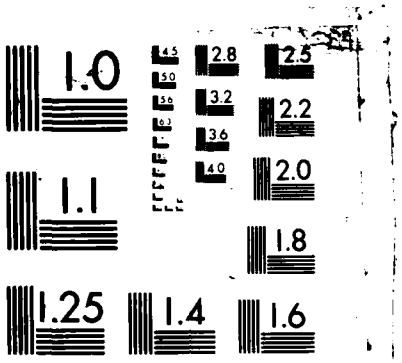
AD-A179 142 REFERENCE GUIDE FOR BUILDING DIAGNOSTICS EQUIPMENT AND TECHNIQUES(U) AIR FORCE ENGINEERING AND SERVICES CENTER TYNDALL AFB FL ENER C MCKENNA ET AL JUL 86 1/2

UNCLASSIFIED AFESC/DEB-TR-86-06 MIPR-F82-79 F/G 13/1 NL



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Reference Guide for Building Diagnostics Equipment and Techniques

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COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
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JULY 1986

ENERGY GROUP
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SECURITY CLASSIFICATION OF THIS PAGE

ADA179142

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704 0188
Exp Date Jun 30 1986

1a REPORT SECURITY CLASSIFICATION Unclassified	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY Unclassified	3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
2b DECLASSIFICATION/DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S)	5 MONITORING ORGANIZATION REPORT NUMBER(S) DEB-TR-86-06
6a NAME OF PERFORMING ORGANIZATION Army Cold Regions Research & Engineering Laboratory 6b OFFICE SYMBOL (If applicable) EC	7a NAME OF MONITORING ORGANIZATION Air Force Engineering and Services Center
6c ADDRESS (City, State, and ZIP Code) 72 Lyme Road Hanover, NH 03755-1290	7b ADDRESS (City, State, and ZIP Code) Energy Group Tyndall AFB, FL 32403-6001
8a NAME OF FUNDING/SPONSORING ORGANIZATION Air Force Engineering & Services Center 8b OFFICE SYMBOL (If applicable) DEMB	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER MIPR F82-79
8c ADDRESS (City, State, and ZIP Code) Tyndall AFB, FL 32403-6001	10 SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO / PROJECT NO / TASK NO / WORK UNIT ACCESSION NO

11 TITLE (Include Security Classification)
Reference Guide for Building Diagnostics Equipment and Techniques

12 PERSONAL AUTHOR(S)
C. McKenna, R. Munis

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Final	FROM Aug 82 TO Jul 86	July 86	148

16 SUPPLEMENTARY NOTATION

17 COSATI CODES		
FIELD	GROUP	SUB GROUP

18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Building diagnostics, energy conservation, energy management, energy diagnostics equipment, energy diagnostics techniques, heat flow measurement, air leakage, building enclosure, energy meters, temperature measurement, humidity measurement. (OVER)

19 ABSTRACT (Continue on reverse if necessary and identify by block number)
This report is designed for use by facilities engineers as a guide in the initial phases of investigating building diagnostics equipment and techniques. It provides information related to energy management and building environmental considerations resulting from energy conservation measures. Subjects covered include: 1) building enclosure system evaluation (Chapters 1-4); 2) heating, ventilating and air conditioning (HVAC) system evaluation (Chapters 5-8); 3) lighting illuminating system evaluation (Chapter 9); 4) electrical system evaluation (Chapters 6, 8 and 10); and 5) indoor air quality measurements (Chapter 11).

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION Unclassified
22a NAME OF RESPONSIBLE INDIVIDUAL FREDDIE L. BEASON	22b TELEPHONE (Include Area Code) (904) 283-6461 / 22c OFFICE SYMBOL DEMB

DD FORM 1473, 84 MAR — All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

18. SUBJECT TERMS (CONT)

velocity measurement, volume measurement, stack gas analysis, illumination measurement, lighting system evaluation, electrical measurements, indoor air quality.

PREFACE

This report was prepared by the Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire 03755, for the Air Force Engineering and Services Center, Tyndall Air Force Base, Florida 32403, with tri-service funding. The report documents work performed during the period Aug 1982 to July 1986. Air Force funding was provided via USAF MIPR F82-79 dated 2 Aug 1982 to CRREL. Navy funding was provided via MIPR N6830582MP20023 dated 20 April 1982 to CRREL. Army funding was provided through the AT42 project area in January 1982. The CRREL Project Manager was Charles M. McKenna.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

The authors wish to acknowledge S. Flanders, C. Korhonen and S. Marshall of CRREL for their contributions.

