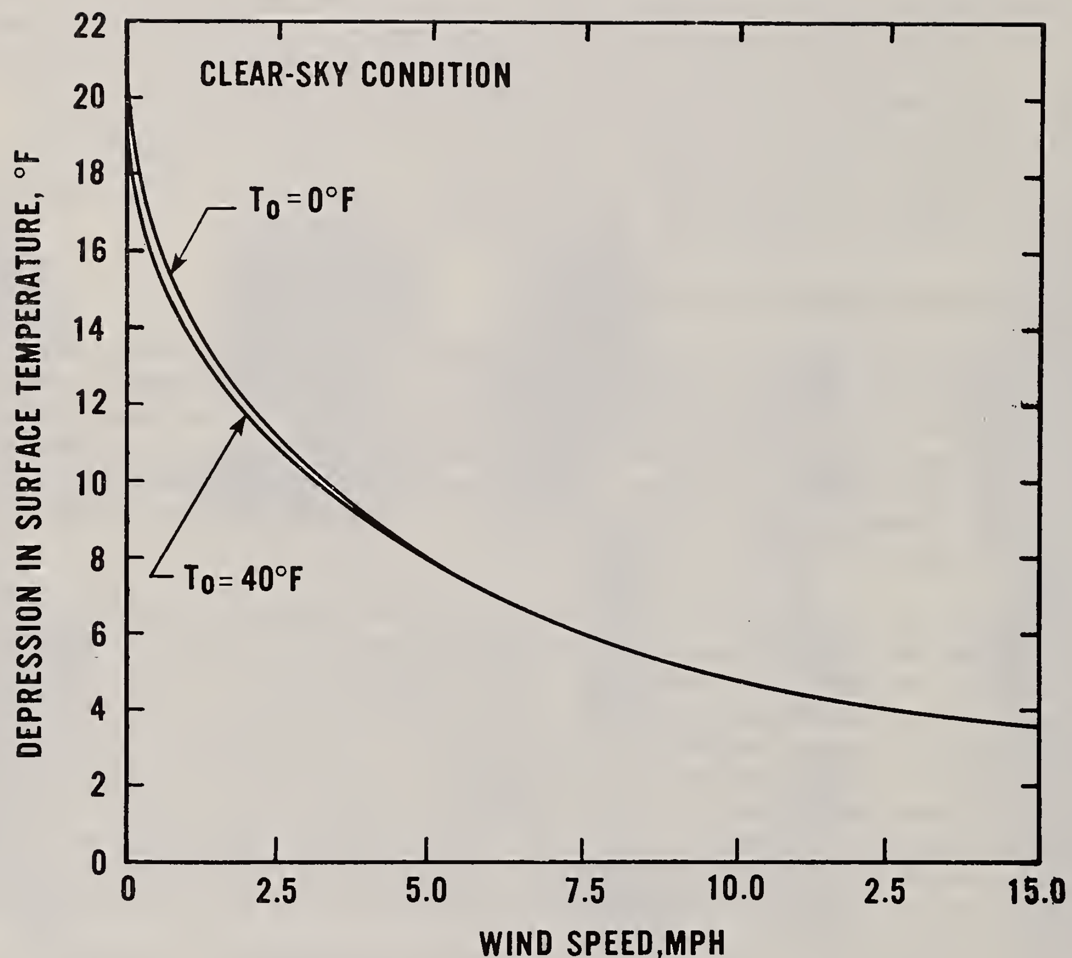

Figure 3.6 Depression in surface temperature on a built-up roof having 4 inches of insulation as a function of wind speed

would be that the dew-point spread (difference between the dry-bulb and dew-point temperatures) of the outdoor air should be larger than the surface temperature depression from that of the outdoor air.

To illustrate the use of figure 3.6, consider the following example: An aerial infrared survey is carried out at an outdoor temperature of 20°F and a relative humidity of 75 percent. The dewpoint temperature corresponding to this psychrometric condition is 14°F, giving a dew-point spread of 6°F. From figure 3.6, the depression in the surface temperature for wind speeds less than 7 mph is greater than 6°F. Therefore, if this aerial infrared survey is to be performed without dew or frost formation on a built-up roof, then the local outdoor wind speed should be greater than 7 mph.

The following data should be recorded during an aerial infrared survey:

1. Date of survey
2. Time of survey
3. Outdoor ground-level temperature
4. Wind speed at ground level
5. Sky conditions (i.e., clear, solid overcast, etc.)
6. Flight line location and orientation
7. Approximate ground speed and altitude of aircraft
8. Site conditions (i.e., foliage, roofs having low emittance, etc.)

3.5 EQUIPMENT SPECIFICATIONS

The spectral response of the detectors used in airborne infrared imaging scanners should be within the spectral region 2.0 to 14.0 microns. However, for most applications the 8.0 to 14.0 micron subregion is preferred since it is optimal as an atmospheric transmission window for most measurement conditions.

The spatial resolution of the airborne infrared scanner is expressed as the object plane resolution, which is a function of the instantaneous field of view and the altitude above the roof surfaces being surveyed; it is also referred to as the ground resolution (expressed in terms of the side of a square scanning spot). The object plane resolution at the flight path nadir should not exceed a 3-foot scanning spot.

The usable field-of-view for airborne infrared imaging scanners should be no larger than 90°. Devices with wider fields of view or scan angles may be used, but the actual usable data for thermographic assessment shall be no greater than ± 45° with respect to the flight path nadir.

It is desirable that the line scanner incorporate two internal blackbody reference sources, so that the range in radiance temperature displayed in the thermal image is known.

Automatic-gain systems are not recommended. Manual gain adjustments for signal amplification are necessary to preclude changes in background component temperature conditions from masking building radiance characteristics. Scanners should employ a method of displaying the scanner video signal or thermal map to the operator during data collection to facilitate proper settings of the instrument controls. Data may be recorded directly on hard copy film or on magnetic tape, disc, or on other media in analog or digital form for subsequent processing into hard copy thermograms.

Scanners should be operated within an aircraft speed and altitude envelope to provide contiguous line scanning or overscanning of the building roof surfaces. The thermal image should not be significantly degraded as a result of aircraft vibration, roll, or other unwanted motions.

Required instrument sensitivities for an aerial line scanner system to distinguish an uninsulated built-up roof from one having 2 inches of perlite insulation are given in table 3.1. Note that as the ground-level temperature increases and as the wind speed increases, the instrument sensitivity must be increased (minimum resolvable temperature difference must be reduced) to permit these insulation levels to be distinguished.

Table 3.1 Required MRTD to Permit an Uninsulated Built-Up Roof to be Distinguished from One Having 2 Inches of Perlite Insulation.

Exterior	Wind Speed		
Temperature	0 mph	7.5 mph	15 mph
0°F	7.5°F	2.6°F	1.6°F
20°F	6.6°F	2.2°F	1.3°F
40°F	5.0°F	1.6°F	0.9°F

Required instrumentation sensitivities for pitched ventilated roofs are summarized in table 3.2. Here the minimum resolvable temperature differences will permit an uninsulated pitched ventilated roof to be distinguished from one having R-11 ceiling insulation. Note that the minimum resolvable temperature differences are less than 0.5°F at wind speeds of 15 mph.

Table 3.2 Required MRTD to Permit an Uninsulated Pitched Ventilated Roof to be Distinguished from One Having R-11 Ceiling Insulation

Exterior	Wind Speed		
Temperature	0 mph	7.5 mph	15 mph
0°F	2.9°F	0.8°F	0.5°F
20°F	2.4°F	0.7°F	0.4°F
40°F	1.7°F	0.5°F	0.3°F

3.6 INTERPRETATION OF AERIAL THERMOGRAPHIC DATA

The general principles used for the interpretation of ground-based thermographic data always apply to interpretation of aerial thermographic data. However, more care should be taken before conclusions from air inspections are drawn [9-10] from aerial thermographic data since the aerial survey thermograms record emitted and reflected radiation and tonal differences are a function of object temperature, emissivity and the surroundings. The interpreter must have knowledge about the particular structure and know the overflight conditions, primarily aircraft altitude, time-of-night of data collection and the environmental conditions prevailing at the time of data collection and the roof conditions, (snowcovered, dry, wet). The tonal differences in an aerial thermogram are relative, and therefore only comparisons of buildings in close proximity should be made. Analyses should be restricted to only the roof of the building.

3.7 PREVIOUS USE, AVAILABILITY AND COSTS

Aerial infrared thermography has been widely used by utility companies, municipalities, or institutions which have large numbers of buildings in close proximity, which they want to inspect. There are approximately eight firms offering this service in the United States [11]. Aerial infrared equipment is manufacturered by about five companies and costs from $100,000 to $250,000. The cost of aerial surveys start at about $5,000 (and range upward) depending on the number of buildings to be examined.

3.8 PROGRAM APPLICATION

Aerial infrared surveys are most suitable for the inspection of large built-up roof areas. They can readily detect areas of moisture damage on areas of insufficient insulation, and aid in the performance of ground-based inspections. In large facilities they are useful for inspecting underground distribution systems. For the evaluation of the building envelope, aerial infrared surveys are restricted to inspection of flat roofs.

3.9 TRAINING REQUIREMENTS

Aerial infrared thermography should only be undertaken by specially trained technical personnel. The staff training requirements are similar to those of level 2 in the Canadian training program. The interpretation of aerial thermograms requires a training equivalent to level 3 (see Section 2.8).

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4. AIR INFILTRATION MEASUREMENT METHODS

4.1 SUMMARY

Excessive air leakage in a building is indicative of, and may serve as a primary diagnostic tool for determining construction flaws. Measurements of the air leakage characteristics of a building provide data to determine the four primary factors of: (a) the natural air leakage rates occurring in the structure under various climatic conditions and use patterns; (b) tightness of the building compared with other buildings and with itself after corrective measures have been completed; (c) location of the leakage paths in the structure; and (d) the magnitude of each air leakage path [1]. Air leakage is the uncontrolled entry of air from outdoors. Direct measurements under natural conditions can be accomplished by "labeling" indoor air with a gas not normally found in either outdoor or indoor air, such as sulfur hexafluoride (SF_6) [2,3], or by labeling it, in great excess, with a normal component such as carbon dioxide (CO_2) [4-6], or even by measuring the excess concentration indoors over outdoors of a naturally produced component (CO_2, CO or radon). Such substances are called tracer gases. Results obtained by this method are not meaningful, nor useful for comparison with other buildings or with the same building at different times, unless they consist of long-term average results which encompass many different weather conditions, or the indoor and outdoor temperatures, wind speed (and perhaps less important for many buildings the wind direction) are specified.

Another purpose of air leakage tests is to determine whether overall building ventilation is adequate. There are numerous complaints in office buildings of symptoms related to an insufficiently clean air supply [7,8], for example, headaches, nausea, fatigue, respiratory symptoms, and feelings of stuffiness. These complaints may be due to excessive concentrations of CO, smoke, formaldehyde or other contaminants, or to excessive relative humidity, heat or insufficient air movement. Building ventilation rates are often specified in order to reduce the potential for indoor contamination at 5 ℓ/sec per person or greater [9,10]. Failure to achieve the specified rates indicates a potential for employee complaints of symptoms and of contamination by such pollutants as radon "daughters" (decay products) which cause no complaints. Naturally, overall leakage rates are not the whole story; ventilation might be more adequate in some parts of a building than in others and insufficient local air movement might occur even when total ventilation is adequate [11,12]. However, an excessively low air exchange rate is considered to be prima facie evidence of poor air quality. Tracer gas methods are the preferred means of determining whether ventilation is adequate because it is very difficult to relate envelope permeability measurements to naturally induced pressure differences.

Various air infiltration measurement techniques using tracer gases are classified as: tracer decay, constant concentration, and constant flow methods. The first method requires varying degrees of automation, the latter two methods are primarily automated. Sulfur hexafluoride (SF_6) concentration measurements will be considered in detail because it is the most commonly used tracer gas and the theory and data analysis is common to all.

4.2 DESCRIPTION OF EQUIPMENT--ALL TRACER GAS METHODS

4.2.1 Tracer Gases

Many gases have been used for tracer gas measurements; table 4.1 lists some of them and their important properties [13]. According to Honma [14], tracer gases should have the following attributes:

1. The content of the gas in ordinary air must be relatively small (see table 4.2), and there must be no source of the same gas in the building concerned.
2. It must be possible for the low concentration to be accurately assessed and detected.
3. The density of the gas must be as near as possible to that of air.
4. The gas must not react with the constituents of air.
5. The gas must not react with, or be adsorbed onto, the surfaces of walls, furniture, clothes, etc.
6. The gas must not be harmful to the human body.
7. The gas must not be flammable.
8. The gas must be easy to handle, easily available and inexpensive.

In addition, Hunt suggests that the analytical method for data analysis should be readily available and lend itself to automation [2].

Sulfur hexafluoride has recently become the most widely used tracer gas because it satisfies all of Honma's and Hunt's criteria except for its high density compared to air. It is the only gas listed in table 4.2 whose concentration can be measured in the ppb range; the others must be present at concentrations in at least the ppm range or even higher. Therefore a small tank of SF_6 will suffice to measure a large building, whereas several large tanks of other gases may be required. Table 4.3 shows that although SF_6 is relatively expensive per unit volume, the total cost per building is among the lowest of all tracer gases because of the extremely small volume required [3]. A point that requires care, however, is that a small leak from an SF_6 tank could affect the measured infiltration rate; this is unlikely to occur when other gases are used. One might expect that because of its high density, SF_6 would settle out of air towards the lower portion of a room, where the detector is located, and give lower apparent infiltration rates than a lighter gas. Similarly, a very light gas like helium (He) might be expected to rise towards the ceiling, away from the detector, and yield spuriously high infiltration rates. In practice, these problems have has not been found to occur. Where gas-dependent differences in infiltration rates were found, a physical cause, unrelated to molecular weight, could be determined or the difference in rate was small. Howard [15] reported higher apparent infiltration rates with hydrogen (H_2) than with nitrous oxide (N_2O) in buildings with bare gypsum walls, but obtained similar rates with the two gases in buildings with less porous walls, such as concrete or painted gypsum. Hunt and Burch [16] double-labeled air inside a townhouse having gypsum board surfaces with SF_6 and He, two inert gases with a molecular weight ratio of 36/1. Helium did not disappear faster than SF_6; the opposite occurred, but the difference in infiltration was only 17 percent. Similarly, Grimsrud et al., [17] obtained infiltration rates with SF_6 which were 10 percent greater than those obtained with N_2O and methane (CH_4).

Table 4.1 Gases and Techniques for Tracer Dilution Method [17]

Tracer	Measuring Apparatus	Maximum Allowable Concentration, in Air (vol/vol)	Minimum Detectable Concentration, ppm	Toxicology [43]	Chemical Inertness	Comments [42]	Density Compared to dry air
Hydrogen	Katharometer [43]	4% (lower explosive limit)	200	nontoxic	extremely reactive in presence of oxygen and heat or flame	flammable or explosive in presence of oxygen and heat or flame	0.07
Helium	Katharometer [44,45]		300	nontoxic	nonreactive	nonreactive	0.14
Carbon monoxide	infrared absorption; heat of absorption measurement [45], gas chromatograph followed by reduction to methane and measurement with flame ionization detector [46]	50 ppm	5 0.4	combines with hemoglobin to produce asphyxia	can be dangerous when exposed to open flame	can also react with oxygen in air in sufficient concentration: may explode when when exposed to open flame	1.0
Carbon dioxide	infrared absorption [47]; gas chromatograph with thermal conductivity detector	5000 ppm	1 70	nontoxic	very soluble in water		1.5
Sulfur hexafluoride	electron capture [34,34,48] gas chromatograph	1000 ppm	0.000002	nontoxic	chemically inert when pure	When heated to decomposition (550°C), toxic byproducts may be formed	4.9
Nitrous oxide	infrared [49] absorption	25 ppm [50]	1	nontoxic	very soluble in water	can form explosive mixtures in air	1.5
Ethane	flame ionization [51] detector [72] gas chromatograph with flame ionization detector	3% (lower explosive limit)	5	nontoxic	will burn when exposed to flame	may explode in presence of oxygen and heat or flame	1.0
Methane	infrared absorption [52]	5% (lower explosive limit)	5	nontoxic	will burn when exposed to flame	may explode in presence of oxygen and heat or flame	0.53

Table 4.2 Atmospheric Constituents [3]

Compound	Average Tropospheric Background Concentrations, ppm	Typical Indoor and Urban Ambient Concentrations, ppm	Anthropogenic Sources
H_2	0.5	0.5	...
He	5.2	5.2	...
CO	0.1	5 to 50	combustion
CO_2	320	30 to 5000	combustion
N_2O	0.3	0.3 to several ppm	combustion
CH_3CH_3	1.5×10^{-3}	0.1	incomplete combustion
CH_4	1.5	2 to 5	incomplete combustion
SF_6	10^{-8}	$<10^{-5}$	telephone switching stations

Table 4.3 Relative Gas Cost for Tracer Dilution Study Taking Account of Detectability [3][a]

Gas	Gas Volume Per Dollar (m^3)	Maximum Volume Measurable Per Dollar Spent on Tracer Gas (m^3)
He	0.08	300
CO_2	1.5	1.5×10^6
CO	0.16	1.5×10^5
CH_3CH_3	0.37	30,000
N_2O	0.34	3×10^5
SF_6	0.06	3×10^{10}

[a] Gas Costs figured on June 1977 prices on West Coast of United States.

Bassett et al., [18] compared SF_6, CO_2 and direct flow (induced controlled air exchange) measurements in 2 rooms, 2 houses and a school building in a careful study that conclusively demonstrated that for practical purposes the three methods give interchangeable results. Air was exhausted from the test spaces by fans. Agreement between gases and flow measurements, or between the two gases, was nearly always at the 95 percent confidence level; any disagreement was only a little beyond the expected experimental error. The only significant difference noted was that in one sheltered room used to study the effects of low flow rates, both tracer gases yielded an air exchange rate of 0.13 h^{-1}. The authors attributed this effect to pressure differences induced by the air handling circulation fan.

4.2.2 Sulfur Hexafluoride Measurements

Some details of performing measurements using SF_6 are described. Before starting any measurements it is necessary that the detector be brought to a stable condition. Also, it is important to calibrate the apparatus to ensure that operation is in the linear range. A linear response together with a sufficiently high standing current (corresponding to a potential of 70 V or higher) indicate proper detector operation. The detector should frequently be cleaned with ethanol or acetone, and the column should occasionally be cleaned by passing air heated to 100°C through it.