This technical report has been reviewed and is approved for publication.

Freddie L. Beason, P.E.
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Major, USAF
Chief, Energy Division

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REFERENCE GUIDE FOR BUILDING DIAGNOSTICS EQUIPMENT AND TECHNIQUES

INTRODUCTION

The energy crisis of the 1970's fostered a sudden, urgent need for energy conservation measures and, as a result, the field of building diagnostics was greatly stimulated. Traditional building codes had been centered on the health, safety and welfare of the occupant. But with the rapid upsurge in energy saving needs, traditional demands were often overlooked. Recently, the urgent need for energy savings has subsided, although conservation needs have not. Often conservation has been accomplished at the expense of occupant welfare, creating a whole new set of problems. As a result, the array of energy-efficiency diagnostic equipment and techniques has been augmented by other equipment for measurement of health and safety factors such as air quality, lighting, noise pollution, etc. This guide is intended to help the facilities engineer provide environmentally sound energy conservation.

Those using this reference guide may find it useful to use the information presented to help better define their problems and to select reasonable solutions. There are many ways to effect energy conservation. This guide attempts to present information on diagnostic equipment and techniques which should be generally applicable to all building types. Sections on Building Enclosures; Heating, Ventilating and Air Conditioning; Lighting/Illuminating; Electrical; and Indoor Air Quality provide information on the different aspects of energy system diagnostics that should aid analysis of existing facilities as well as new construction.

Cost figures are 1986 dollars unless otherwise noted.

Where possible, manufacturers of equipment are listed so that, as the energy diagnostic approach becomes better defined for the readers specific application, more detailed informaiton can be obtained than is possible to present here. The manufacturers listed for each item are intended to give the reader a start in obtaining more information and are not intended to be exhaustive. Readers will eventually develop a more exhaustive file of data applicable to their specific areas of concern.

SUMMARY

Three classes of portable infrared devices can be used for building diagnosis: thermal imagers, spot radiometers and line scanners. None of these devices used by themselves can produce an absolute measurement of temperature, but some devices or systems will produce differential measurements of temperature.

Each class and production model of infrared device has certain advantages and limitations. Their uses overlap.

Much of the recent development in thermal imagery has occurred with accessories manufactured specifically for these imagers.

Some thermal imagers are multiple component systems, with a view finder or monitor. Some require cooling. They, like all infrared imagers, work on the principle of converting thermal energy reaching a sensor into an electrical signal, which is then displayed as shadings of light.

Spot radiometers are cheaper, less sophisticated devices than thermal imagers. A spot radiometer does not produce an image of the surface, and since the area "viewed" by the device increases with distance from the surface to the instrument, a calculation must be made to determine the size of the target at each distance.

Only one portable line scanner is being manufactured and sold in the United States. There are, however, mounted airborne line scanners also in current use. The unique quality of some portable line scanners is that they feature a composite thermal/visual display that enables the operator to view a scene and obtain an image of that scene superimposed by a line of temperature distribution.

All portable imaging systems/devices can be used for energy audits, for quality control inspection of insulation installation and nondestructive detection (but not confirmation) of moisture in walls and built up roof systems. In most cases, the imagers can be used for interior or exterior inspections, although there are instances in which only one is possible.

Procedures for the use of thermal systems or devices have been and continue to be developed through ASHRAE and ASTM. The ASHRAE Standard 101-1981 describes most of the infrared sensing devices currently available from commercial sources and the accompanying procedures. For wood frame cavity walls, the ASTM proposed procedure describes the use of thermal imaging devices for quality control inspection of new insulation.

There are two techniques other than infrared thermography that are used for non-destructive inspection of built up roofing systems to detect moisture intrusion under the membrane. Nuclear meters and capacitance sensors have been used successfully to detect moisture under built up roof membranes. The nuclear meter requires a grid system to be marked on the roof for identification of measurement location. The capacitance meter can use either a grid or continuous strip reading to locate moisture. The resolution depends on the fineness of the grid. The number of measurements

goes up as the square of grid frequency. Since it is only possible to make a measurement at specifc locations with these instruments, an inspection will take considerably longer using one of them than with thermal imager and some areas of moisture may be overlooked. However, they can be used during daylight hours when operations are considerably less difficult.

In other areas, recent advances in technology have made it possible to automatically measure the air leakage in buildings with tracer gas releases. The three tracer gas methods are dilution, constant concentration and constant flow. The tracer dilution method is versatile and the simplest to use of the three. With the use of air sample bags, tracer dilution does not require highly skilled techniques.