Sufficient SF_6 is injected to give a final concentration of about 20 to 50 ppb, depending on the detector. Sampling is done at various times after mixing is completed. Sulfur hexafluoride concentration is determined by a gas chromatography-electron capture-detector unit. The unit pumps air through an aluminum oxide column that separates SF_6 from oxygen (O_2), which also captures electrons; O_2 is eluted first. The gases then pass through a detector containing a radioactive source of electrons, either tritium (H_3) or nickel (Ni_{63}). The decrease in the standing current established by the source is measured and converted into arbitrary concentration units. The column is flushed with argon (Ar) or nitrogen (N_2) between samples, depending on the type of detector.

The chromatography-detector unit is compact and simple to operate. It costs approximately $6000 to $8000. It is portable, but tanks of SF_6 and Ar or N_2 must also be transported along with it. An attachment can be made available so that up to ten sites may be automatically sampled almost simultaneously. This sampling procedure is in contrast to other types of detectors, such as infrared absorption spectrometers, which may be operated in a truly continuous mode. For such detectors, no elaborate automation schemes are necessary for continuous operation, unlike that for SF_6 detectors.

4.3 THEORY

4.3.1 All Tracer Gas Methods

There are several ways of using tracer gas to measure infiltration rates [9]: (1) a single injection followed by tracer gas concentration decay; (2) continuous injection at a constant rate; and (3) frequent injections to try to maintain constant concentration. All of these methods have shortcomings but the first method is the most widely used and is undoubtedly the simplest. All three approaches are based on mass balance; that is, all the tracer gas released into the building must be accounted for, so whatever is not in the building must have leaked out. It is assumed that tracer gas mixes thoroughly and instantaneously with air.

The parameters related to the infiltration rate are the indoor and outdoor temperature difference and the wind speed. The simplest equation, with those parameters as independent variables, can be expressed as

$$I = a + b \cdot \Delta T + c \cdot w \tag{4.1}$$

where

- I = air exchange rate, h^{-1}
- ΔT = indoor-outdoor temperature difference, °K
- w = wind speed, m/s.

While the relationship assumed may not be physically correct [19], it has been found to be as accurate as more complicated models for houses [20]. More complicated equations, for example, taking into account both shielding by nearby buildings and wind direction, are probably required for tall buildings. The best known equations of Tamura and Shaw equations [21,22] require knowledge of air leakage characteristics of building components, which are determined by fan pressurization tests discussed in Chapter 5. Indoor-outdoor temperature differences and winds are the sources of the indoor-outdoor pressure differences that cause air infiltration. There is little air leakage during mild weather even in poorly constructed buildings. Conversely, there may be a great deal of air leakage during heavy wind conditions in even well constructed buildings. Not all air leakage paths are equally detectable by air leakage measurements; under low wind conditions, where temperature difference induced leakage predominates (stack or chimney effect), most of the leakage may be concentrated in openings relatively far from the neutral pressure height (that height at which net indoor-outdoor pressure difference vanishes). The stack effect arises because the density gradient of air is steeper at higher than at lower temperatures, in winter it is therefore greater indoors. The indoor-outdoor pressure difference increases with height, i.e., becomes more marked the taller the building. Under wind induced infiltration, of course, most of the leakage occurs in windward and leeward faces of the building. Therefore, any defective construction at approximately midheight on the walls not facing into prevailing winds can easily be overlooked by tracer gas tests.

The mass balance equation is:

$$V \cdot C(t) + q \cdot C(t) = F(t) \tag{4.2}$$

where:

- V = volume (m^3)
- C = tracer gas concentration (g/m^3)

q = air infiltration rate (m^3/h)
F = tracer gas flow rate (g/h)
t = time (h).

A useful quantity, the air exchange rate, is related to the infiltration rate by:

$$I = q/V \tag{4.3}$$

where:

I = air exchange rate (h^{-1})

The term "infiltration rate" is also sometimes used for I.

The solution of equation 4.2 is given by:

$$C(t) = C_o e^{-It} + e^{-It} \int_o^t e^{Iu} F(u)/V \, du \tag{4.4}$$

where:

C_o = concentration at zero time (g/m^3)

Usually F is constant; in this case:

$$C(t) = C_o e^{-It} + (1 - e^{-It}) (F/q) \tag{4.5}$$

The "volume" used above is, strictly speaking, the "effective" volume [23,24] and not necessarily the physical volume of the space being measured, which may be either greater or smaller. There are several reasons for the difference: furnishings may occupy space, the air with which the tracer gas is well mixed may not fill the entire space (in contradiction to the assumption underlying the entire treatment), or the tracer gas may enter an adjoining space (storage areas, basement or attic). Lawrence Berkeley Laboratory (LBL) researchers [23,24] claim that the effective volume may differ from the physical volume by up to 50 percent; however, when the divergence is so large the reasons for the discrepancy can probably be readily determined. Usually, the difference is probably less than 25 percent, in which case it is of the same order of magnitude as the scatter in the infiltration rate data caused by changing wind speeds, temperature differences, occupant effects and poor mixing.

Buildings--especially large ones--have uniform infiltration rates only in special cases. To treat tracer gas measurements in the greatest generality, multisector buildings must be assumed. The immediately following subsection deals with such buildings. The theoretical discussion presented above will be expanded below, in the descriptions of tracer decay, constant concentration and constant flow techniques.

Multisector Infiltration Measurements

If a building is divided into distinct sectors which exchange air incompletely among one another, a multisector method for measuring infiltration might be required. For some purposes (e.g., energy conservation and fresh air supply) only the outdoor contribution to building air exchange rates is important, while for other applications (e.g., migration of smoke and contaminants from one place to another) sector-to-sector air exchange rates are also important. A sector may be part of a room [11,12], especially when air supply ducts are poorly situated; it may be a room itself [14] (as in a building with no mechanical air circulation systems); it may be a collection of rooms (e.g., in a building with air supply units that serve different floors or sections of the building [25]; or a single-family house with an attic or basement [26,27]); or it may be the entire building. In the latter case, and in the case of a building having sectors with little communication among each other, multisector techniques are unnecessary.

Multisector techniques may involve either tracer decay, constant concentration or constant flow techniques. The tracer method is the simplest technically but the constant concentration method is by far the simplest to analyze, provided only external air exchange rates are of interest. There appears to be no really adequate method for measuring sector-to-sector air flows unless the number of sectors being considered at any one time is small. Otherwise too much equipment is required. Air-bag sampling provides a technique to determine concentrations across several sectors; the sampling can be performed simultaneously or successively to obtain time average results. Sampling of different sectors at different times provides measurements that may not be consistent since transient disturbances can cause changes in concentrations.

Another method for measuring air flows in multisector buildings is to simultaneously use two or more different tracer gases, one in each sector, and to measure all of the gases in each sector. Again, this approach is only practical for a small number of sectors at a time. Etheridge [26] reported on the use of 2 tracer gases, CO_2 and N_2O, simultaneously in a constant concentration mode to measure the infiltration rate of an entire house and its loft.

The equation for the multisector case (actually, a set of simultaneous equations) is similar to the single-sector equation 4.2, with the addition of terms for exchanges among sectors. In the constant-concentration case, those terms disappear and the treatment is reduced to the single-chamber case. In both the tracer decay and constant flow methods, conditions can be designed to reduce, but not eliminate, the size of these terms relative to indoor-outdoor air exchange rates.

The equations are given by [14,28]:

$$V_i C_i = \sum_{j=1}^{N} q_{ij} (C_j - C_i) - q_{io} C_i + F_i \qquad (4.6)$$

where:

subscript "i" refers to the i th sector, i = 1,...,N
subscript "o" refers to outdoors
q_{ij} = air flow rate from sector j to sector i.

The volume and infiltration rate expressions are

$$V = \Sigma V_i$$
$$I = \Sigma q_{io}/V \qquad (4.7)$$

As usual, C_o is taken to be much smaller than C_i; for many tracer gases, such as SF_6, C_i = 0 and this case is shown in equation 4.6. In many multisector cases, most of the q_{ij} = 0 since many sectors are not adjacent. Now, if the C_i are nearly constant in equation 4.6, the first term on the right is small and equation 4.6 reduces to the single-chamber case. For example, if one ensures that the concentration of gas is more or less constant throughout the building at the start of the experiment by seeding gas appropriately, then the concentrations will remain approximately equal as long as too much time is not allowed to elapse (approximately 1 hour). This procedure is the basis for treating a multifloor house as a single sector in the tracer-decay air-bag method. Of course, by measuring concentrations in the different sectors, one can determine whether or not concentrations are sufficiently close to a constant value throughout the building. In the constant concentration method:

$$C(t) = 0$$
$$C_i = C \text{ for all i except 0 so that:}$$
$$F_i = q_{io}\ C_o \qquad (4.8)$$

and I from (4.7) can readily be determined by summing all of the flows in the building.

4.3.2 The Tracer Decay Method

<u>Summary</u>

The tracer-gas decay method [13] is very versatile and is the simplest of the tracer-gas measurement systems. It can be used for short- and long-term measurements. The measuring equipment may be located on site or the samples may be collected into air bags and analyzed offsite [1]. Injection of gas and measurements of the concentrations can be made manually or automatically to study the dependence of air exchange rates as weather changes over time.

A single injection of tracer gas suffices for each measurement and no complicated apparatus is required to control the concentration or automatically inject gas, although several automated techniques have been developed and are described below. As much time as necessary may be allowed for mixing the tracer gas with air. A fan may be used to thoroughly mix the tracer gas with the air and then be turned off, or the fan may be run throughout the entire measurement procedure. Bassett et al., [18] report that a fan might induce an artificial air flow, but only at very low air exchange rates; 0.13 h^{-1} in their study. It is convenient to inject tracer gas into the building's air handling system, if it has one. In that case, air is sampled at the return air ducts. If the

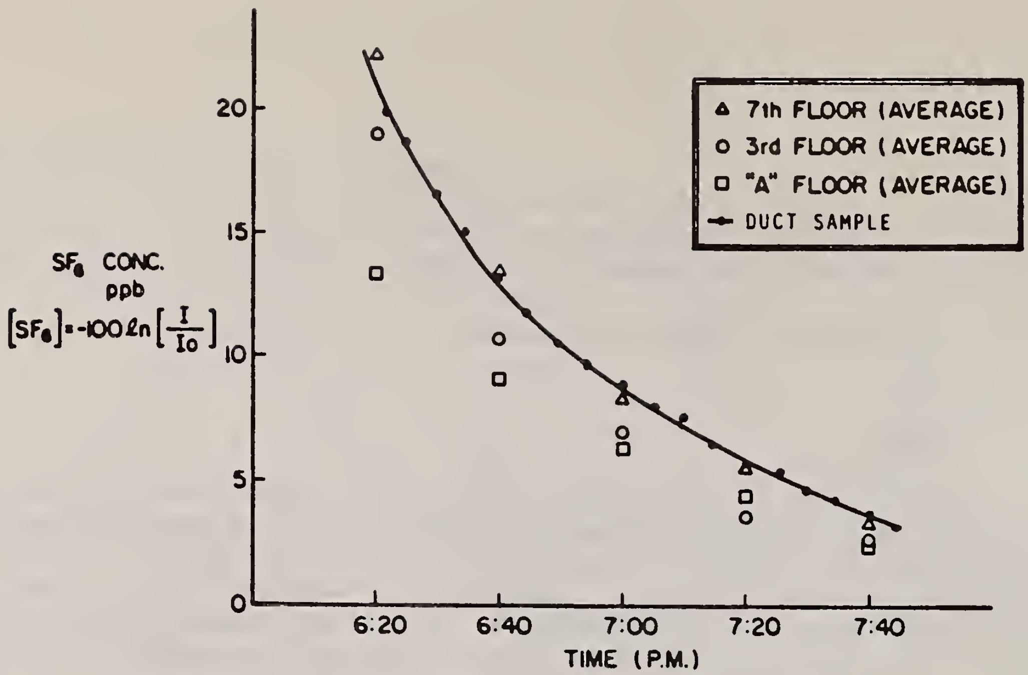

Figure 4.1 Sample of tracer gas decay method data

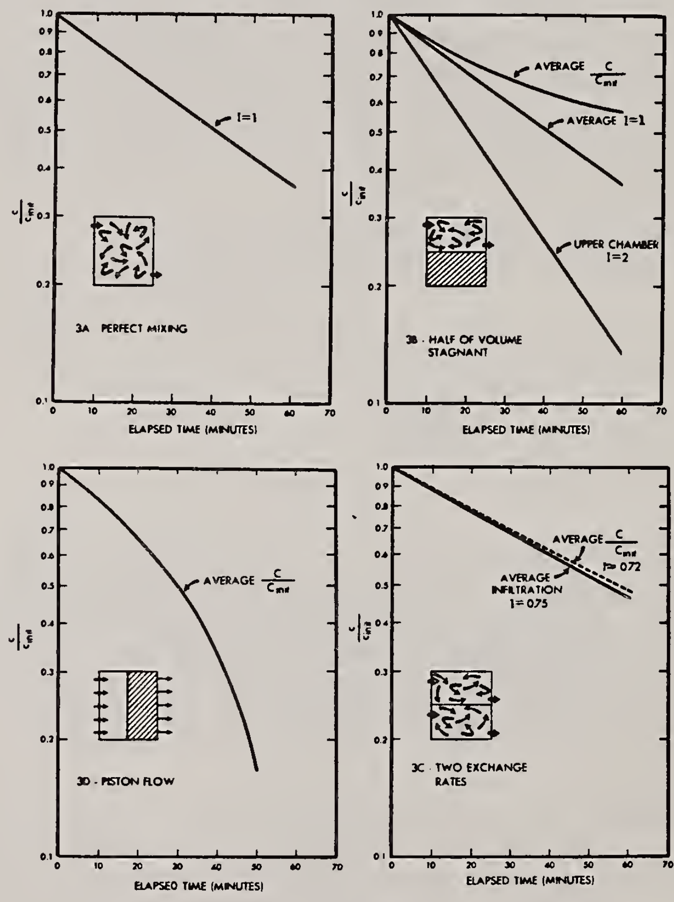

Figure 4.2 Comparison of concentration versus time relationships for four simple models ranging from perfect mixing to complete nonmixing.

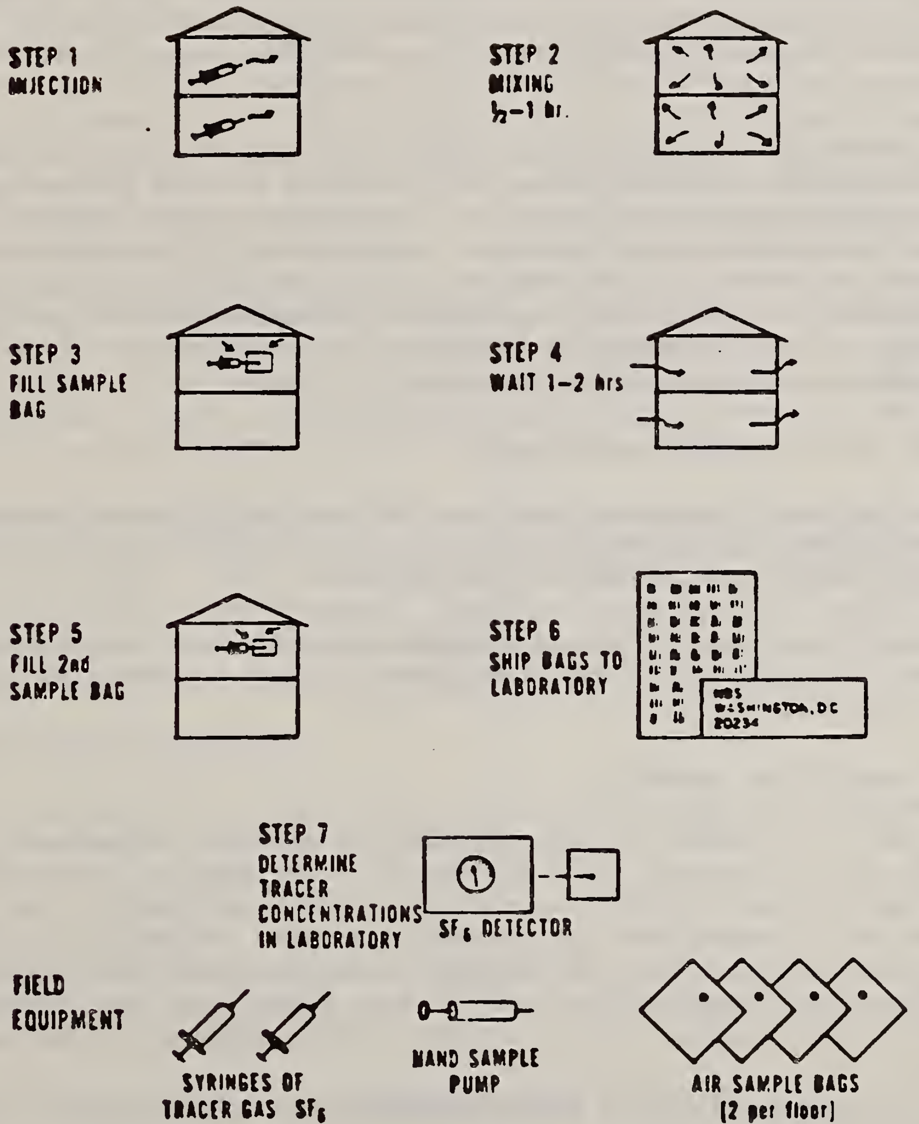

Figure 4.3 Schematic of air sample bag procedure

building is large and/or divided into many rooms (and there is no mechanical air handling system) it may be difficult to obtain a uniform tracer gas concentration throughout the building. Even if a uniform distribution of tracer-gas is accomplished initially, concentrations may decay at different rates in different parts of the building. The measurements will reveal the extent of the non-uniformities; if the divergence in room concentrations is large a multisector method should be used.

The basic tracer decay technique, followed by air-bag and automated variants of air infiltration measurement methods are described below.

Description of Equipment--Basic Tracer Decay Technique

1. Tracer gas monitor. The monitoring instrument should either have been calibrated by the manufacturer or should be calibrated on site. Standard mixtures of at least two different concentrations used in the range of the test should be used.

2. Sampling network. The network consists of tubing, tubing junctions, a pump, and possibly an aspirator. This network is used to draw samples from remote locations within a structure, blend them, and bring the blended sample to a convenient place for analysis. In general, it is best to avoid plasticized tubing such as vinyl, and use copper, stainless steel, or possibly polypropylene or nylon. The experimenter should be aware that surface absorption within the sampling network can be a major source of confusion in any concentration decay measurement.

3. Syringes for injecting tracer gas.

4. Circulating fans. Fans are used to circulate air within a structure and should be capable of circulating air in any direction. The building's air handling system can also serve this purpose.

5. Meteorology stations. A portable meteorology station that records wind speed and direction and outside temperature is required to provide local external conditions.

6. Indoor temperature monitor.

7. Tracer gas. A cylinder or container of gas selected from among those listed in table 4.2 is necessary as a source of tracer gas for the test. The concentrations listed in table 4.2 should never be exceeded. Good experimental practice is to ensure that the maximum allowable concentration of the particular tracer gas is below the maximum by at least a factor of four. The initial tracer gas concentration should never exceed the OSHA time-weighted average for substances included in the latest OSHA-controlled gases list.

Description of Automated Tracer Decay Equipment

Automated air infiltration measuring equipment using the tracer decay method, developed by researchers at the National Bureau of Standards (NBS) and Princeton University, has been used in the United States since 1974. These systems use an electron capture gas chromatograph which measures SF_6 in the ppb range, as previously described [29-36]. The latest version of this equipment consists of an S-100 bus microcomputer with two 5 1/4 inch dual-sided floppy disc drives, a real-time clock, a CRT terminal, an electron-capture detector gas chromatograph, a 10-port sampling manifold, 5 injection units, and interfaces for both analogue and digital data [33]. This system costs approximately $20,000 and must be specially assembled. This system has been used in air infiltration studies in large buildings.

Figure 4.4 shows a schematic of a 26-story, 450,000-m^3 office building (from another on-going project in which air infiltration measurements are currently being taken) where two systems are being used. One system measures the air infiltration rates in the tower (floors 3 to 26) portion of the building and is located in the mechanical equipment room of the 26th floor. The sampling network for this system is shown in figure 4.5 and 4.6. This system includes a local weather station on the roof, and thermistors to measure interior temperatures on each of the sampled floors. The second system is located in the lower mechanical equipment room and monitors the four lower zones of the building and an adjacent four-story Plaza Building. A typical trace of data from the tower is shown in figure 4.7. Injection occurs 10 minutes before each hour. Note that the tracer gas is fairly well mixed after 20 minutes. Figure 4.8 shows the average daily air infiltration rates for April and May, 1981. Data are usually not collected on weekends or holidays, when the building HVAC systems are not operating. Such air infiltration measuring systems have operated 18 days without attention and for 30 days without data loss.

Hartmann and Muhlebach [34] of the Swiss Federal Laboratories for Material Testing and Research designed a tracer-decay system with a controller that can handle up to six rooms. Data are analyzed off line on a central computer. The system also measures air temperature, humidity, wind velocity and direction, and pressure. An infrared analyser (MIRAN) is used to measure the concentration of the tracer gas, N_2O, in the 10 to 20 ppm range.

<u>Theory--Tracer Decay Technique</u>

In the tracer decay method, there is no source of tracer gas once the measurement has begun, equation 4.5 then becomes:

$$C(t) = C_o e^{-It} \tag{4.9}$$

and then solving for the infiltration rate

$$I = (1/t) \ln (C_o/C(t)) \tag{4.10}$$

<u>Measurement Guidelines [13]--Basic Tracer Decay</u>

The basic tracer test is carried out as follows:

Step 1: An amount of tracer gas sufficient to produce a readily detectable response in the gas-measuring instrument is released at one or more points in each sector of the test structure, or into the air handling system. The

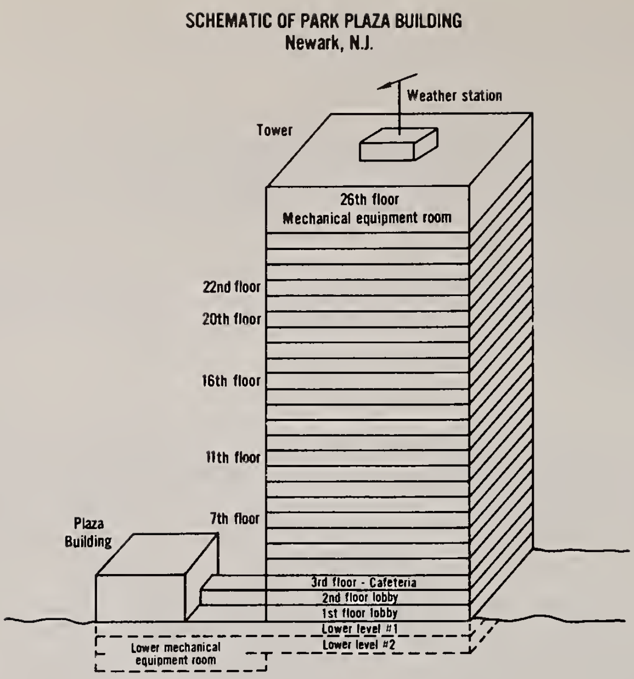

Figure 4.4 Schematic of 26-story Park Plaza Building in Newark, N.J.

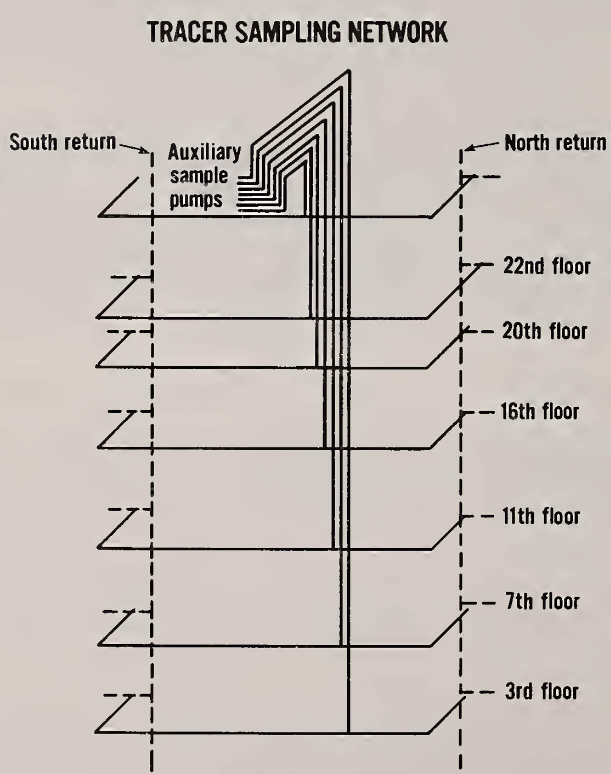

Figure 4.5 Schematic of sampling network for tower of Park Plaza Building

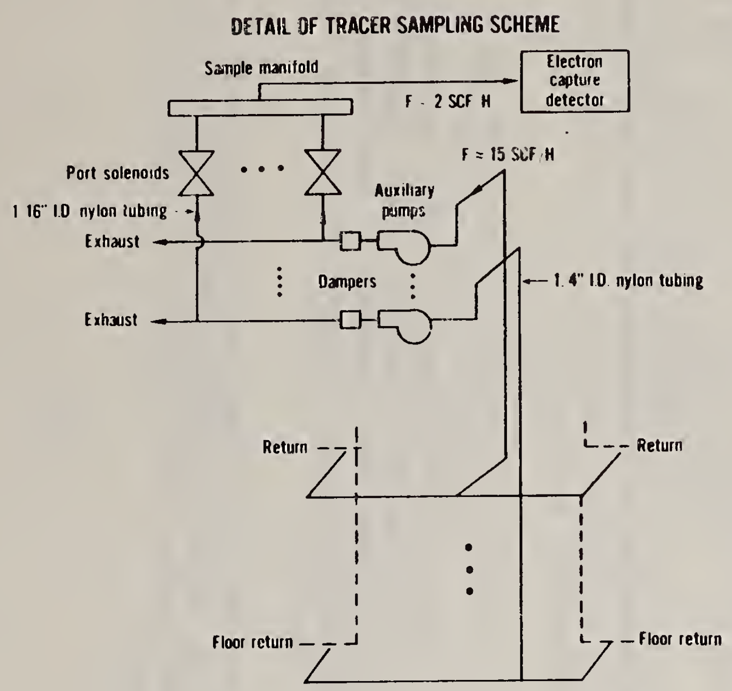

Figure 4.6 Detail of sampling network for tower of Park Plaza Building

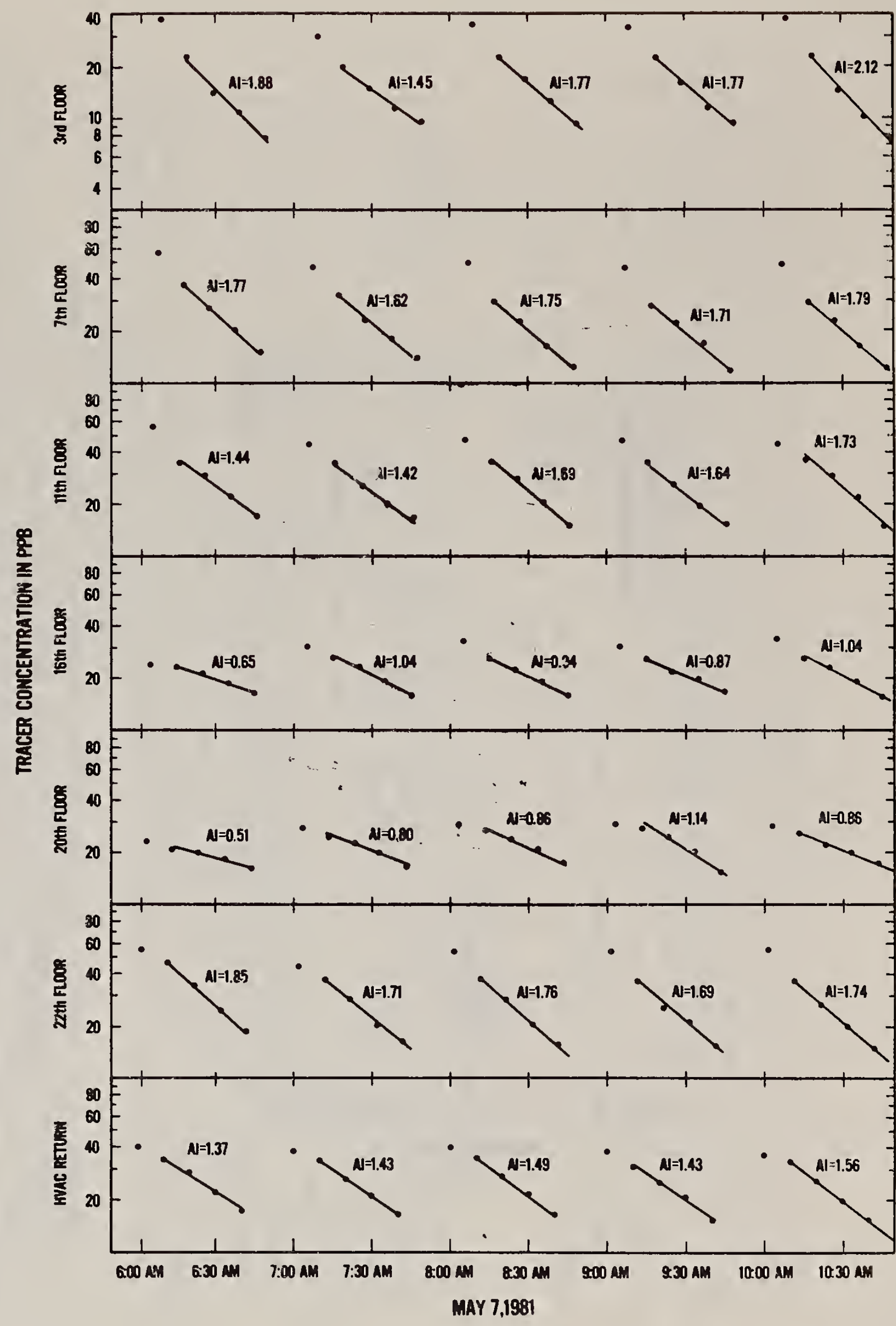

Figure 4.7 Typical sequence of test data from tower of Park Plaza Building

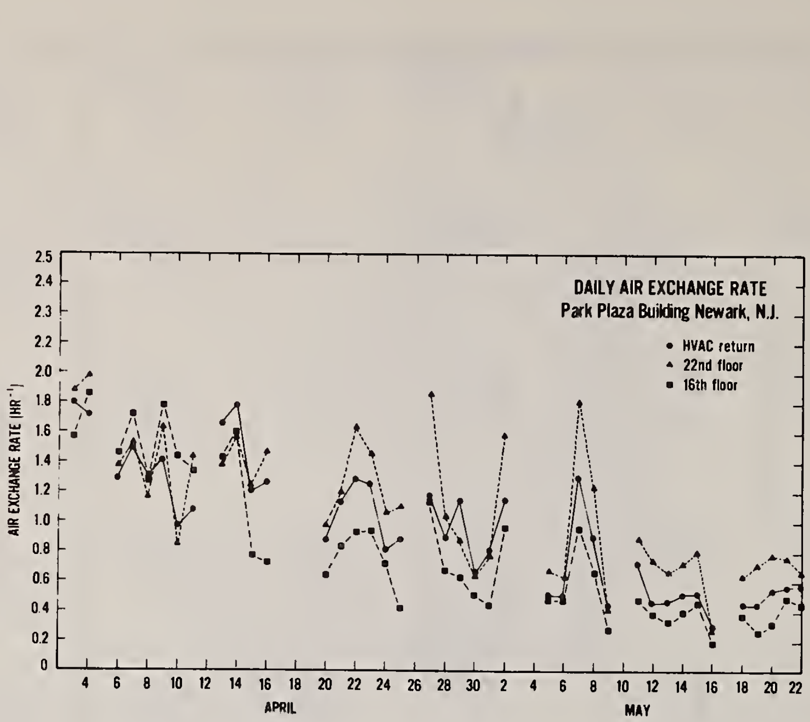

Figure 4.8 Daily average air exchange rates for Park Plaza Building

release site is governed by the location of the air handling system(s) (or mixing fan(s) in a structure with no air-handling system). Tracer gas release can be from a disposable syringe.

In a building with central-heating and air-conditioning system(s), the main fan(s) is (are) operated continuously. Here, tracer gas is introduced into the main supply or return duct(s), preferably in the vicinity of the main fan(s).

Fans are used to circulate the air and mix the gas in a building without central-heating and air-conditioning system(s). Tracer gas is released at one or more points within the structure. Care must be taken not to affect the pressure distribution within the structure.

Step 2: Allow at least 30 minutes for mixing of the tracer gas.

Step 3: Homogeneity of tracer concentrations is tested by sampling at a number of building locations. Monitoring the decay of tracer concentration is begun when concentrations differ by less than 5 percent of the average concentration (measured within the building). In multi-story structures, 2 widely separated samples are required on each floor.

Tracer samples may be measured at a single central location by drawing samples from a number of locations through a common network (multipoint sampling). Alternatively, individual samples (grab samples) at a number of distinct locations should be obtainable.

When multipoint sampling is used, the sensors are to be located at strategic points within the test structure and conducted to the central location. With a single measurement device the sampling network conveys blended air samples to the analyzer; if the dilution rates are different for different rooms or floors the samples drawn by this method yield air leakage rates slightly lower than the true average rate. For example, if one of the rooms (or floors) leaks air at twice the rate of the other room, the result of analysis of the blended samples of the two rooms leads to an air leakage rate estimate about 4 percent lower than the true average rate (see figure 4.2).

The number of sampling intervals and their duration depend on several considerations. generally, an interval should not exceed 2 hours because the air exchange rate may vary too much over longer intervals (unless measurement of the long-term air exchange rate is the objective). Enough tracer gas must remain at the end of the measurement period for detection purposes. The number of sample times should be chosen so that each successive calculated value of I does not change from the previous one by more than 10 percent [35]. Alternatively, one can calculate the standard error of the slope of the regression curve of ln C vs. t (or its correlation coefficient) and continue taking more measurements until these values stabilize sufficiently [32]. For large-scale air-bag sampling, where great precision is not required, a single time interval of about 1 to 2 hours is usually used.

In addition to scatter, another reason several measurements are recommended is to be sure one is operating in the linear response range of the instrument. If there is a consistent trend away from linearity on a log-linear plot of concentration vs. time, either excessive tracer gas may have been injected, or inadequate mixing may be the cause. Hunt and Burch [16] derived relationships as shown in figure 4.2 relating various deviations from linearity to particular mixing problems. The converse is not true; a linear response does not guarantee thorough mixing.

Interpretation of Results--Basic Tracer Decay

Calculate the air infiltration rate as described above or by a finite difference method:

$$I = (t_{i+1} - t_i)^{-1} \ln(C_i/C_{i+1}) \tag{4.11}$$

where subscript "i" denotes the i th interval.

Accuracy of Technique--Basic Tracer Decay Technique

With this method a mean and standard deviation may be computed as follows:

$$\begin{aligned} I &= \Sigma I_i/N \\ S_I &= [(\Sigma I_i^2 - I^2/N)/(N-1)]^{1/2} \end{aligned} \tag{4.12}$$

where:

N = number of sampling intervals

S_I = standard deviation (h^{-1})

The errors involved in tracer gas concentration measurement are approximately 2.5 percent [9]. This error is negligible in comparison to the usual "scatter" caused by wind gusts and to a lesser extent, changing temperatures and furnace cycling.

Air Bag-Sampling Measuring Guidelines [1]

There are several advantages to air-bag sampling. A single detector suffices for any number of measurements. This procedure is useful for a multisector building where a large number of detectors would be prohibitively unwieldy and expensive. The test is performed as described in figure 4.3. Steps 1 and 2, injection and mixing of tracer gas (SF_6), are as described above for the tracer decay method.

Step 3: Fill initial sample bags. After adequate mixing of tracer gas, one fills an initial air sample bag in each sector of the building (while walking around) using a small manually- or battery-powered pump. A convenient air bag size is 5 or 10 liters. The important point is that the air bag must be filled slowly, ensuring that an integrated sample is collected. A hand pump requires about 50 strokes to fill a bag and the electric pump takes about 5 minutes to perform this same function.

Step 4: Decay of tracer gas. Tracer gas concentration requires 1 to 2 hours to decay. During this period the mechanical air-handling systems are operated in the desired mode.

Step 5: Fill final sample bags. The procedure in Step 3 is repeated, obtaining a second sample bag of air for each sector of the building.

Step 6: Ship sample bags to laboratory.

Step 7: The tracer gas concentration is determined as described above for the tracer decay method.

Accuracy of Technique--Air Bag Sampling

In an infiltration test of a mobile home under controlled temperature conditions in the absence of wind, agreement between infiltration rates obtained by air bag and basic tracer gas methods was within 15 percent [35].

Previous Use--Air-Bag Sampling

Infiltration rates of large numbers of buildings can be conveniently measured; Grot and Clark [36] evaluated energy conservation retrofit measures in hundreds of homes using this method. The bags were sent by mail to the laboratory for contents analysis and then reused.

Training Requirements--Air-Bag Sampling

Very little training is required to sample in this way; no highly skilled technicians are needed.