Tracer gas methods are highly dependent upon weather conditions at time of tracer release. Fan pressurization and depressurization can measure building tightness independent of weather conditions. But, the larger the building, the more cumbersome the fan method becomes. The fan method can enhance observation of air leakage paths with infrared thermography.

Infrasonic apparatus have been used experimentally for characterizing air leaks in small buildings.

Other air leakage methods employ commercial smoke tracer devices that can provide smoke at a well-defined location so a stream of smoke will follow the leakage path giving visual evidence.

Heat flux transducers (HFTs) are wafer-like sensors which, when placed on building walls or roofs with temperature sensors, can provide a field measurement of R-value. A data acquisition system typically must accumulate differences in temperature and heat fluxes for 48 hours in 40°F cooler weather.

It is desirable to combine thermal imagery with multiple HFT/ temperature measurement to map and quantify the thermal resistance of a building enclosure.

Portable calorimeters are relatively new developments for evaluating the thermal performance of walls. They should be used in conjunction with thermal imagers.

There are many measuring devices used for HVAC system evaluations. These devices measure surface and air temperatures, ambient humidity, air velocity, volume and pressure. A relatively recent development is the combining of many of these measuring devices into an energy management and control system (EMCS). The EMCS is a centralized energy management system that employs an off-the-shelf mini or micro computer system. This serves to control functions, at multiple locations, for HVAC, lighting and boiler systems. In order to control a certain system, the EMCS must be able to monitor various functions. This monitoring can be considered a part of the diagnostic process since it usually provides a display of data that relate to building system performance.

Energy metering is an important part of energy management and control. Many different types of meters are available to measure the flow of liquids, gases, steam and electricity. The choice of which meters to use and where to locate them depend on how the data will be used and how the energy system is designed.

Stack gas analyzers are available in portable and fixed types and are useful in maintaining high efficiency condensation in boilers and furnaces.

Thermal imagers can safety detect hot electrical equipment, such as transformers, insulators or connections. The chief advantage of a thermal

imager is that it can be used remotely and rather quickly to monitor the temperatures of an electrical system without disrupting normal system operation.

One of the most widely used devices for conducting an energy audit of a building's illumination system is the light meter. This device consists of a photocell, appropriate filters and a meter to register the lighting level. Selenium and cadmium sulphide cells are commonly used in a typical light meter. With the development of the microcomputer, the results of a walk-through lighting audit can be processed on the site immediately by sending the data over telephone lines to a central computer.

Indoor air quality has recently become a major concern of professionals responsible for the design, operation and maintenance of large buildings, especially those that are energy efficient. With the introduction of potentially toxic chemical compounds into furnishings, construction materials and insulation for the residential market, concern has become even more widespread. In order to obtain some measurement of indoor air quality to determine maximum acceptable concentration levels of pollutants, a number of both passive and active monitoring devices have been developed. These devices can be used to monitor concentration levels of carbon monoxide, formaldehyde, fibrous aerosols, nitrogen dioxide, ozone, radon and sulphur dioxide. These measuring devices range widely in cost.

CHAPTER 1

NONCONTACT TEMPERATURE MEASUREMENT/THERMAL PATTERN RECOGNITION

THERMAL IMAGERS

Measurement and Analysis. Infrared technology is used for the observation and recording of surface temperature variations. Differences in the thermal resistance or the thermal storage capacity of a building enclosure system (walls, roof) produce variations of temperature over the surfaces as does the leakage of cold or warm air through the enclosure system. These variations can be located and recorded to determine the position and size of insulation defects, thermal bridges, air leaks and moisture damage.

Thermal radiation emitted by any object (e.g. building surface) can be used to form an image of that object and to determine its temperature. The amount of radiation from a surface depends on the temperature of that surface and its composition, color, and texture. An infrared-radiation-sensing device can be used to (1) record an image and measure the temperature of the surface, (2) record only the image of the surface, or (3) measure the temperature of the surface.

Infrared sensing devices that image and/or measure surface temperature can determine only relative temperature differences across a surface. If the actual temperature of the complete surface is to be determined, it is necessary to first find the actual temperature at one point on the surface. If that is not possible, then the surface spectral emittance (often available in certain literature) and the calibration data of the infrared device must be known.

Three classes of portable infrared devices are used for building diagnosis: imagers, spot radiometers, and line scanners.