4.3.3 "Constant" Concentration Technique

Summary

In practice, the "constant" concentration method is a special case of the tracer decay method, but with short intervals between automated tracer gas injections. The advantages of this method are that: 1) measurements may be taken over long periods of time; (2) nearly instantaneous responses to changes in weather can be studied [33]; and 3) data analysis is straightforward since gas injection rate is simply proportional to infiltration rate. The disadvantages are as follows. Since mixing is never instantaneous, the system is always responding to a previous, not the current concentration, and the equipment is more complicated than that used for other methods. It is difficult to consider a constant concentration system which is not automated.

Description of Equipment

Several groups have designed automated equipment which frequently monitors tracer gas concentrations and injects an amount required to maintain constant concentration. A variety of gases are used by the groups. These groups include the British Gas Corporation (N_2O and CO_2) [26], the Division of Building Research of the National Research Council of Canada (NRCC) (SF_6) [37], the Institute of Technology in Taastrup, Denmark (N_2O) [38], and the Swedish National Testing Institute (N_2O) [39].

British Gas Corporation Method

The British Gas Corporation automated air infiltration unit [26], called Autovent, is based upon a microprocessor and rapid sample analysis. Gas is released so as to maintain constant concentration in each room of a house. Rooms are read in sequence for 6 seconds each, an injection valve is opened and the duration of injection is recorded. Results are summarized for 30-minute periods. Sampling is accomplished through tubes of equal length. The two most recent concentrations are used to determine the amount of N_2O injected to maintain a constant level of gas prior to the next sampling. The nominal concentration is maintained at 50 ± 2 ppm. Injection takes place for as long as half of the period (up to a maximum of 30 seconds). Each of the injection lines is calibrated prior to the experiment so that the injection rate is suitable for each room. A 4- to 5-fold ratio of maximum to minimum air infiltration rates for each room can be accommodated.

The British Gas Corporation method has been used over a period of almost 2 years with up to twelve rooms measured simultaneously. Six houses have been carefully analyzed with an overall reported accuracy of 10 percent. Etheridge et al., [26] also used this system to measure two different tracer gases simultaneously in order to obtain infiltration rates for an entire house and the loft.

National Research Council of Canada (NRCC) Method

In the NRCC method, concentration is measured every 2 or 2 1/2 minutes. Fixed amounts of SF_6 can then be injected up to 90 times over the next interval, the intervals spaced as closely as 0.9 seconds apart. The same electron capture-gas chromatography unit is used to measure tracer gas concentration as described above for the tracer decay method. Since a level of 15 ppb SF_6 is generally maintained, the amount of tracer gas used during an experiment is very small. At the start of an experiment, it usually takes about 1 hour to reach the desired setpoint level of SF_6.

The major weakness of the apparatus is the operation of the detector. Under heavy usage, the column and the electron capture detector requires considerable maintenance, cleaning and calibration. Zero drift of the detector is a continuing problem. In addition, the switching valve, which uses a spool valve arrangement with O-rings, requires maintanence. Small leaks from the pressurized SF_6 supply, that is normally kept in the house being measured, can yield incorrect air change rates. Comparing NRCC experience with that of other investigators, the maintanence problems cited here suggest that infrared would be preferable to electron capture-gas chromatography equipment if the higher concentrations (50 ppb range) were tolerable.

Kumar et al., [37], in a report on two houses, claim that agreement between constant concentration and tracer decay methods was better than 2 percent. In order to achieve good mixing in these houses, the furnace fan was operated continuously. The reason for the successful use of 2-minute intervals in these houses is that the air exchange rate was stable for almost 2 hours at $0.6\ h^{-1}$.

The NRCC apparatus has been functioning for three years and is now available as a commercially packaged unit [40]. The unit has demonstrated its ability to hold SF_6 concentrations in a house constant to within 4 percent over 15-minute intervals and 2 percent over a one-hour interval. The unit has run 72 hours unattended. To date more than twenty houses have been tested using this equipment.

The Danish Institute of Technology Method

The Danish Institute of Technology automated air infiltration system [38] is also microcomputer-based. There are many similarities between the British Gas Corporation system and the Danish system. Injection of N_2O is essentially continuous. Small (12-cm diameter), fans are located near the N_2O injection port in each room to promote rapid mixing of tracer gas. Ten solenoid valves are used to control injection, and 10 other valves control sampling to the URAS-7N infrared detector. The experimental design also provides a tank of N_2O reference gas at 50 ppm to check periodically the design value of 50 ± 2 ppm N_2O concentrations within the home. Temperature and humidity sensors are added to further increase reading accuracy. The tubing that runs throughout the house has been kept as unobtrusive as possible (only 3 to 4 mm in diameter) since the study emphasizes occupancy effects. Metal tubes are used near door hinges to provide tubing paths, so that door operation is unaffected. The N_2O injection orifices for each room were carefully designed to provide choked flow and were subsequently calibrated. The system can operate for up to six days unattended. Records are maintained on floppy disc, with a viewing screen provided to check on site operation. Also a statistical package can be used on site to provide further system checks.

The Danish Institute of Technology research effort is focused on the effect of such occupant activities as opening and closing of windows and doors on air exchange rates in each of ten rooms in a house south of Copenhagen.

Greater than 10-fold variations in air change rates can be accommodated (from a few tenths to greater than 5 h^{-1}) with an accuracy from 5 to 10 percent.

Swedish National Testing Institute Method

The Swedish National Testing Institute automatic air infiltration measurement method [40] is similar to the Danish one. The short response time of the N_2O analyzer allows collection of a large number of samples per unit time. In the case of field measurements on a variety of buildings, the problem of a 2-hour equipment warmup time for the URAS-7N analyser has been solved by a 12 V/220 V transformer in the instrumentation van. Warmup is accomplished in transit. An alternate MIRAN 101A analyzer requires 10 minutes or less to warm up. The arrangement of the ten tubes to the analyzer allows nine air samples and one fresh air purge. The fresh air must be raised to room temperature to avoid analysis problems. The pumping system transports the samples to the analyzer through 10-m long, 6-mm diameter plastic tubes within the house. When operated from the van, special 25-mm tubing is used to thermally insulate the enclosed nine plastic tubes. Measurements are made at set intervals and used by the microprocessor to calculate air exchange rates for each room.

Theory--"Constant" Concentration Method

The equation that describes the "constant" concentration method is derived from equation 4.2 by setting C(t) = 0, then

$$C(t) = F/q \tag{4.13}$$

In practice, since the mixing of tracer gas takes about 20 minutes, $V \cdot C(t)$ is unequal to zero and the "effective" volume term cannot be eliminated by this technique. This is the reason for placing quotation marks around the term constant.

Because of the time lag the system is always responding to the concentration prevailing minutes before. If the concentration is rapidly changing, either an excessive (or an insufficient) quanitity of tracer gas will be injected. This system response can cause the method to break down as the concentration drifts hopelessly away from the constant value it is set to maintain, according to Condon et al., [30], who suggest the use of a mixing factor to compensate for the time lag. They calculate the mixing factor only for the period immediately after tracer gas is first injected as $C(t) \cdot V/F_o$. It is unclear how this technique can be used in practice.

One of the major advantages of the constant concentration technique over other methods is its effectiveness in dealing with air infiltration in buildings with sectors having separate air supply systems that only partially communicate with each other. (If there were no communication at all, each sector could be separately measured by any available technique.) In practice, the number of sectors must not be excessive since a separate instrumentation system is required for each one, unless air-bag sampling is used.

4.3.4 Constant Flow Technique

Summary

The constant flow technique, like the constant concentration technique, permits continuous measurement of the ventilation rate. Sherman et al., [41] call this system "continuous flow." The instrumentation is simpler, however, as no feedback loops are needed to maintain constant concentration.

The disadvantages are that the infiltration rate may drop considerably from one interval to another (due to changing weather conditions) causing the concentration to rise beyond the detection limit of the detector. A microprocessor can be used to adjust the rate of tracer gas injection in order to avoid the off-scale problem. Measurements can only begin when equilibrium is reached.

In common with the constant concentration method, constant flow methods are nearly always automated.

Description of Equipment--Constant (Continuous) Flow Technique

The continuous flow method was developed at LBL to permit automated measurement of infiltration in a test space at half-hour intervals. This interval was chosen to ensure stability in the the controller feedback loop. This unit originally used N_2O with an infrared analyser but later, due to U.S. exposure limits (see table 4.2), was modified to use SF_6, with an infrared analyser. The system was designed to permit researchers to carefully examine the mechanisms that drive infiltration: weather and mechanical systems. The system is designed around a microcomputer that: (1) controls the injection of tracer gas into the test space; (2) selects the sampling port used during an interval; (3) processes and records weather and system operation data; (4) calculates and records half-hour average infiltration values; and (5) computes a new injection flow rate based upon the previous calculated infiltration rate in order to keep the concentration in the test space within a particular target range. Infiltration rate is calculated using equation 4.5. In practice, equation 4.5 is solved numerically by the microcomputer using a search algorithm that finds the set Q, C_1 and V having maximum likelihood consistent with the measured values of C and F for the time interval.

A useful application of the constant flow technique, which eliminates the problem of exceeding the detection limit of the detector, is the average infiltration monitor (AIM), to permit simple, unattended measurement of the long term infiltration rate of a building. This monitor was developed at LBL [41]. The AIM minimizes both inconvenience to building occupants and the technical skills required to install the system. It consists of two small outwardly identical suitcases: the injector and the sampler. Each case contains a small positive-displacement solenoid pump that is pulsed at a rate controlled by an internal timer. Each pump, connected to a gas sample bag, is either slowly emptied, injecting tracer gas into the space to be tested, or filled, sampling the mixture of tracer gas and room air present in the space. The concentration is determined after the desired interval, which can be a period of days. Using equation 4.13, the average air infiltration rate can be determined from the concentration and from F, which is calculated from the duration of the test and the total volume of injected tracer gas.

Theory--Constant Flow Technique

The equation that governs the constant flow technique is obtained from equation 4.5 by setting $C_o = 0$:

$$C(t) = (1-e^{-It})\, F/q \tag{4.14}$$

Previous Use--Constant Flow Technique

Honma [25] used an electric heating element to release CO_2 at a constant rate, in succession in each room of one apartment at a time, in Swedish tall buildings. He assumed that a room is only affected by other rooms separated at most, one removed from each other. His method is a combination of constant flow and tracer decay because the gas was released for a significant interval and its concentration then permitted to decay. There are no reports of multi-sector measurements beyond the small number of rooms, as performed by Honma.

4.4 PROGRAM RECOMMENDATIONS

The tracer gas technique is extremely useful for the determination of the actual air infiltration rates for large buildings. Except for the most complex multi-sector buildings, the air bag sample method is the easiest to implement and will most likely yield the necessary information needed to assess the air infiltration characteristics of the buildings. The air bag sample technique could be used to easily collect air infiltration data on a large number of federal buildings at a reasonable cost.

If very accurate measurements are needed for legal reasons, for example, certification of air infiltration rates of a new building, or if air bag sampling data cannot be interpreted, then an automated system should be used.

4.5 RESTRICTIONS TO IMPLEMENTATION

There is no general restriction to the use of the tracer gas technique for federal buildings if SF_6 is used as a tracer. For large buildings (greater than 100,000 sq. ft) the other tracers discussed in this chapter are not suitable due to the large quantities of gas required. This test can be performed at all times of the year and times of the day when the air circulation system is operating.

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5. FAN PRESSURIZATION TECHNIQUES

A building may be pressurized by a fan and the air flow rate measured to estimate envelope tightness. At a fixed pressure difference, the smaller the air flow rate, the tighter the envelope. In order to overpower any natural pressure differences, and to obtain measurable air flow rates, large pressure differences are usually induced. For even medium-sized buildings this may require the use of an enormous fan or the simultaneous use of a number of fans. Figure 5.1 shows a fan mounted in a tall building [1]. A way to avoid the necessity for using large fans is to measure isolated wall and roof areas [2]. This step method also yields permeabilities of individual building surface components. To estimate the overall envelope permeability a calculation can be made based upon the assumption that the building as a whole shows permeability similar to the measured ones [1-4]. This procedure is useful in estimating naturally occurring air flow rates from pressurization data.

Figure 5.1 Tall building installation of large fan

Another method is to use the building's air handling system to pressurize the building. Only overall permeabilities for the combined effects of walls and top and bottom separations are obtained by curve fitting. This method cannot be used to derive permeabilites of individual components such as windows or doors.

In this section the basic pressurization technique individual component testing, and use of the building's air handling system to calculate overall surface permeabilities is described.

5.1 SUMMARY

The fan pressurization technique [5-7] measures envelope tightness directly, independent of weather conditions unless they are extreme, and includes the contributions from all leakage openings. The building is pressurized or depressurized by a fan and the inward or outward air flow (as the case may be) is measured. Buildings can be directly compared by expressing the induced air leakage at a standardized pressure difference, usually 50 Pa [7]. When this type of test can be applied it is much easier to perform than a tracer study; a fan mounted in an airtight "blower door" assembly is mounted either in a window or doorway, and the measurement can be accomplished in minutes. The potential problem of inadequate mixing tracer gas measurements does not represent an important factor (e.g., stagnant pockets or air) with fan measurements.

The fan pressurization method has the advantages of simplicity, direct comparability with other buildings and times, intrinsic meaningfulness without reference to temperature and wind conditions, usefulness in locating leakage openings when used in conjunction with infrared thermography (see chapter 2) [5,8,9], and the ability to assess the effectiveness of retrofit measures applied one at a time. The pressure differences induced by fans are so large that by comparison weather has hardly any effect. A disadvantage under some circumstances is that pressure differences are 10 to 100 times as great as those that occur naturally, and consequently, leakage pathways may be different. However, Tamura and Shaw devised methods [3,4,10,11] to calculate air leakage rates under natural conditions for large buildings. Several models permit this to be done for houses as well [12-17], with poor to fair predictability.

An alternative pressurization technique that which presumes that pressures closer to naturally occurring ones are developed is the infrasonic [18], or "AC fan" [19], method. A piston totally inside the building, or mounted in a wall, alternately causes air to leak in and out. If the driving frequency is low enough, there is little compression and decompression [20]. The frequency also provides a means of distinguishing induced from natural effects; the former can be electronically filtered. This method has not been widely used yet and it may prove as difficult to apply to large buildings as the usual fan pressurization test.

Infrasonic methods may be helpful in simulating natural conditions since they produce lower pressure differences than fans, but their relationship to natural conditions has not yet been determined. The positive displacement of the piston is capable of overcoming the effects of external (wind driven) pressure distributions which would normally be induced by natural weather conditions. This method probably indicates leakage openings in a manner closer to fan-induced pressure differences.

5.2 DESCRIPTION OF EQUIPMENT

1. Air moving equipment: a fan, blower, or blower door assembly (illustrated in figure 5.2), which is capable of establishing indoor-outdoor pressure differences in the range 10-70 Pa. The air flow should be constant at each fixed pressure for the time required to read the air flow rate or velocity.

2. Pressure-measuring device: manometer or pressure indicator capable of measuring pressure differences to within 2.5 Pa.

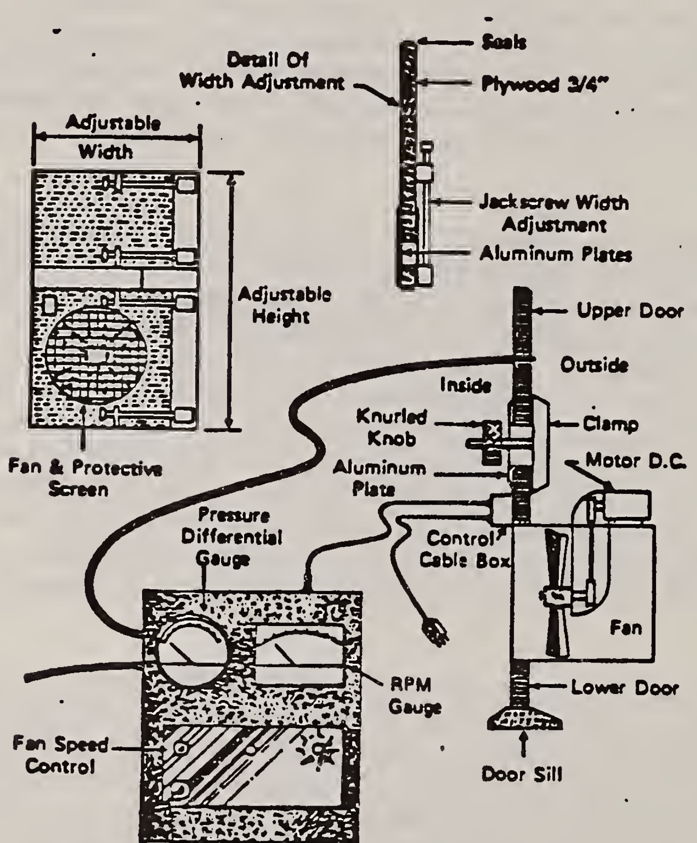

Figure 5.2 Schematic of blower door assembly used by Princeton University

3. An air flow or velocity measuring system should be capable of measuring the air flow rate to within 6 percent of its average value. The instrument should be calibrated according to the manufacturer's instructions or in a calibrating wind tunnel.

4. Wind speed measuring device accurate to 1 km/h or 0.3 m/s.

5. Temperature measuring device accurate to 1°C.

6. Air flow regulating system: a device such as a damper, or variable motor speed control, which will regulate and maintain air flow within specific limits.

7. Ductwork should accommodate both pressurization and depressurization.

8. The size of the air duct and the capacity of the fan or blower should be matched so that the linear flow velocity within the air duct is within the range of measurement of the air flow meter.

Table 5.1 Approximate Fan Capacities Required for Various Spaces

Building Type	Building Volume (m^3)	Fan Capacity (m^3/s)	Approximate Cost
Schools	7500-20,000	23.6	$20,000
5-Story Apartment House	not specified	23.6	$20,000
Single-Family Houses	"normal"	1-1.5	$2000 to $16,000
Single-Room Office	"normal"	0.7	$2000
Wall Section in Room	"normal"	0.04	$500 to $1000

A blower door assembly (figure 5.1) is a convenient way to perform the tests. Components unique to this assembly are:

1. A door mount for a fan or blower adjustable to fit common door openings.

2. A fan or blower with a variable speed DC motor capable of establishing an air flow rate of 5000 m^3/h. The fan or blower should be calibrated according to the manufacturer's instructions or with a set of standard flow orifices.

3. Fan speed controls (with display indicator) for fan speed; if calibrated it can be used for measurement of flow rate.

5.3 THEORY

The fan pressurization method is a procedure which uses a fan to pressurize or depressurize a building relative to outdoor conditions [5]. Almost instantaneously, nearly stable air flow is induced through leakage openings. The air flow rate through leakage openings must be equal to the flow through the fan. The latter can be measured and is given by:

$$q = C \cdot A \cdot \Delta P^n \qquad (5.1)$$

where:

C = flow coefficient
A = surface area, m^2
n = flow coefficient, a number between 0.5 and 1.0.

Caution: The relative air flow induced in any given leakage opening may bear little relation to the share of natural air infiltration through that opening.

5.4 MEASUREMENT GUIDELINES [5]

Tests are conducted as follows:

Step 1. Preparations. Make general observations of the condition of the building, including windows, doors, walls, roof, and floors. Measure and record the wind speed (direction is optional), and outdoor and indoor temperatures. Place the air-moving apparatus near the structure and connect the air duct or blower door assembly to the building envelope, using a window, door, or vent opening. Seal or tape openings to prevent leakage.

If no other flow meters will be used it is necessary to calibrate the fan to obtain air flow rates.

If a damper is used to control flow, it should be in fully closed position at the beginning of the test and adjusted to obtain desired pressure differences.

Step 2: Measure air flow rates at pressure differences from 10 to 70 Pa at 10-Pa increments.

Several flow meters are available; for example, orifice plates and pitot tubes; these measure pressure differences from which air flows can be calculated:

$$q = k \cdot (2 \cdot \Delta P \cdot A/T)^{1/2} \qquad (5.2)$$

where

A = cross-sectional area of measuring tube, m^2
T = absolute temperature, °K
k depends on the instrument.

Generally the indoor-outdoor temperature difference is not large enough for a correction term to be required. The correction term is given by:

$$(T_i/T_o)^{1/2} \tag{5.3a}$$

for pressurization, and the reciprocal:

$$(T_o/T_i)^{1/2} \tag{5.3b}$$

for depressurization. For example, suppose that during a pressurization test T_i = 20°C and T_o = -10°C. Then the flow rate only has to be corrected by 5 percent; the correction factor may safely be ignored.

Similarly, an atmospheric pressure correction term may be used in high altitude areas:

$$(P/101.325)^{1/2} \tag{5.3c}$$

with pressure, P, in kPa.

This factor can also usually be neglected; for example, for Denver, where the elevation is 1600 m; the correction term would correct the air flow rate by less than 10 percent.

A uniform pressure should be maintained in the building to within 20 percent of the measured indoor-outdoor pressure difference. The maximum pressure variation due to stack or wind effect should be no more than 10 percent of the measured pressure difference. Some researchers do not perform tests when wind speeds are above 15 km/h or 4 m/s [21]. Kronvall [7] asserts that in a pressurization test, a wind speed of 8 m/s can create a 10 percent variation in the flow rate; for depressurization, a 10 m/s wind speed is needed to produce the same effect.

The thermal stack effect may be disregarded for one-story buildings. Kronvall calculates that for a single-story house the pressure contribution of the stack effect for ΔT = 30°K is only 1 Pa. A rule of thumb for two or more stories is that the stack effect results in a pressure difference of approximately 0.1 Pa/K per story [5]. At a temperature difference of 20°K, for example, the stack effect in a 10-story building would result in a pressure difference of approximately 20 Pa, which is substantial when compared to the induced pressures. The Swedish Council for Building Research recommends that tests not be performed when the temperature difference exceeds 30°K [7]. Both pressurization and depressurization tests are recommended.

A major practical problem with using the pressure method for large buildings is that either an extremely large fan or a number of ordinary-sized fans must be used. Table 5.1 lists approximate fan capacities reported for various types of spaces that have been measured. This table cannot be used as an absolute guide, inasmuch as fan capacity is governed by building tightness as well as by volume. It may be found impractical to try to achieve a pressure difference of 50 Pa for an especially loose building; one may have to settle for a pressure difference on the order of 5 Pa.

Another major problem is that the cross-sectional area of the ducts may be too large to conveniently permit air flow measurements. In this situation tracer gas may be required. Because the air exchange rate during fan testing is so large, the tracer study would probably have to be operated in an automated mode with frequent readings. Bassett et al., [21] report that in a school a number of small fans mixed the air better than a single fan ; a single fan caused imbalanced tracer-gas concentrations. This suggests that several small fans result in better mixing than a single large fan, which causes a moving front of air that may not have time to become mixed. If tracer gas is used to measure flow, the possibility of having nonuniform concentrations may be an important consideration.

Nylund [22] claims it is very difficult to isolate a space from adjoining spaces. He also indicates that it is difficult to pressurize adjoining spaces so as to maintain the same pressure difference with outdoors as the space being measured. He suggests an alternative method to correct for the flows. In this method, the pressures (with respect to the outside) are measured within houses attached to the one of interest, the cross-flows are then calculated from the pressurization curve of the measured house, and subtracted. There is a correction term which must also be subtracted, but it is unclear how it is calculated. An advantage of his method, (assuming adjacent space corrections are valid) is that it requires only one fan. Unlike the case of tracer-gas measurements, different rooms may be measured at different times and the results may be meaningfully combined. Whether this method can be applied in office buildings where an office may be next to not only two other offices, but also to a hallway, (and over and under other offices) is unclear. Nylund [23] has developed a "reciprocity" test for this situation, but it is very difficult to understand. Also, Nylund [22] is working with houses where the indoor-outdoor pressure difference in the adjoining houses is measured through the water trap of the toilet. In an office building, this approach may be impractical and a method of measuring pressure differences such as the one [20] used by Shaw et al., [24] may have to be used.

Interpretation of Results

Step 3: Analyze the data. Calculate air flow rates if these are not read directly, e.g., from fan speed, rpm, or from pitot tube pressure differences. For both pressurization and depressurization, plot air flow rates vs. pressure differences on log-log paper. The slope of this line is the flow exponent. Alternatively, the flow exponent, as well as the flow coefficients, may be calculated by linear regression analysis.

Calculate, or read from the graph, the value of the air flow rate at a pressure difference of 50 Pa [7,8].

Accuracy of Technique

ASTM [9] estimates the uncertainty of the measurements as about 10 percent. Kronvall [11] uses the following equation to estimate uncertainty:

$$m = \left(\sum_{1}^{3} m_i^{2}\right)^{1/2} \tag{5.4a}$$

where

m = probable measurement error of a step, percent

The m_i are explained in figure 5.3. The total measurement error is obtained from:

$$m_{total} = \left(\Sigma\, m^2\right)^{1/2} \tag{5.4b}$$

From the data shown in figure 5.3 he calculates that uncertainties are less than 10 percent.

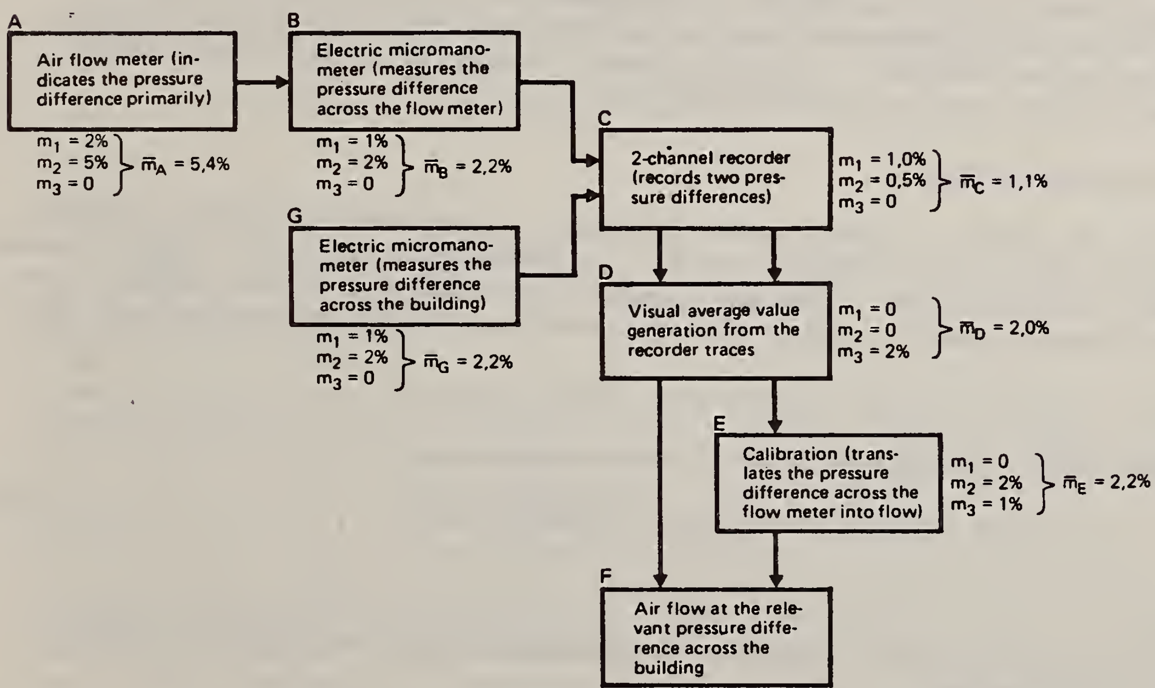

Figure 5.3 Schematic of errors in fan pressurization measurements

Previous Use

There are only a very small number of reports of fan pressurization measurements of large buildings in their entirety [2,3,25]. For example, Shaw and Jones [3] measured the air leakage characteristics of schools using fans with variable-pitch blades which can be manually adjusted to obtain flow rates between 0 and 23 m^3/s. The fan was connected by ducts to a door that replaced the schools' entrance door. This procedure is similar to the "blower doors" [5] used for smaller buildings. Measurements were obtained only when wind speeds were less than 15 km/h. The volumes were as high as about 20,000 m^3. Pressure difference measurements were first taken with the air handling systems operating and sealed. This reading, which indicates the amount of pressurization resulting from an imbalance between outside air supply and exhaust rates of the air-handling systems, was then subtracted from the pressure difference readings produced by the fan. Tests were run with various components, both sealed and unsealed, to determine their contribution to air leakage. It was found that the air handling system ducts themselves contributed 15 to 45 percent of the schools' air leakage rates.

5.5 COMPONENT TESTING BY FAN PRESSURIZATION

Summary

An alternative to using many fans in a tall building is to sample parts of the building that one hopes are representative of the entire building and then use Tamura and Shaw's [1,4] equations. The drawback of this approach, however, is that there is no assurance that all of the wall sections of the building have equal permeabilities. In such a study, a section of wall needs to be isolated from the rest of the building.

Description of Equipment

An example of using the above system follows. A portable fan with a maximum capacity of 200 l/s at 2 kPa was used. The fan was fitted with a manual damper to control the flow rate. The test chamber surrounding the wall assembly was built of plywood panels covered with polyethylene sheets and sealed with tape.

Theory

The Tamura-Shaw equations [1,4] for stack action are:

$$q_s = C \cdot S \, (0.0342 \cdot \gamma \cdot P(\Delta T_1/T_o))^n (\beta H)^{n+1}/(nH) \qquad (5.5)$$

where

γ = ratio of actual to theoretical pressure difference (thermal draft coefficient)

β = ratio of height of neutral pressure level above ground to building height

H = building height, m

n = flow exponent,

Subscript "s" refers to stack action.

The coefficient γ arises because the floors obstruct air flow. It is estimated to range from 0.63 to 0.88.

The equation is simplified for practical purposes by assuming P = 101.325 kPa, T_i = 294°K, n = 0.65 and β = 0.5. The equation then becomes:

$$q = 0.96\ C \cdot S(\gamma \cdot \Delta T/T_o)^{0.65}\ H^{1.65} \qquad (5.6)$$

For wind action, the equation is:

$$q_w = 0.0925 \cdot \alpha \cdot C \cdot L \cdot H^{1.435}\ V_s^{\ 1.30} \qquad (5.7)$$

where:

α is a factor depending on wind direction.
L = length of wall facing wind.
V_s = wind speed at weather station.
Subscript "w" refers to wind action.

Shaw and Tamura [4] suggest combining wind and stack action as follows:

$$q = q_{lrg}\ [1 + 0.24\ (q_{sml}/q_{lrg})^{3.3}] \qquad (5.8)$$

where:

q_{lrg} = larger of q_w and q_s
q_{sml} = smaller of q_w and q_s

Measurement Guidelines

Shaw [2] described 2 methods (direct and indirect) for measuring induced air leakage rates of walls, windows and doors of multistory apartment buildings. The direct method for measuring an entire wall assembly is illustrated in figure 5.4. The test chamber was slanted towards the wall in order to facilitate sealing the top to prevent leakage. Each wall component can also be measured by a similar technique (figure 4.13). However, since it is difficult to obtain a tight seal in this case, the adjoining areas are also pressurized, as illustrated in figure 5.4 for the direct method. Shaw [2] states that these pressures could be set to within 2.5 Pa of each other. The indirect method is performed identically to the direct wall assembly in question but the measurements are performed twice: with the component of interest sealed and unsealed. The difference in flow is the leakage attibuted to the component.

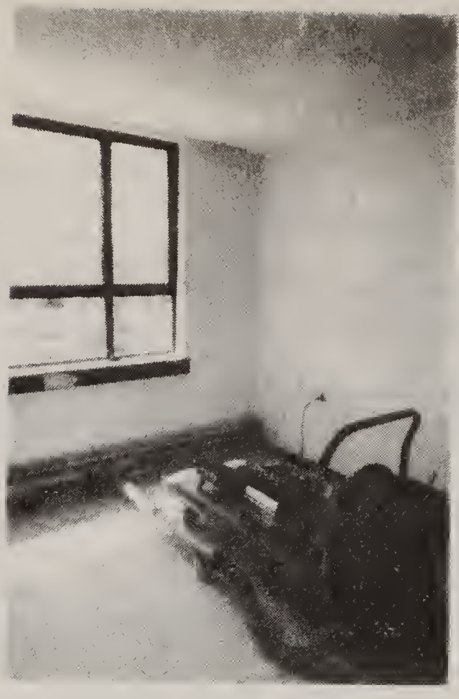

Figure 5.4 Direct method for testing a wall

Accuracy of Technique

It was found that the air leakage rate of entire wall assemblies was within 15 percent of the summed leakage rates of the components.

5.6 USE OF BUILDING'S AIR HANDLING SYSTEM

Summary

The stack effect was usefully employed by Shaw et al., [24] in calculating flow coefficients (i.e., permeabilities) of building walls, and top and bottom separations. They used the air handling system to pressurize a building. All typical floor spaces between the ground floor and the top mechanical floor of a building were pressurized using 100 percent outside supply air, with return and exhaust systems shut down. Supply air rates were varied and pressure differences across the enclosure were measured. To ensure stable pressure differences, tests were conducted in the absence of strong winds.

Theory

Under steady-state conditions, the rate of outside supply air equals the sum of the leakage rates through the exterior walls of typical floors and bottom and top separations:

$$q = C_w \sum_{j=1}^{N} [A_w \cdot (\Delta P_w)^{n_w}]_j + C_b \cdot A_b \cdot (\Delta P_b)^{n_b} + C_t \cdot A_t \cdot (\Delta P_t)^{n_t} \qquad (5.9)$$

where:

N = total number of floors with typical wall construction and subscript:
"w" = exterior wall
"b" = bottom separation
"t" = top separation

Measurement Guidelines

Note that q, ΔP_w, ΔP_b and ΔP_t are measured quantities. The total air leakage rate for the three components depends upon the values of pressure differentials across each separation. The tests should be conducted when outdoor temperatures are lower than indoor temperatures, creating a stack effect that will produce different pressure differences for the three components.

Fresh air supply rates were measured using total pressure averaging tubes [24], a method with accuracy better than 6.5 percent. Pressure differences were measured with a pressure recording instrument located on the top mechanical floor. One side of the meter was connected to the rooftop pressure tap which served as a reference pressure; the other side of the meter was connected to a pressure selector switch, from which plastic tubes were installed vertically in a stair shaft ending at various floor spaces and to ground level outdoors.

Interpretation of Results

The data were analyzed by computer. The unknowns can be estimated by a trial and error technique used in conjunction with the method of least squares. The three flow exponents were assigned combinations of values between 0.5 and 1.0 (as this is the range of accepted values). The flow coefficients were then obtained by the method of least squares for various combinations of exponents. The set of values of flow coefficients and exponents were selected that gave the lowest value of estimated error.

Accuracy of Technique

This method has not been validated for an actual building but a computer simulation revealed that the lowest standard error did not necessarily yield the values of the coefficients specified by the simulation. The authors state that this is because the standard error of estimate is related to overall air leakage rates. The wall leakage rates calculated from the computed wall flow coefficients were within 10 percent of the specified wall air leakage rates.

Previous Use

Tamura and Shaw [1,4] conducted investigations to correlate natural flow rates with weather conditions. In those studies the values of the flow coefficients were determined from test data and solution of equation 5.9.

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6. TEMPERATURE MEASURING SPOT RADIOMETERS

6.1 SUMMARY

For this technique, a hand-held infrared thermometer (spot radiometer) is used to measure the inside surface temperature of a building component and the inside air temperature. Another measuring device is used to measure the coincident air temperature at the exterior surface of the component. These three measured temperatures are subsequently substituted into simple mathematical relations for estimating the apparent thermal resistance of the component. This technique is considered inaccurate under typical transient thermal conditions to which buildings are subjected. A suitable application is to determine qualitatively whether a wall is insulated or if insulation voids or other thermal defects are present. This technique is not accurate enough to permit an R-13 wall to be distinguished from an R-15 wall.

6.2 DESCRIPTION, SPECIFICATION AND COST OF EQUIPMENT

A spot radiometer is a hand-held device used to radiometrically measure the equivalent blackbody temperature of a relatively small area of a surface. It is generally small, light weight, and frequently gun-shaped (see figure 6.1). Spot radiometers are calibrated by pointing the device at a surface of known temperature and adjusting a knob on the device such that the device radiometrically determines the correct temperature of the reference surface. Manufacturers frequently provide reference surfaces having approximate blackbody characteristics (i.e., reflecting little radiation from surrounding surfaces). Interior surfaces of buildings generally have emittances which range from about 0.80 to 0.95. Consequently, the apparent surface temperature determined using a spot radiometer differs from the actual surface temperature by a small amount. This problem may be partially avoided by using a reference surface which has a surface emittance more nearly equal to that of the subject surface.