Imagers can be separated into two distinct categories: cooled and uncooled. Both types of imagers can be further divided into (1) multiple component systems (composed of a separate scanner and monitor) that provide the operator with a thermal image of a surface on a TV-type monitor, and (2) a single component system that must be hand-held in order to obtain an image of a surface through a view-finder/monitor provided on the device. Within these two classes ther are imagers that can (1) record an image and measure the temperature of the sample and (2) display the image of the surface.

The operation of all thermal imagers can be explained by the same basic principle. An optical system transparent to thermal energy focuses this energy onto a sensor that converts it into electrical energy. This electrical signal is processed to produce a display on a monitor in the form of a "heat picture" image of the object on which the infrared device is focused. Depending on the type of imager, the monitor screen displays varying intensities of grays, reds, or greens. In the conventional mode of imager operation, the lighter images depict higher surface temperatures, and the darker images lower surface temperatures. Intermediate tones indicate temperatures between the two extremes.

The image on the screen can be recorded with a Polaroid or 35-mm camera, or on video or digital tape. If the image is video taped, photographs can be made of the video image. Photographs of a heat image are known as thermograms.

Cooled Sensors

There are two types of cooling techniques used in single and multiple component imagers: cryogenic and thermoelectric. Liquid nitrogren and

high pressure argon gas are used as cryostat coolants in both multiple and single component imaging systems, while thermoelectric coolers (heat pumps) are used currently in only a few systems.

The portable systems that utilize cryogenic cooling have the advantage of drawing only a relatively small amount of power from their batteries; however, this is balanced by the requirement that these systems need Dewar flasks, cylinders, compressors or other storage and that the sensor cryostats require periodic refilling. Thermoelectric coolers do not require bulky reservoirs or periodic refilling and are so reliable that a failure is usually defined as a loss of a few degrees in cooling over a long time period.

Uncooled Sensors

Pyroelectric vidicon systems (thermal television cameras) require no cryogenic cooling. The sensors in these systems respond only to changes in radiance so that radiation from a target must be modulated in order to produce a thermal image. In lieu of mechanical modulation of the image, panning the camera will produce changes in the radiation emanating from a target, which in turn will produce an image. A stationary camera will also produce an image if there is target movement in the scene.

More important to building dianostics and preventative maintenance are the types of recording available for documentation. Not all systems can record thermal images on photographs, video or digital tape.

The techniques by which apparent temperature differences are measured vary somewhat among these systems. However, the most important point to remember is that no thermal imaging system or device can be used to make an actual temperature measurement of a surface without a reliable radiation

calibration source (which produces a reference temperature). This reference temperature can be established through (1) a contact measurement of the surface, (2) placement of a reference radiation temperature source in the field of view, or (3) a radiation measurement using a calibrated spot radiometer. Both (2) and (3) require knowledge of the spectral emittance of the surface.

Whether a measurement of apparent temperature differences or just a documentation of thermal patterns is required, a parameter known as the Minimum Resolvable Temperature Difference (MRTD) is significant in order to determine if an infrared sensing device at a critical distance from a target of a certain size can resolve and measure its temperature. The MRTD of any infrared sensing device is established through a standardized measurement procedure. Since not all devices have an established MRTD, a valid comparison among all those in current use is not currently possible. However, the difference in inherent image resolution between any two devices, e.g. single component and multiple component, can be attributed to the MRTD of each device.

Accuracy

Some imaging systems do not have the capacity for measuring surface temperatures. The data that are obtained with these systems are qualitative and subject to interpretation. The only quantitative data that can be generated by such a system are the percentages of black-white/color contrast displayed/recorded by the system. For example, a black-white thermal image of an insulated wall shows a certain percentage of that wall characterized by gray tones ranging from black to white. The area of each gray tone can be determined and related to the amount of insulation in the

actual wall. It is difficult to specify the accuracy of this procedure because those areas are various sizes and shapes and are subject to qualitative interpretation. No baseline tests to determine accuracy have been conducted at this time.

It is also difficult to specify an accuracy for those imaging systems that can be use for measurement of surface temperatures. Since almost all infrared systems and sensing devices require an independent reference temperature (e.g. blackbody, contact thermometer) with which to derive a complete and absolute temperature map of a surface, the precision of the measurement will depend upon the reference temperature source as well as the infrared system/sensing device and can only be as good as the stated precision of the temperature reference source. The lack of a linear relationship between the electrical output signal of the sensor and the operator marker settings over a wide range of temperatures makes it difficult to specify the accuracy of temperature differences measured with an imaging device. The accuracy of these measurements depends upon the application and the device and can vary from a few percent to approximately 15 percent.