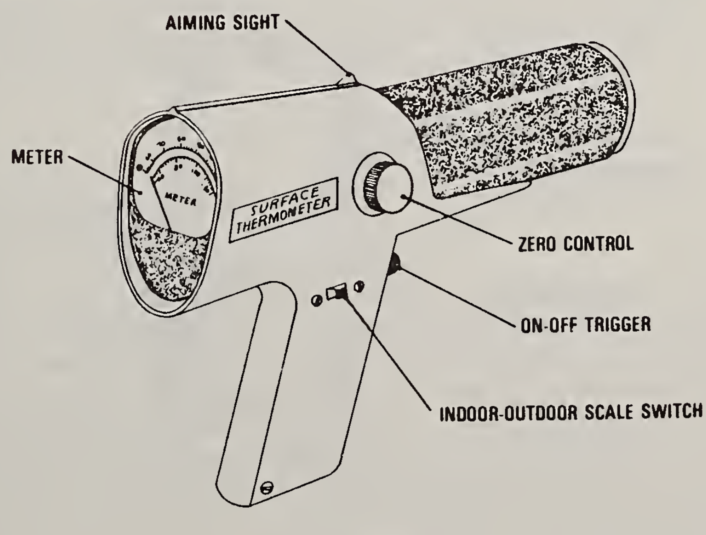

Figure 1. Spot radiometer

Figure 6.1 Spot radiometer

The device is pointed at a surface area of interest and depressing the on-off trigger. The device senses the total infrared radiation over a particular wavelength band emanating from the surface, including both the self-emitted surface radiation and reflected radiation from surrounding surfaces. The device is calibrated to read out the apparent radiance temperature on either a digital or meter display. The apparent radiance temperature is defined as the temperature of a perfectly black surface which would radiate the same amount of thermal radiation as a real surface at the same temperature and having a surface emittance different from unity.

Typical specifications for spot radiometers include a temperature measurement resolution within ± 0.5°F, although a device with a reported resolution of within ± 0.1°F is now commercially available. Spot radiometers generally have their principal spectral response in the range of 10 microns, and a response time of less than 2 seconds. Since contact with the surface to be measured is not necessary with these devices, it is possible not only to minimize the error due to disturbing the thermal regime of the subject surface, but also to determine the surface temperature of otherwise inaccessible objects, such as second-story walls. The target size increases with increasing distance from the object to the instrument at a typical ratio of 1-inch diameter target per 15-inch operating distance. A spot radiometer indicates the average apparent temperature for the surface being measured over its entire field of view. Therefore, operation close to a wall will indicate apparent surface temperature of a small region, while operation at a distance will indicate apparent surface temperature for a larger region. Spot radiometers which measure temperature are made by approximately five firms in the United States. They vary in price from $300 to $1500.

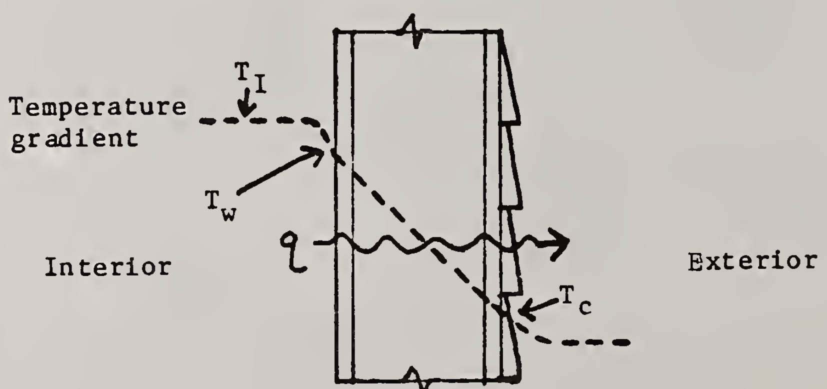

Figure 6.2 Exterior wall schematic

Spot radiometers may be equipped with an audio device which can be adjusted to produce a change in audible tone when the radiometer is panned across a thermal anomaly of the building envelope such as an air infiltration path or a place in the wall where insulation is missing. A spot radiometer equipped in this fashion can be used to quickly pan the envelope of a building, readily detecting gross thermal defects.

6.3 THEORY

Consider the exterior wall schematic shown in figure 6.2.

The instantaneous heat-loss rate (q) at the inside surface is given by:

$$q = h_I \cdot (T_I - T_W) \quad (6.1)$$

where h_I is the overall heat-transfer coefficient at the inside surface, T_I is the interior air temperature, and T_W is the interior surface temperature. Under steady-state conditions, the heat-loss rate through the wall may also be determined using the relation:

$$q = (T_I - T_O)/R \quad (6.2)$$

where R is the air-to-air thermal resistance and T_O is the exterior surface temperature. Under steady-state conditions, we may combine Eq. (6.1) and (6.2) to give:

$$R = (T_I - T_O)/h_I \cdot (T_I - T_W) \quad (6.3)$$

If this model is valid, the thermal resistance of an exterior wall can be determined based on the three pertinent temperature measurements, together with an assumed value for the interior surface heat-transfer coefficient.

The overall heat transfer coefficient (h_I) at the inside surface is equal to the sum of the radiative and convective heat transfer coefficients. The radiative heat transfer coefficient (h_r) can be estimated by the relation:

$$h_r = 4 \cdot \sigma \cdot T_s^3 \quad (6.4)$$

where σ is the Stefan-Boltzmann constant and T_s is the average absolute temperature of the surroundings.

Under typical indoor conditions, a representative value for h_r is 1.0 Btu/($h \cdot ft^2 \cdot °F$). The convective component of the overall surface heat transfer coefficient (h_c) is a complicated function of: 1) the surface-to-air temperature difference; 2) large-scale convective air movement patterns present in a room; and 3) the height above the floor. In the absence of large-scale convective air movement, a laminar free-convection boundary layer will exist at the top of the wall. This boundary layer will grow in size, passing through a transition region, and then turn into a turbulent boundary layer farther down the wall. Generally, the convective component will vary between 0.2 and 0.4

$Btu/(h{\cdot}ft^2{}^\circ F)$. It is recommended that the following convective heat transfer coefficient be used to represent the average conditions existing on the wall:

$$h_c = 0.22(T_I - T_w)^{0.33} \qquad (6.5)$$

where $(T_I - T_w)$ is the surface-to-air temperature difference in degrees Fahrenheit. This relation is applicable for natural convection in the turbulent regime.

6.4 GUIDELINES FOR CONDUCTING MEASUREMENTS

Spot checks to determine the apparent thermal resistance of a surface should be carried out no sooner than 3 hours after sunset in order to avoid solar loading effects on exterior surfaces and to obtain a minimum variation of the outdoor air temperature [1]. Another requirement is that the indoor-to-outdoor temperature difference shall exceed 18°F in order to produce measurable temperature differences between the inside surface of a building component and the indoor air [1]. It is also recommended that the building heating plant be turned off for approximately 30 minutes prior to carrying out measurements in order to minimize the effect of surface-to-air temperature fluctuations due to the cyclic operation of the heating plant. Once the foregoing conditions have been met, the interior shading devices (such as blinds and draperies) should be closed in order to minimize the effect of radiation exchange between interior window surfaces and other interior room surfaces.

Next, the spot radiometer is calibrated by pointing it at a reference surface of known temperature. The spot radiometer is adjusted to read the temperature of the reference surface. The spot radiometer is subsequently aimed at a spot on a building surface and the surface temperature, T_w, is recorded. The indoor ambient temperature, T_I, is then determined by pointing the spot radiometer at a low-heat-capacity object having an emittance comparable to that of the subject surface. The object should be in front of the subject surface and in thermal equilibrium with the surrounding air. A spray-painted polystyrene board with an attached thermocouple and associated digital readout device will serve both as a reference surface for calibrating a radiometer and also as a low-heat-capacity object for measuring the indoor air temperature. The average temperature, T_s, of the surrounding surfaces may be estimated by attaching a highly radiometrically reflective surface onto the subject building surface. A spot radiometer aimed at such a surface will sense predominantly reflected radiation from surrounding surfaces and therefore will essentially measure the equivalent blackbody temperature of the surroundings. The outdoor air temperature, T_o, should be measured with a conventional thermometer in order to avoid inaccurate measurements of the spot radiometer at low temperature. The measured values for T_s, T_I, T_w, and T_o are substituted into eq. (6.3), (6.4), and (6.5) to calculate the thermal resistance, R, of the building component.

6.5 INTERPRETATION OF RESULTS

If the thermal resistance, R, as determined by the foregoing technique is found to be less than 7, then the wall should be considered to be uninsulated. Otherwise the wall is insulated.

6.6 ACCURACY OF THE TECHNIQUE

One of the main contributing factors to inaccuracies of this technique is the inability to accurately resolve the temperature difference (T_I-T_W) required in Eq. (6.3). Most commercially available spot radiometers are able to resolve temperatures to within ± 0.5 °F. For this tolerance, the maximum uncertainty in measuring (T_I-T_W) is ± 1.0 °F. Consider an insulated wall (R = 15) and an uninsulated wall (R = 5) both subjected to a 40 °F inside-to-outside temperature difference. The resulting heat-flow rates as given by Eq. (6.2) are 2.7 Btu/(h•ft^2) for an insulated wall, and 8.0 Btu/(h•ft^2) for an uninsulated wall. A representative value for the inside surface heat transfer coefficient is 1.2 (Btu/h•ft^2•°F). Using Eq. (6.1), the air-to-surface temperature difference (T_I- T_W) is estimated to be 2.3 °F for an insulated wall and 6.8 °F for an uninsulated wall. Hence, the error in estimating (T_I-T_W) is 1.0/2.3 = 43 percent for an insulated wall and 1.0/6.8 = 15 percent for an uninsulated wall. Using a spot radiometer with a resolution of ± 0.1 °F, which is now commercially available, would reduce these errors by a factor of 5 (8 percent and 3 percent, respectively). The uncertainty in measuring (T_I-T_o) in Eq. (6.3) is also about ± 1.0 °F, and the uncertainty in specifying the overall heat transfer coefficient (h) is probably about ± 0.2 Btu/(h•ft$_2$•°F). The foregoing uncertainties are summarized in table 6.1.

Table 6.1 Summary of Uncertainties in Measuring the Thermal Resistance of Insulated (Uninsulated) Walls

Parameter	Uncertainty: Normal Range	Uncertainty: % Error
h_I	± 0.2 Btu/h•ft^2•°F	± 17%
T_I-T_W	± 1.0°F (± 0.2°F)	± 43% (± 8%)
T_I-T_o	± 1.0°F	± 2.5%

It has been shown in ref. [2] that when these uncertainties are introduced into Eq. (6.3), the net uncertainity (E_r) is given by the relation:

$$E_r = (E_x^2 + E_y^2 + E_z^2)^{0.5} \qquad (6.6)$$

where E_x, E_y, and E_z are the uncertainties given in table 6.1. Substituting the uncertainty values, the net uncertainty in determining the thermal resistance of an insulated wall is 46 percent. The uncertainty in determining the thermal resistance of an uninsulated wall is found to be 23 percent. The foregoing error analysis is optimistic because the effect of time-dependent heat flow due to diurnal temperature fluctuations was not considered.

6.7 AVAILABILITY OF EQUIPMENT AND ENERGY AUDITS WITH SPOT RADIOMETERS

Temperature-measuring spot radiometers are manufactured by approximately six firms in the United States. In the DoE survey of firms providing infrared services, no firm used only a spot radiometer [5]. There are indications that that energy audit firms and insulation contractors do use these devices, but detailed information describing such usage is unavailable.

6.8 PREVIOUS USE

The major previous use of this technique has been for quality control purposes [5] and made by firms engaged in retrofit installations of blown and foam-in-place insulation.

6.9 TRAINING REQUIREMENTS FOR PERSONNEL USING SPOT RADIOMETERS

These devices are simple to use and require little special training if used for quality control. If they are used in energy audits, the responsible person should be trained in energy audits and also have training to level I for a paraprofessional as indicated by the training program of Public Works Canada (see section 2.8).

6.10 PROGRAM APPLICATION RESTRICTIONS

This technique should be restricted to finding gross deficiencies in smaller federal buildings in colder climates. It is advisable that spot radiometer measurements should be made in conjunction with thermographic surveys.

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7. RADIOSITY MEASURING SPOT RADIOMETERS

7.1 SUMMARY

In this technique a hand-held infrared spot radiometer is used to measure the radiosity emanating from a surface and the radiosity incident upon the surface to obtain the net radiative heat flow from the surface. The total heat flow from the surface is then estimated by assuming standard values for the ratio of the convective heat transfer coefficient to the radiative heat transfer coefficient. By measuring the inside-to-outside temperature difference, an estimate of the thermal resistance can be made if the building element is close to steady-state conditions. The spot radiometer used for this technique indicates radiosity directly in energy flow units of (Btu/(ft^2•h) or watts/m^2 and is referred to as an energy meter.

7.2 DESCRIPTION AND COST OF EQUIPMENT

The device used for this type of measurement is basically a spot radiometer which does not have the linearization circuitry to convert from radiosity to temperature. The device is calibrated to indicate radiosity in energy flow units, either Btu/(ft^2•hr) or watts/m^2. The sensitivity of these devices is approximately $\pm$ 0.1 Btu/(ft^2•hr). This equipment has a spectral response in the 8-14 micron band, a response time of 3 seconds and a spot size of 4 in at 6 ft (a ratio of 1 in target diameter to 18 in operating distance).

At present one manufacturer makes this type of spot meter for approximately $1000. An additional temperature-measuring device is required for use with the equipment if thermal resistance measurements are to be made.

7.3 THEORY

The theory of operation for the energy meter version of the spot radiometer is based on the equation for heat flow from the surface of the wall to be measured:

$$\begin{aligned} q &= q_r + q_c \\ &= q_r\,(1 + q_c/q_r) \\ &= q_r\,(1 + hc/h_r) \end{aligned} \tag{7.1}$$

where

- q is the total instantaneous heat loss rate,
- q_r is its radiative component,
- q_c is its convective component,
- h_c is the inside convective surface heat transfer coefficient, and
- h_r is the inside radiative surface heat transfer coefficient.

Since q_r is the net radiative heat transfer from the surface, it is the difference between the radiosity, J_I, from the surface and the irradiance (or the incidence radiation on the surface), G_I,

$$q_r = J_I - G_I \tag{7.2}$$

The radiosity measuring spot radiometer (obtained by pointing at the wall surface) measures J_I directly in energy units. The measurement of G_I is obtained by one of two techniques.

The simplest method is to point the spot radiometer at the interior surfaces of the room and measure their radiosity J_k ($k = 1 \ldots\ldots n$).

The incidence radiation can be determined by the relation

$$G_I = \sum_{k=1}^{n} A_k \phi_k J_k \tag{7.3}$$

where A_k is the area of the interior surfaces, and ϕ_k is the view factor between the interior wall and the spot being measured.

If the radiosities J_k are approximately equal, then

$$G_I \simeq J_i\left(\sum_{k=1}^{n} \phi_k A_k\right) = J_i \tag{7.4}$$

since $\Sigma\, \phi_k A_k = 1$ for a closed room. In Eq. (7.4) J_i is the average of J_k and usually taken to be the radiosity of the wall opposite to that being measured [1].

A second method is to place a small reference pad [2] in the field of view near the surface being measured (see figure 7.1). If the pad is constructed of insulating material so that the net heat flow is zero then it can be shown that

$$q_{net}^{ref} = 0 = J_i^{ref} - G_I + q_c^{ref} \tag{7.5}$$

where

J_i^{ref} is the radiosity of the reference pad and q_c^{ref} is the convective heat flow between the reference pad and the room air.

If $q_c^{ref} \approx 0$, then measuring J_i^{ref} gives the incident radiation on the reference pad which is the same as that incident on the wall:

$$G_I \approx J_i^{ref} \tag{7.6}$$

By performing a heat balance on the reference pad, it can be shown that

$$q_c^{ref} \approx \frac{h_r' h_c'}{h_r' + h_c'} (T_s - T_a) \tag{7.7}$$

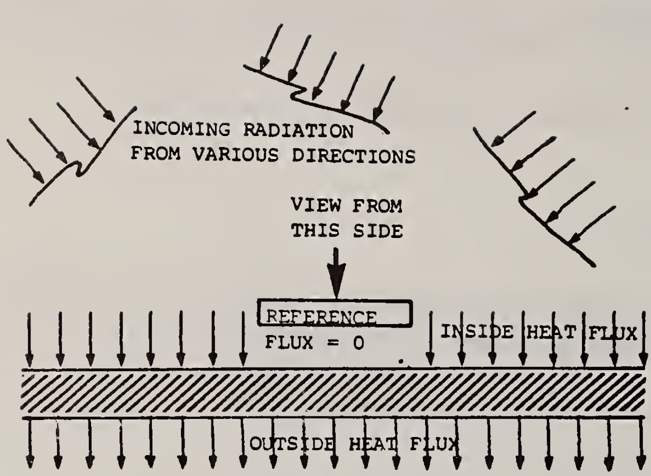

Figure 7.1 Use of reference pad for measuring incident radiation [2]

where

T_a is the room air temperature,

T_s is the average temperature of the interior surfaces, and

h_r' and h_c' are the radiative and convective surface heat transfer coefficients of the reference pad.

If the reference pad is constructed from low emissivity material, then $h_r' \approx 0$ and relation (7.6) would be valid. The thermal resistance of the wall is then determined from the equation

$$R = \frac{\Delta T}{q} = \frac{\Delta T}{(1 + h_r/h_c)(J_I - J_i)} \qquad (7.8)$$

where

J_I is the radiosity of the wall being measured and J_i is either the radiosity of the reference pad or of the interior walls.

7.4 GUIDELINES FOR CARRYING OUT MEASUREMENTS

As with temperature indicating spot radiometers the determination of the thermal resistance of a building element using radiosity-measuring spot radiometers should not be carried out sooner than 3 hours after sunset in order to avoid solar loading effects on exterior surfaces and to obtain minimum variations of the outdoor temperature. The indoor-to-outdoor temperature difference should be greater than 10°C (18°F). It is recommended that the building heating system be turned off 30 minutes prior to performing the measurements. The spot radiometer is pointed at the exterior element and its radiosity is measured.

The radiosity of the interior surfaces is then measured using either the reference pad or following the description with Eqs. (7.2) and (7.4). For rooms that have more than one exterior wall, an exterior ceiling, an uninsulated ground floor or radiant sources of energy, such as hot pipes or radiators, the reference pad should be used. It is important that sufficient time be allowed after positioning the reference pad to permit it to come to equilibrium with the surroundings. The inside and outside temperatures should be measured with appropriate conventional thermometers.

7.5 INTERPRETATION OF DATA

If the thermal resistance, R, is found to be less than 7, then the walls should be considered to be uninsulated. Otherwise, the wall is insulated.

7.6 ACCURACY OF THE TECHNIQUE

If the Eq. (7.8) is used to determine the resistance of a wall, then the probable error in the value of R is $\pm$ 21 percent for an insulated wall and $\pm$ 10 percent for an uninsulated wall. The errors of each component are given in table 7.1. No independent laboratory or field verification study of these error estimates has been performed; the data are those reported by the manufacturer of the equipment. The error estimate does not include errors due to transients or errors in measuring J_i other than instrument error.