Advantages

Thermal imagers are noncontact devices used to monitor the temperature of remote surfaces.

Both types of imagers may be operated by one person, and can be either carried or vehicle mounted. Most imagers can utilize either video or photographic processes. Because of the two-dimensional monitor image presented, identification of the exact target area surveyed is relatively easy. Most imagers, also, have a fairly large field of view at short distances from the target, and will develop an image in real time. Some

imagers can quickly measure discrete surface temperature differences. In all, anomalous reflections from a target are relatively easy to discern from real temperature variations of the target.

Some imagers have self contained systems that need no additional coolant. One of the chief advantages of uncooled detector imagers is that they can be operated in a horizontal or vertical position.

Limitations

An imager used for ground-based surveys cannot easily be adapted for simultaneous display of visual and thermal images. Some systems canot measure discrete temperature differences. The cost of an imaging system is greater than that of other noncontact radiation sensing devices.

Liquid-cooled imagers require a mirror for vertical viewing. Uncooled imagers require change or interruption of target radiation.

Cost. Depending upon the characteristics of each of the infrared systems/sensing devices and optional equipment that can be ordered with each the cost will range from $11,000 to approximately $90,000.

New Technology/Developments. The basic technology in cooled detector imaging systems/devices has been evolving during the past 15 years. Much of the development of new technology has been associated with accessories that are sold with those systems/devices. Development of new technology for uncooled detector imaging systems/devices has occurred during the past [illegible] years. One of the most recent developments in uncooled systems/devices is the capacity to measure apparent surface temperatures.

Manufacturers. AGA Corp., 550 County Ave., Secaucus, N.J. 07094, (201) 867-5390; Inframetrics, 12 Oak Park Drive, Bedford, MA, 01730, (617) 2[illegible]-3940; Hughes Aircraft Co., Industrial Products Div., M/S 514, 6155 El

PORTABLE LINE SCANNERS

Measurement and Analysis. The line scanner is a portable infrared scanning instrument which is pointed at a target and allows the operator to see a thermal line scan which may or may not be superimposed upon a visual image of the target. This line scan represents the temperature distribution along a single line on the target. The composite display enables the operator to locate and analyze thermal characteristics of a target surface. Unlike some scanners, the line scanner sensor operates wthout cryogenic cooling. A line scanner can be hand-held or tripod-mounted. When records are required, a photographic recording accessory is available. Measurements can be made over various selectable temperature scans. Some thermal imaging systems also include a line scanner capability.

Accuracy. The accuracy of the portable line scanner is difficult to assess for some of the same reasons as for imaging systems.

Advantages

The line scanner can be used to obtain a temperature distribution on a lineal plane of the target image for remote locations. The scanner creates a composite thermal/visual display and the operator views the image of a scene superimposed by lines of temperature distribution. The scanner can be positioned either horizontally or vertically and the sensor does not need cooling.

Only one photograph of the surface is required for a single line temperature distribution analysis.

Limitations

Unlike thermal imaging systems which require one scan of a surface (e.g., building wall), many scans (and a photograph) must be used for line scanners, and actual temperatures cannot be measured directly. Videotape recording is not available with the line scanner. Line scanners are only slightly less costly than two-dimensionally imaging systems.

Cost. The cost of portable line scanners is approximately $9,000 to $13,000.

New Technology/Developments. Currently there is only one basic type of portable line scanner being manufactured. There are no known major technological developments/changes being made to this device.

Manufacturers. Pyrometer Instrument Co., Inc., 234 Industrial Parkway, Northvale, NJ 07647, (201) 768-2000; Wahl Instruments, Inc., 5750 Hannum Ave., Culver City, CA 90231, (800) 421-2853 or (213) 641-6931. Mikronel Instrument Co., 1570 Cherokee St., San Marcos, CA 92069, (619) 744-2690.

Camino Real, Carlsbad, CA, 92008, (619) 931-3617; FLIR Systems Inc., 16505 S.W. 72nd Ave., Portland, OR, 97224, (503) 684-3731.

SPOT RADIOMETERS

Measurement and Analysis

A spot radiometer is a relatively light-weight, compact, hand-held device (often manufactured with a pistol grip). A measurement is made by pointing the device at a surface and depressing the on-off switch. The radiometer senses both the radiation from the surface and the reflected radiation from surrounding surfaces. The device incorporates either a temperature-indicating display (meter or digital) in degrees Celsius or Fahrenheit or a radiosity display in BTU/ft^2/hr or watts/in^2.

A typical range of temperature resolutions for spot radiometers is ±0.1° to 1.5°F with a response time of approximately 2 sec. The target size "viewed" by the device increases with increasing distance from the surface to the instrument (a 3-in. increase for every 4-ft distance to the target is typical, although this ratio varies for different instruments).

A temperature-indicating spot radiometer is calibrated by pointing it at a reference surface of known temperature and emittance, and adjusting the device until it determines the indicated temperature of that surface. If the emittance of the test surface is equal to that of the reference surface, the radiometer will be measuring actual temperatures. If a reference surface temperature cannot be determined by other methods, then the instrument operator must estimate the emittance of the surface and set the dial to that value.

There are several design variations on the basic radiometer in current use. The use of microprocessor technology, selectable emissivities and

sighting scopes for defining object size are all found in radiometers used in building diagnostics.

Accuracy. Typical accuracy is ± 3% or better.

Advantages

Spot radiometers do not need cooling. They can be used to monitor temperatures in inaccessible locations, thus avoiding dismantling or destructive testing of the building. They are less expensive and more portable than line scanners and imaging systems, and unlike imaging systems can be calibrated in temperature and radiosity.

Limitations

Since an image is not provided, pinpointing an exact location can be difficult; and although the display is calibrated in degrees, actual temperature is not measured directly. There is often a limitation of field view according to distance from the target. And too, anomalous reflections from the target are difficult to separate from real temperature variations. Also, some instruments are sensitive to large ambient temperature fluctuations.

Cost. The cost of typical spot radiometers is between $750 and $2000.

New Technology/Developments. The most recent developments in the fabrication of spot radiometers includes the use of microprocessor technology, state-of-the-art optical and sighting systems, LCD displays, and automatic internal calibration reference.

Manufacturers. Wahl Instruments, Inc., 5750 Hannum Ave., Culver City, CA 90[illegible] (800) 421-2853 or (213) 641-6931; Raytek, 1201 Shaffer Rd., Santa [illegible], CA [illegible], (800) 227-8074, (408) 458-1110; Micron Instrument Co., 445 [illegible] St., Wyckoff, NJ 07481, (800) 631-0176 or (201) 891-7330.

DETAILED PROCEDURE FOR NONCONTACT THERMAL INSPECTIONS

All portable imaging systems have at least one factor in common: they can be used for energy audits, electrical and mechanical inspections, insulation installation inspections and nondestructive tests for the determination of the presence of moisture in walls and builtup roof membranes. In each category, however, the system would be used somewhat differently.

Energy Audits

Interior Inspections

For this procedure a portable imaging system is used to record and document thermal patterns related to air leakage, radiation, conduction and convection. The evaluation of the thermal imagery is qualitative most of the time; however, there have been recent attempts to conduct quantitative analyses.

The objective of an energy audit conducted from the interior of a building is to document and analyze all heat losses from a building enclosure system for the purpose of recommending cost effective retrofit procedures. Interior energy audits of large buildings can be time consuming if only one system is used and the complete building enclosure system must be inspected.

ASHRAE draft standard 101-1981 specifies that, "a thermal imaging system used to assess heat loss characteristics of a building shall provide sufficiently specific and detailed data to permit recognition of the presence or absence of insulation and air infiltration. This category of survey includes three levels of measurement: Class A, Class B and Class C. The Class A survey identifies the probably cause of a heat loss

anomaly, such as distinguishing between insulation voids and air infiltration as well as providing information to estimate the R-value of the structural component observed. The Class B survey only provides an indication of gross thermal anomalies with limited information on probably cause while the Class C survey provides for locating gross thermal anomalies with no significant information on probable cause."

According to the ASHRAE standard, there are three basic requirements which the survey must achieve, depending on the class of survey used.

. For Class A surveys, the thermal imaging system should provide and document specific data to permit recognition of the probable cause of the heat loss anomaly, i.e., air infiltration or insulation void. To accomplish this, the imager must resolve anomalies 4 cm x 4 cm in size or smaller when the temperature difference between the anomaly and its background is equivalent to or less than the interior surface temperature difference between an R-10 and R-15 surface. Futhermore, the data should be suitable for calculation of the Temperature Index.

. For Class B surveys, the thermal imaging system should provide and document specific data to permit the location of gross heat loss anomalies with limited information on probable cause. To accomplish this, the imager must resolve anomalies 16 cm x 16 cm or smaller when the temperature difference between the anomaly and its background is equivalent to or less than the interior surface temperature difference between an R-5 and an R-15 surface.