7.7 AVAILABILITY OF EQUIPMENT AND PREVIOUS USE

At present this equipment is available from only one manufacturer. Due to the newness of this equipment there are no public data on how many energy audit service firms use this equipment. Reference [2] does describe the use of the radiosity measuring radiometer in an instrumented audit and claims that such an instrumented audit can be undertaken for only a little more cost and effort than non-instrumented energy audits of buildings.

7.8 TRAINING REQUIREMENTS

This equipment is relatively simple to use. However, there are no data to indicate exactly what training requirements would be required. It is safe to assume that the personnel who use this technique should be trained as energy auditors and also have training comparable to that given by Public Works of Canada for level I personnel (see section 2.8).

Table 7.1 Summary of Uncertainty in Measuring Thermal Resistance of Insulated (Uninsulated) Wall

Parameter	Uncertainty	
	Normal Range	% Error
h_c	$\pm$ 0.1 Btu/h•ft^2•°F	$\pm$ 8%
h_r	$\pm$ 0.5 Btu/h•ft^2•°F	$\pm$ 2%
$J_I - J_i$	$\pm$ 0.2 Btu/h•ft^2•°F	$\pm$ 20%
$T_i - T_o$	$\pm$ 1.0°F	$\pm$ 2.5%

7.9 PROGRAM APPLICATION RESTRICTIONS

It is considered that this technique initially should only be used for smaller buildings in colder climates and then only to assess where gross deficiencies exist in the building.

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8. HEAT FLOW METERS

8.1 SUMMARY

For this technique a heat flow meter is spot-glued to a representative location on the interior surface of a building component, and the 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 heat flow meters are accurately calibrated. The thermal resistance measurement is applicable to only 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.

8.2 DESCRIPTION AND COST OF EQUIPMENT

Heat Flow Meters

A heat flow meter consists of a thin flat wafer (comprised of a series of pairs of thermocouple junctions) either circular 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 (see figure 8.1).

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 $Btu/(h{\cdot}ft^2)$. The sensitivity of a heat flow meter is a function of its average temperature. In selecting a heat flow meter for a particular application, it is important that the heat flow meter provide a signal sufficiently large for measurement and resolution by the readout device at the lowest expected heat flow rate. Heat flow meters cost approximately $100 to $200 each.

Consider the example where it is desired to measure the thermal resistance of an insulated wall (R = 13). The expected temperature difference is 10°F, giving a heat flow rate of 0.77 $Btu/(h{\cdot}ft^2)$. If the read-out device has a resolution of $\pm$ 5 microvolts, then the heat flow meter 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 $0.10/0.77 = 0.14$ $mv/Btu/(h{\cdot}ft^2)$.

Another important characteristic of a heat flow meter 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

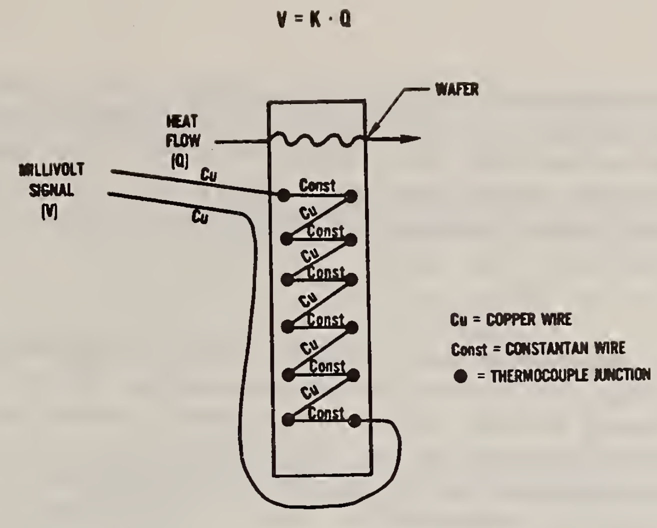

Figure 8.1 Schematic drawing of heat flow meter

Figure 8.2 Example of commercially available heat flow meter

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 flow meters having a thickness of about 1/8 inch. Heat flow meters 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 higher copper-constantan thermocouple wire. 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 thermopiles on the interior and exterior (across the building component). Here, 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. In the case of 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 will cost approximately $7000 to $10,000.

8.3 CALIBRATION OF SENSORS

Heat Flow Meters

The problem that has contributed to a poor reputation for heat flow methods has been the lack of accuracy in the calibration of commercially manufactured components. Precision laboratory assemblies have provided precisely calibrated heat flow meters. The accuracy of data reported in this section is limited to the accuracy to which the heat flow meters are calibrated. The following procedure should be utilized to calibrate heat flow meters: The heat flow meters to be calibrated are first sandwiched into a composite assembly having heat transfer properties comparable to those of the heat flow meters. This composite assembly 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 flow meters 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 flow meters is determined by taking the ratio of millivolt output to the heat flux rate.

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

Temperature Sensors

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.

8.4 GUIDELINES FOR CARRYING OUT HEAT FLOW METER MEASUREMENTS

In assessing the thermal performance of a building component, 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 a measuring location which is representative of the bulk performance of the component. Since small defects in the envelope insulation do not contribute largely to the overall performance of the building envelope providing these defects are few in number, it is desirable to mount heat flow meters at locations free of minor insulation defects. When the measuring location 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 in the room will be comparable to that of the subject surface. Mounting heat flow meters 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 flow meters 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 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 divided the average temperature difference by the average heat flow over a sufficiently long period of time. This may be expressed mathematically by the relation:

$$R = \frac{\int_0^t \Delta T dt}{\int_0^t Q dt} \tag{8.1}$$

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 with respect to time lags for building components in table 8.1. Here "time lag" tefers 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 8.1 Typical Phase Lags for Various Wall and 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
Wood-frame cavity wall	2	1.0
Masonry walls	2.5 - 9.5	1 - 5
Metal curtain walls	0.2	<0.5

Typical phase lags for various wall and roof construtions along with estimated required measurement times, are summarized in table 8.1. The indicated measurement times should ensure an accuracy of 5 percent. The phase lag values were taken from ref's. [1,2]. When the required measurement time is less than one day, it is recommended that a measurement period of a full day be used. In summary, wood-frame walls, built-up roofs having steel decks, metal curtain walls require a measurement time of one day. Masonry walls require a period varying from one to five days depending upon the thermal capacity of the wall, and built-up roofs with concrete decks require about six days.

8.5 ACCURACY OF TECHNIQUE

When the heat flow meter technique has been used in field and laboratory studies to determine the thermal resistance of walls and roofs, the agreement between measured thermal resistance and the corresponding predicted thermal resistance calculated, using steady-state heat transfer theory, has agreed to within 6 percent [1,3-5] when the material composition of the wall was known accurately. For the predicted thermal resistance values, heat transfer coefficients from engineering handbooks were used in the calculations. Therefore, it could not be determined whether the difference between the measurement and the theory was due to the use of incorrect values of the material properties or to inaccuracies associated with the measurement technique.

Significant sources of errors may be introduced due to the envelope construction and location of heat flow meters on wall surfaces over studs or on conductive wall coverings. Details of construction and materials should be reviewed by examination of blueprints and specifications. Whenever multiple heat flow paths exist then the normal heat flux measurement inherent with these devices provides only a fraction of the total.

This technique has accuracy sufficient for verification that the performance of the building component meets thermal specification required of building contractors for either new buildings or retrofit installations of insulation.

8.6 INTERPRETATION OF DATA

The thermal resistance calculated by this method is sufficiently accurate to allow the accurate prediction of the long term heat loss through the component. It is important that a sufficient number of measurements on different points of the building be made so that representative values will be obtained. If the more sophisticated analytic methods developed by the researchers at Lawrence Berkeley Laboratory are used [6,7], the dynamic response of the component can be determined from the data obtained when using this technique.

8.7 PREVIOUS USE

Heat flow meters have been used for measuring building heat flow for more than 30 years. However, due to the lack of good calibration procedures and insufficient understanding of the dynamics of the thermal response of building, the technique developed a bad reputation. Recent research has corrected these deficiences. A large scale application of this technique for measuring, in situ, the thermal resistance of buildings has been carried out in Sweden [8].

8.8 TRAINING REQUIREMENTS

Qualified technicians are required to carry out this procedure. The field personnel should be experienced with techniques for making proper low-level electrical measurements and also have an understanding of the fundamentals of building heat transfer. If the dynamic response of the building component is to be determined, graduate level training in mathematics is required.

8.9 PROGRAM APPLICATION RESTRICTIONS

This technique should be used only when accurate determination of the thermal performance of the building is required. It can only be used during periods when there is no reversal of direction in the heat flow. It should not be used on glass surfaces.

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9. PORTABLE CALORIMETER BOXES[1]

9.1 SUMMARY

Recently, the Building Research Division of the National Research Council of Canada (BRD/NRCC) developed a portable calorimeter (guarded hot box) for measuring in-situ heat transmission through building components.

The calorimeter 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.

9.2 DESCRIPTION OF EQUIPMENT

Calorimeter Box

The construction details for the BRD/NRCC calorimeter are given in figure 9.1a. The size of the metering area is 1.2 x 2.1 meters. The walls consist of two layers of 72 kg/m^3 glass-fiber insulation board glued together with an exterior 6 mm plywood covering to provide structural support. The thermal resistance of the walls is 2.8 $m^2 \cdot K/W$. The edge portion of the calorimeter which contacts the surface of the building component contains a gasketing material for providing an air tight seal. A 150-watt electric heating wire is suspended in a zigzag fashion within the calorimeter as shown in figure 9.1b. A multijunction thermopile is placed across the rear surface of the calorimeter. The controller shown in figure 9.1b 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.

Surface Temperature Sensors

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, copper-constantan thermocouple wire.
iii. precision bead-type thermistors

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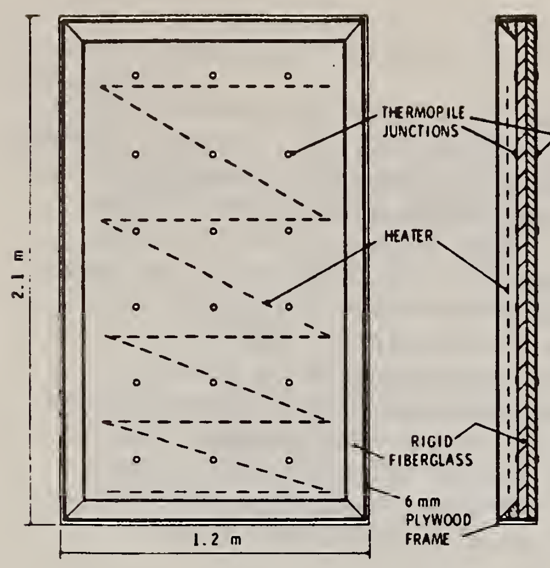
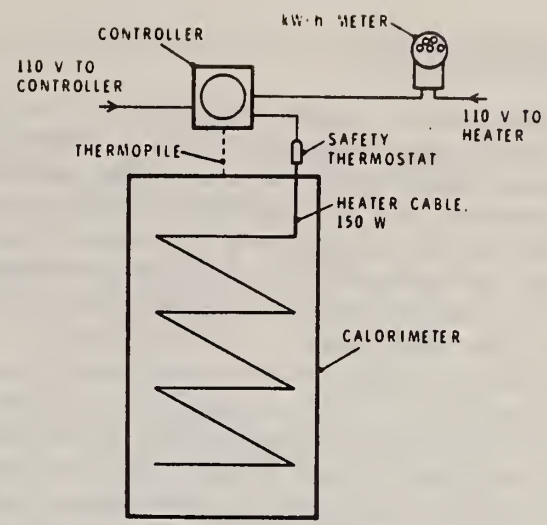
[1] The material in this section is based mainly on ref. [1].



(a) Cross sections



(b) Wiring diagram

Figure 9.1 Construction details of calorimeter

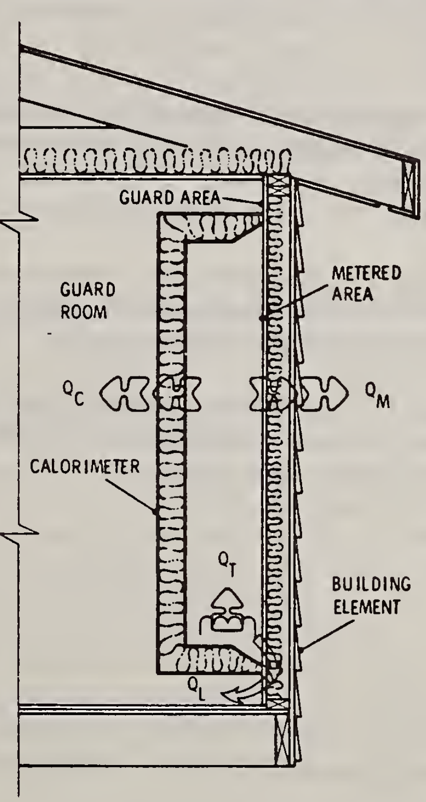


Figure 9.2 Illustration of measurement technique

Read-Out Device

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 closures 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.

9.3 MEASUREMENT TECHNIQUE

Prior to conducting a calorimeter box measurement of a building component, a representative measuring station should be selected. While thermal anomalies such as missing insulation need to be located, usually one is more interested in the performance of a building component in areas free of such defects, unless the purpose of the survey is to measure the effect of such thermal anomalies on the envelope performance.

The calorimeter box is subsequently sealed to the measurement station as shown in figure 9.2. 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 room 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:

$$R = \frac{\int_0^{\tau} \Delta T \cdot dt}{W_T} \tag{9.1}$$

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 components are summarized in table 9.1.

Table 9.1 Required Measurement periods (τ) for Various Building Components (based on information in ref's. [2,3])

Component	Measurement Time (t) days
Built-Up Roof, Concrete Deck	6
Built-Up Roof, Steel Deck	0.5
Wood-Frame Cavity Walls	1.0
Masonry Walls	1 - 5
Metal Curtain Walls	>0.5

The foregoing measurement periods should insure an accuracy of 5 percent in determining the thermal resistance, R.

9.4 GUIDELINES FOR CONDUCTING MEASUREMENTS

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.

9.5 SPECIFICATIONS FOR 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 a 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 surfaces of the room. This will help to maintain the exterior box temperature more closely to the room temperature.

9.6 ACCURACY

The accuracy of the BRD/NRCC calorimeter was checked by measuring the heat transmission rate through a test wall of known thermal resistance. The thermal resistance of the test wall had previously been measured using a guarded-hot-box apparatus. The field calorimeter was installed against the test wall with the temperature conditions on both sides of the test wall maintained identical to those prevailing during the hot-box test. The accumulated heat transmission measured with the calorimeter box agreed within 5 percent of the corresponding value predicted using the wall resistance value and the measured surface temperature difference. In order to achieve this accuracy it is important that there be no lateral heat flow from the metered area (to adjacent areas) especially by convection loops within cavities within the metered wall.

9.7 INTERPRETATION OF DATA

The methods described in section 8.6 for the interpretation of data from heat flow meters are applicable to data produced by this technique. In the case of the portable calorimeter, the results are applicable to greater areas of the building component.

9.8 PREVIOUS USE, AVAILABILITY OF SERVICE AND TRAINING REQUIRED

This technique has been used only by BRD/NRCC of Canada. They have constructed about 10 portable calorimeters and have had private contractors construct other portable calorimeters using their specification. The cost of construction is estimated to be from $800 to $1000. No data are available describing training requirements; however, they should be equivalent to those described for heat flow meters in chapter 8.

9.9 PROGRAM APPLICATION RESTRICTIONS

The comments made in section 8.9 also apply to this technique.

REFERENCES

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[2] Treado, S. J. Thermal Resistance Measurements of a Built-Up Roof System, NBSIR 80-2100, National Bureau of Stadards, October 1980.

[3] Arumi, A. N. Thermal Inertia in Architectural Walls, DoE Report, University of Texas, Texas, February 1978.

10. ENVELOPE THERMAL TESTING UNIT

10.1 SUMMARY

The envelope thermal testing unit (ETTU) was developed by the Lawrence Berkeley Laboratory in order to evaluate the in-situ transient thermal performance of walls. It consists of two blankets which are attached to opposite sides of a wall and through which the heat flux to opposite wall surfaces can be controlled [1]. This unit was designed to overcome some of the difficulties in using heat flow meters and calorimeters for the in-situ evaluation of building components. It differs from those devices in that it is the heat flow that is controlled and not the temperature.

10.2 DESCRIPTION OF EQUIPMENT

The physical arrangement of the ETTU is shown in figure 10.1. The unit consists of two identical "blankets" which are placed in close thermal contact with opposite surfaces of a subject wall. The term "blankets" is used because they cover the wall section under test and are slightly flexible, so that they can be made to conform to slight irregularities in the wall surfaces. Placing the blankets in direct thermal contact with the wall eliminates complications associated with air film and considerably reduces the bulk of the unit.

Each blanket consists of a pair of large area electric heaters separated by a low-thermal-mass insulating layer. Embedded in each heater layer is an array of temperature sensors. Heat drive is provided by the primary heaters according to the time-dependent program which covers the relevant frequency spectrum. Each electric heater is designed to provide a heat output that is uniform over the whole area. The actual heat output is controlled by adjusting the voltage applied to the heater.

The guard function in the transverse direction is accomplished by the secondary heaters. The secondary heaters are driven by a servo-control which drives the measured secondary temperature T_s toward the measured primary temperature T_p. This reduces the temperature difference across the guard insulation and minimizes the portion of the drive heat that flows into the blanket and does not contribute to driving the wall. A microprocessor-controlled data-acquisition system is used to drive the system and to record the system response.

10.3 MEASUREMENT TECHNIQUE

The blankets are installed across a wall section as shown in figures 10.2 and 10.3. The microprocessor is programmed to give the schedule of heat fluxes to which the wall is to be subject. Since the guard function in the transverse direction limits multipath heat flow and when uniform heat flow, i.e., power is attained, the data and analysis applies to the central test section where normal heat flux is developed. The data is analyzed in the manner as the data obtained from heat flow meters and calorimeters if the thermal resistance of the wall is to be calculated. In particular, the periods of measurement noted in the sections on those methods must be observed.