. For Class C surveys, the imager should provide and document specific data to permit location of the gross thermal anomalies wiht no significant information on probable cause. To accomplish this, the imager must

resolve anomalies 16 cm x 16 cm in size or smaller when the temperature difference between the anomaly and its background is equivalent to or less than the interior surface temperature between an R-2 and an R-10 surface.

For all classes of survey, the thermal imaging system should be capable of producing thermal data on hard copy records that provide documentation of findings for future reference.

The ASHRAE standard specifies that surface and air temperature thermometers, smoke pencils and air velocity probes may be used in conjunction with the thermal imaging system to record survey conditions. The measurements to be recorded are described in Table 1-1.

Table 1-1

Date
Time of day
Indoor air temperature
Outdoor air temperature
Wind speed
Wind direction
Surface finish and materials
Description of building construction
Window glazing
Orientation of surface
Other factors which might affect data

Thermal anomalies of the building should be recorded as thermograms and supported by data necessary to identify the extent of the anomalies within the thermogram. These data may take the form of drawings, photographs or video tapes. Equipment with photographic capabilities should record such characteristics. For Class A surveys, interior photographs should also be taken to properly orient characteristics of areas within the survey.

The ASHRAE standand specifies the following survey conditions:

1. A relatively stable condition of heat transfer should prevail.

2. Class A surveys should only be conducted after it is obvious that any solar radiation absorbed during the day has dissipated. This is critical because of the calculation of approximate R-value.

3. Class B and Class C surveys should be conducted only for the purpose of detecting anomalies. They may be performed any time during the day when there is no solar radiation on the walls, as long as the minimum indoor-outdoor temperature differences in Tables 1-2 and 1-3 exist for a minimum of two hours prior to the survey.

4. Environmental factors should be noted including date, time of day, wind speed, precipitation, and site factors such as shading, sun loading, convective and radiative sources.

5. Approximately one hour before the start of the survey, preparation should include elimination of thermal artifacts to the extent practical by turning off heat, moving furniture away from the walls, opening cabinet doors, opening inside doors, drawing curtains to expose the walls, and taking pictures off walls.

6. Equipment designation and serial number should be recorded.

7. Temperature measurements should be made of indoor (Class A only) and outdoor air.

8. Data should be recorded with each thermogram to allow reference to some form of calibrated grey scale for the purpose of indicating the relationship between contrast and temperature difference.

9. If the survey is used to characterize the apparent thermal resistance, the inside surface temperature of outside walls should be recorded for the purpose of computing the Temperature Index.

Table 1-2
Class B Survey

Required Minimum Resolvable Temperature Difference @ 0.13 cycles/cm		Inside to Outside Air Temperature Difference	
(°C)	(°F)	(°C)	(°F)
0.4	0.7	8	14
0.6	1.1	12	22
0.8	1.4	16	29
1.0	1.8	20	36

Table 1-3
Class C Survey

Required Minimum Resolvable Temperature Difference @ 0.13 cycles/cm		Inside to Outside Air Temperature Difference	
(°C)	(°F)	(°C)	(°F)
1.0	1.8	7	13
1.2	2.0	8	14
1.4	2.5	9	16
1.6	3.2	11	20

Within the past two years, the Task Force on Infrared Inspections, Section 7.1 operating under ASTM Subcommittee C16.30, Thermal Measurements, has developed a draft procedure for the thermographic inspection of insulation installations in building enclosure cavities in wood frame buildings. While the procedure has been developed specifically for insulation inspections it could also be used for that part of an energy audit which does not deal with the identification of air leakage. The specifics of this procedure will be described under the topic of quality control insulation inspections.

Interior inspections have certain advantages and limitations depending upon the size and location of the building, time of day, and the meteorological conditions prevailing at the time of the inspection. Inspections of large buildings will require progressively more time. This is the major limitation of an interior survey. However, this limitation could be minimized by the use of more than one imaging system and operator.

The advantages are the following: solar loading of the exterior surface of the building enclosure would not bring an immediate end to the survey, wind scrubbing of the exterior would not have a direct effect on the interpretation of the thermal image, and meteorological conditions (precipitation, temperature, wind chill) would not reduce the productivity of the operator of the imaging system. Also, natural barriers (e.g., trees, [illegible], water, steep slopes) would not be a factor in providing an impediment to the operator's mobility.

Qualitative pattern recognition analysis of thermal images has been and will continue to be the primary means of providing data for audits of both residential and nonresidential buildings. Recently there has been a trend in the development of procedures to obtain actual temperatures from those imaging systems which have that potential. While most of this effort is in the primary stage, it is anticipated that within the next few years enough progress will have been made to consider the measurement of actual surface temperatures of buildings as routine.