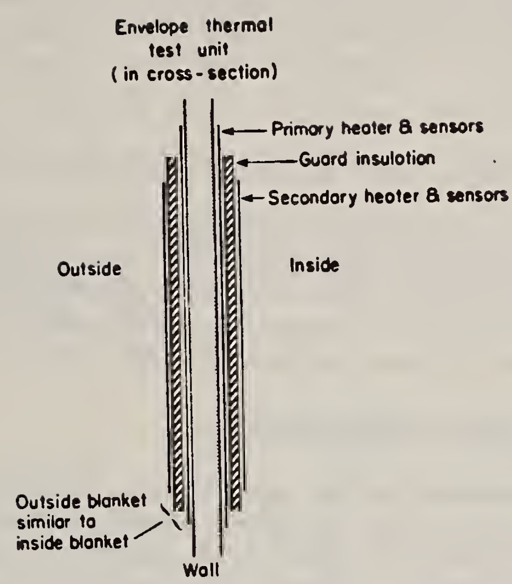

Figure 10.1 Schematic of envelope thermal testing unit [1]

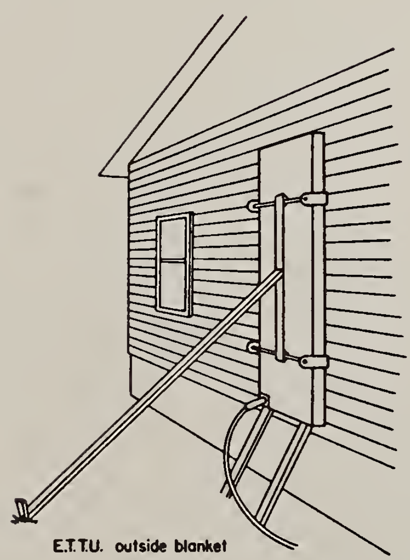

Figure 10.2 Outside blanket

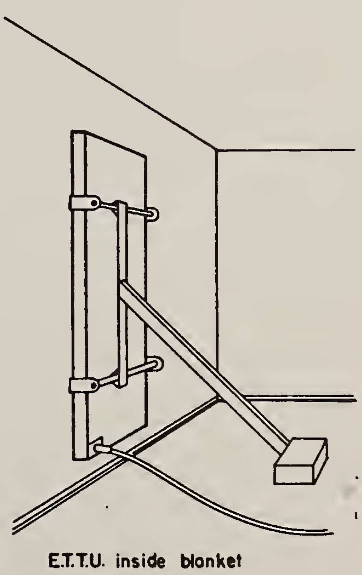

Figure 10.3 Inside blanket

10.4 ACCURACY OF THE METHOD

After calibration of the envelope thermal testing unit, it is reported that the thermal resistance of the building element can be determined within ± 5 percent. If a suitable heat flux schedule is programmed into the computer, the dynamic reponse of the building element can be accurately modeled using a simplified thermal parameter model which determines the thermal conductance, the time constant of the wall and a series of inside and outside surface thermal storage coefficients [2,3].

10.5 PREVIOUS USE, COST, AVAILABILITY OF EQUIPMENT AND TRAINING REQUIRED

This equipment has been only used in research situations and must still be considered as being under development. The training of the personnel who performed the measurements would probably be comparable to that required of personnel who perform portable calorimeter measurements (section 9.8). This equipment is estimated to cost between $5,000 and $10,000.

10.6 PROGRAM APPLICATION RESTRICTIONS

This measurement technique can be used where accurate determination of the thermal characteristics of the building envelope are required. Its high accuracy makes it suitable for the verification of thermal specifications in new and retrofit buildings. Since this technique requires the application of both an exterior and interior blanket, it may be difficult to use on the upper stories of tall buildings. It cannot be used in below grade applications. This technique should be applicable to both cold and warm climates. Where possible it should be used after a thermographic survey of the building has been performed.

REFERENCES

[1] Condon, P. E., Carroll, W. L., and Sonderegger, R. C. A New Measurement Strategy for In Situ Testing of Wall Thermal Performance, Proceedings of the Thermal Performance of Exterior Envelopes of Buildings, ASHRAE, 1981.

[2] Sherman, M. H., Sonderegger, R. C., and Adams, J. W. The Determination of the Dynamic Performance of Walls, Submitted for presentation at ASHRAE winter meeting, 1982.

[3] Adams, J. W., Sherman, M. H., and Sonderegger, R. C. Dynamic Measurement of Wall Thermal Performance, Proceedings of DoE/ASTM Conference, Thermal Insulation, Materials and Systems for Energy Conservation in the '80's, December 1981, Clearwater, FL.

11. GLOSSARY

Aerial infrared survey - see survey, aerial infrared.

Aerial thermography - see survey, aerial infrared.

Air change rate - air leakage in volume units per hour divided by the building space volume with identical volume units (normally expressed in air changes per hour, ACH or ACHP).

Air flow or velocity measuring system - a device or assembly of components to measure air flow within the ± 6 percent of the average value (air flow or velocity measuring system calibrations shall follow the manufacturers instructions, and be recorded as such; alternatively a calibrating wind tunnel may be used, and recorded as such). Sensors and displays may vary from simple instruments (based on air pressure changes) to complex arrangements of sensing elements with electronic interfaces for amplification and analysis of signals with displays and data recording systems.

Air leakage rate - the volume of air movement per unit time across the building envelope. This movement includes flow through joints, cracks, and porous surfaces, or combination thereof. The driving force for such an air leakage in service can be either mechanical pressurization and evacuation, natural wind pressures, or air temperature differentials between the building interior and the outdoors, or combinations thereof.

Air leakage graph - the graph which shows the relationship of measured air flow rates to the corresponding pressure differences.

Air moving equipment - a fan, blower, or blower door assembly, which is capable of moving air into or out of the building envelope at required flow rates under a range of test pressure differences. The system shall provide constant air flow at fixed pressure for the period required to obtain readings of air flow rate or velocity, and at each incremental pressure difference.

Air sample containers - non-absorbent, inert, low permeability containers (e.g., sample bags, syringes with needle caps, or plastic bottles) used to collect and store air samples from buildings under test.

Anomalies, thermal - the heat loss characteristics of a structure which are not in accordance with intended design characteristics.

Apparent radiant temperature - see temperature, apparent.

Aspect ratio - see ratio, aspect.

Background - the irradiance at the entrance aperture of the infrared sensing system which is not radiated directly from the object being investigated.

Blackbody - An ideal thermal radiator (emissivity = 1.0), which emits and absorbs the maximum theoretically available amount of thermal radiation at a given temperature.

Bridge, thermal - a low thermal resistance path connecting two surfaces.

Building enclosure - the aggregate of materials and components that make up the exterior shell of the building.

Building envelope - the exterior shell enclosing the interior space.

Building heat loss characteristics - see characteristics, building heat loss.

Building performance evaluation - an investigation of the appropriateness and adequacy of the building enclosure as an environmental separator between indoor and outdoor environments.

Building science - fundamental laws of physics and chemistry and their effects on complex assemblies of building materials.

Building science thermologist - a specialist who has fundamental knowledge of the cause and effect for certain building enclosure problems and who has the skills of a thermologist.

Building space - the volume of a building that exchanges air with outside ambient air. In most cases, this volume is the deliberately conditioned space within a building, generally not including the attic space, basement space, and attached structures, unless such spaces are connected to the heating and air conditioning system, such as a crawl space plenum.

Characteristics, building heat loss - those properties of a structure which pertain to the loss of energy through the building envelope.

Coefficient, convective film - constant of proportionality relating the convective rate of heat transfer at a surface to the temperature difference across the air film on that surface.

Coefficient, radiation - constant of proportionality which relates the radiation energy exchange between a surface and its surroundings to the temperature difference between the surface and its surroundings.

Convective film coefficient - see coefficient, convective film.

Copy, hard - see record, hard copy.

Detector, infrared - A device which transduces the infrared irradiance incident upon it into some other form of energy, in most cases electrical.

Device, infrared sensing - A wide class of instruments used to display and/or record information which is proportional to or equivalent to the thermal radiation from any object surfaces viewed by the instrument. The instrumentation varies in complexity from simple spot radiometers which measure only one "spot" or area to full two dimensional thermal imagers which provide photographic type quality pictures which map the scene radiosity.

Emittance, spectral band - The ratio of radiant energy from a surface at a given temperature to the corresponding radiant energy from an ideal surface (blackbody) at the same temperature for a portion or spectral band of the electromagnetic spectrum.

Equilibrium, thermal - Condition where heat flow through a structure has reached a steady state condition. For building diagnostic purposes, this condition is approached when the environmental conditions remain approximately steady over a period of time.

Equipment-use services - Services provided by companies that use infrared sensing devices to perform heat loss surveys of structures.

Exfiltration - Air flow outward through a structure.

FOV - See Field of View.

Field of View (FOV) - The total angular dimensions within which objects can be imaged, recorded and displayed by an imaging device when pointed in a fixed direction.

Fissures - For the purposes of this report, narrow openings or cracks in insulation having dimensions of at least 125 mm (5 inches) by 25 mm (1 inch) and less than the dimensions specified for a void.

Fundamental principles of building science - These principles can be generally divided into the categories of the physics, materials and enclosures with the following subcategories:

A. Physics
   1. heat transfer and radiation
   2. psychrometry
   3. air movement
   4. fluid dynamics
   5. structure
   6. sound

B. Materials
   1. nature of materials
   2. durability of materials
   3. deterioration of materials
   4. strength of materials
   5. combustibility and resistance

C. Enclosure
   1. heat transfer
   2. water and moisture penetration

3. air movement
4. structural stability
5. fire prevention and control
6. sound control
7. performance of enclosure elements
    - roofs
    - walls
    - windows
    - foundations

Heat capacity - the quantity of heat needed to cause a described temperature change in a known mass of material.

Heat transfer - the movement of heat energy from a location of higher temperature to a location of lower temperature. This can occur by conduction, convection, or radiation depending on the characteristics of the material involved and the energy transfer.

Imaging line scanner - See scanner, imaging line.

Imaging system - See system, infrared imaging.

Infiltration - Air flow inward through a structure

Infrared sensing device - See Device, infrared sensing.

Interior space - See building space.

Irradiance - The radiant power per unit area incident on a surface.

Lag, thermal time - The phase difference in hours between the exterior and interior surface temperatures when the exterior surface is subjected to a temperature change.

Line scanner - See scanner, line.

Minimum resolvable temperature difference (MRTD) - See MRTD.

MRTD - Minimum, resolvable temperature difference - A measure of the ability of an infrared imaging system to allow the human observer to recognize periodic bar targets on the display. The MRTD is the minimum temperature difference between a standard periodic test pattern (7:1 aspect ratio, 4 bar) and its blackbody background at which an observer can resolve the pattern as a four bar pattern. Unlimited viewing time and optimization of instrument level and gain controls are allowed.

NADIR - The object point which is directly beneath the aircraft flying an airborne imaging survey

NEΔT - Noise, equivalent temperature difference, - A measure of the noise of an infrared imaging system or line scanner. It is the target to background temperature difference between a low spatial frequency blackbody target and its blackbody background at which a ratio of one is obtained between the peak-to-peak-signal and RMS noise at the output of the detector processing electronics of the sensor in question.

Noise equivalent temperature difference - See (NEΔT).

Object plane resolution - See resolution, object plane.

Partial voids - Areas of similar size to voids which are insulated but where the insulation thickness is less than the full specified insulation

Pixel - A picture element on a video display.

Pressure difference - The actual pressure difference across the building envelope; expressed as lbf/ft^2, Pascals (Newtons/m^2), inches of H_2O, or inches of Hg.

Pressure measuring device - manometer or pressure indicator to measure pressure difference, with an accuracy of $\pm$ 0.01 inches of H_2O ($\pm$ 2.5 pascals).

Pump - A non-contaminating air sample pump, either manual or powered, used to fill air sample bags. Plastic bottles can be filled by hand squeezing.

Qualitative test - Applied to determine the occurrence, the type and the distribution of a property.

Quantitative test - Applied when a numerical value of a property is required.

Radiance - The total radiant flux per unit solid angle per unit projected area which emanates from a surface. It includes the self-emitted radiation plus reflections from sources other than the object of interest, as intercepted from the direction of measurement. See Radiosity.

Radiation Coefficient - See Coefficient, radiation.

Radiometer, spot - An apparatus which measures the average radiosity or average apparent temperature of the surfaces subtended by its field of view, (since the spot radiometer has no scanning mechanism its IFOV is the same as its FOV).

Radiosity - The total radiant flux which leaves a surface per unit area. The radiosity is the sum of the radiant flux emitted and reflected by the surface plus any radiant flux transmitted through the surface. See Radiance.

Ratio, aspect - The ratio of the length to the width of a rectangle. Also, the ratio of length to width to height of a building shape.

Record, hard copy - Any permanent record. Typically, the record will consist of photographs, magnetic tapes or some data log documentation.

Reflection, thermal - That portion of the radiosity from a surface which is contributed by reflection.

Resistance, thermal - A measure of the insulating quality of a building envelope component based on steady-state conditions.

Resolution element - See Field of View.

Resolution, limiting - The highest spatial frequency of an object space target which an imaging sensor is able to resolve. The spatial frequency of the target is determined by taking the inverse of the ratio of two bar widths divided by the distance from sensor to target. This number is generally multiplied by 1,000 and expressed in cycles per milliradian.

Resolution, object plane - The size in the object plane which corresponds to the product of the system's instantaneous field of view in radians and the distance from the system to the object.

Resolution, spatial - The planar angle defined by the instrument instantaneous field-of-view, i.e., the resolution element.

Resolution, thermal - A measure of the capability of an infrared sensing device to distinguish the apparent radiance temperature difference between two blackbodies near the same temperature.

Sampling network - A network consisting of tubing, tubing junctions, a pump, and possibly an aspirator. This network is used to draw samples from remote locations within a structure, blend them, and bring the blended sample to a convenient place for analysis. In general, it is best to avoid plasticized tubing such as vinyl; use copper, stainless steel, or possibly polypropylene or nylon. The experimenter should be aware that surface absorption within the sampling network can be a major source of confusion in any concentration decay measurement.

Scanner, imaging line - An apparatus which scans in a single dimension and is moved perpendicular to the scan direction to produce a two-dimensional thermal map of the scene. See also Survey, aerial infrared and Scanner, line.

Scanner, line - An apparatus which scans along a single line of a scene to provide a thermal mapping of a discrete width or slice of the scene. See also scanner, imaging line.

Sensing device, infrared - See Device, infrared sensing.

Shading - The percentage of total radiation from the surrounding hemisphere which does not irradiate a structure surface because of an obscuration.

Spatial resolution - See Resolution, spatial.

Spot radiometer - see Radiometer, spot.

Surface emittance - See Emittance, spectral band.

Survey, aerial infrared - The generation of thermograms of building structures as viewed from an overhead platform using an imaging line scanner.

Survey, imaging exterior - The generation of thermograms of building outside surface.

Survey, imaging interior - The generation of thermograms of portions of a building as viewed from the building interior.

Survey, non-imaging - The generation of a set of apparent temperature measurements of building surfaces (usually the interior) obtained with a non-imaging thermal sensing device.

Syringes - Disposable syringes may be used to inject gas samples when the gas monitor is the gas chromatograph. The use of a plastic bottle containing tracer gas or tracer gas air mix can also be used.

System, infrared imaging - An apparatus which converts the two dimensional spatial variations in infrared radiance from any object surface into a two dimensional thermal map of the same scene in which variations in radiance are displayed in gradations of gray tone.

Temperature, apparent - The temperature of an object as determined from the measured radiance (see definition of Radiance).

Temperature, blackbody equivalent (apparent temperature) - The apparent temperature of an object as determined from the measurement of its radiance and the assumption that it is an ideal blackbody with emissivity of 1.0.

Thermal anomalies - See Anomalies, thermal.

Thermal Bridge - See Bridge, thermal.

Thermal pattern - A gradient representation indicating regions of temperature variation.

Thermal resolution - See Resolution, thermal.

Thermal time lag - See Lag, thermal time.

Thermogram - A photograph or two dimensional record of an image which maps the apparent temperature of the scene as sensed by an infrared imaging system.

Thermographer - An infrared camera operator who is able to adjust controls to provide useful thermal images. Thermographers also have the ability to produce high-quality thermograms plus isotherm images as well as to use single or dual isotherms. A thermographer has the skill necessary to adjust all images, grey scale or step scale. A thermographer is able to complete a standard recording format for work completed and is expected to provide a preliminary report that identifies problems, interprets the mechanisms of the problems, records the exterior microclimate and orientation of the building, room plan indications, and location and direction of internal thermal imagery.

Thermography - The process of generating a thermogram by using an infrared imaging system, usually with some means of temperature calibration.

Thermography, Aerial - See Survey, aerial infrared.

Thermologist - A camera operator who is competent in all the skills of a thermographer. In addition, a thermologist must have a greater knowledge of building construction, building materials, and basic knowledge of building science principles, especially those related to temperature and psychrometry. In addition, a thermologist must be capable of interpreting causes and effects of common building problems, and proposing appropriate solutions.

Thermology - is a combination of thermography, building science and building technology.

Time lag, thermal - See Lag, thermal time.

Time Lag - See Lag, thermal time.

Tracer gas - A gas that can be mixed with air and measured in very small concentrations, making it possible to detect air movements and measure air change rates. Typical gases are SF_6, N_2O, CO, CO_2.

Transmittance - The ratio of the radiant energy transmitted through a body to that incident upon it.

Void - For purposes of this standard, a void is defined as any localized area of the building envelope which has a significantly different thermal resistance from the area surrounding it.

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBSIR 82-2605	2. Performing Organ. Report No.	3. Publication Date November 1982

4. TITLE AND SUBTITLE

MEASUREMENT METHODS FOR DIAGNOSTIC PROCEDURES IN EVALUATION OF THERMAL INTEGRITY OF BUILDING ENVELOPES

5. AUTHOR(S)

Grot, Richard A., Burch, Douglas M., and Silberstein, Samual

6. PERFORMING ORGANIZATION *(If joint or other than NBS, see instructions)*

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

Public Buildings Service
General Services Administration
Washington, D.C. 20405

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

This report presents reviews of various measurement and inspection techniques appropriate for the development of detailed diagnostic procedure for assessing the thermal performance of the exterior envelopes of federal buildings. The inspection techniques include the use of ground-based infrared thermographic surveys, aerial infrared surveys, tracer gas air infiltration measurement, pressurization tests for measuring the tightness of the building envelope, and spot radiometer surveys for detecting gross defects. Heat flow meters, a portable calorimeter, and a microprocessor-driven envelope testing unit are also considered.

For each technique recommended procedures are provided; they include equipment requirements, conditions under which the techniques can be carried out, calibration, accuracy, and limitations. The detailed diagnostic procedures specific to small and large federal buildings require further development from on-site field testing of representive buildings.

An Executive Summary provides an overview of the Building Diagnostic Program of which Phase I is covered in this report. Field test evaluations will be carried out in Phase 2 and implementation under Phase 3.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

Air infiltration rates; envelope thermal performance; infrared imaging; radiometers; thermal bridges; thermographic surveys; tracer gas techniques.

13. AVAILABILITY

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☐ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.
☒ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES

140

15. Price

$13.50

USCOMM-DC 6043-P80