Exterior Inspections

Most exterior surveys of buildings using imagers are conducted with vehicle-mounted systems or cart-mounted systems. With the rapid advance of technology, diagnosticians are using direct video data recording techniques

while others are using photographic records or simply written notes based on thermal data and visual observations.

In the past, diagnosticians considered the most optimum temperature conditions to be satisfied with a large as possible temperature difference between inside and outside. Such conditions imply that the outside temperature should be very low while the inside temperature remains at ambient. Recent tests by Public Works of Canada of the minimum resolvable temperature difference of various imaging systems indicate that detectors used in these systems become less sensitive as the ambient temperature is decreased from +15°C to -30°C. The minimum temperature difference considered to be acceptable for exterior surveys depends upon whether a high or low resolution imager is being used. If a high resolution system is used a temperature difference of approximately 8-10°C is required for observable contrast in the thermal image. A low resolution imager usually requires a 10-15°C temperature difference for an observable contrast.

A compromise involving the spatial and thermal resolution of the imaging system and the time required to complete the survey must be made. An attempt should be made to include as much as possible of the exterior surface of the enclosure system without violating the minimum resolvable temperature difference specifications of the particular system being used.

With regard to the field-of-view for an exterior survey, the proposed ASTM standard recommends that in the horizontal direction it should not subtend more than approximately 9 ft and in the vertical direction not more than approximately 25 ft.

The sensitivity of the imaging system should be adjusted to give the lowest minimum resolvable temperature differences which keeps the image

from being saturated to black or white. The thermal image from the screen can then be recorded manually, photographically or with video tape. For the purposes of indicating the relationship between contrast and temperature differences, data should be recorded to allow reference to a calibrated gray scale or to two surface reference measurements.

One distinct advantage of an exterior survey of a large building is that it can be conducted in a much shorter period of time than an interior survey. Where time is of the essence and only one imaging system is available an exterior survey can be conducted to quickly identify and document major thermal anomalies within the building enclosure system.

Another advantage is that objects (furniture, etc.) behind the walls of the building enclosure system do not have to be moved as long as there is recognition of those objects at the time of the survey.

One disadvantage of an exterior survey is the problem of solar loading of the building enclosure system. Within a few minutes of the time that solar radiation impinges upon the enclosure system, heat is absorbed and an imager can no longer distinguish between the incident solar radiation and the outgoing thermal radiation. Therefore, an exterior survey should be made at times of minimum solar heating of the enclosure system. If the enclosure system has already been heated, then it is usually (but not always) necessary to wait for at least 3 hours after sunset (or begin 3 hours before sunrise if it has not been heated) to avoid solar storage and allow the solar decay (or buildup) process before initiation of the imaging survey.

Another disadvantage is the problem of wind scrubbing of the surface of the enclosure system. The effect of the wind is to reduce the overall

thermal image contrast by eliminating the surface temperature differences which depict thermal anomalies in the building enclosure system. At the present time there is not general agreement as to what value of wind velocity is considered excessive for observable image contrast. Even though ASHRAE Standard 101-1981 indicates that this phenomenon is wavelength dependent and limiting at wind velocities in excess of 15 mph, there have been documented instances by Public Works Canada of observable thermal image contrast obtained with wind velocities exceeding 15 mph.

Exterior surveys are also hindered by the environment immediately adjacent to a building (e.g. trees, shrubs, fences, water, other structures, sloping landscapes, etc.). Any of these objects may be located in such a manner as to hinder the mobility of the equipment operator or prevent the operator from getting an unobstructed view of section(s) of the building enclosure system.

Public Works Canada has used a helicopter to conduct exterior surveys of large multistory buildings. The helicopter is used in conjunction with a thermal imaging system coupled to an optical system that produces a thermal image superimposed on a visual image. This technique has the distinct advantage of being able to provide for a correlation between thermal anomalies observed in the thermal image and the precise location of those anomalies on the building enclosure system.

Quality Control Insulation Inspections - Interior and Exterior Inspection

Most of the procedures for conducting a quality control inspection are described in the section on energy audits. The procedures are identical for energy audits and quality control inspections with regard to determining whether a new or retrofit insulation installation is done according to

specifications, job contract, proposals, standard installation practice or applicable codes and standards. Other thermal anomalies which are observed during the process of an energy audit may require procedures not covered in a quality control inspection. The Task Force on Infrared Inspections, [illegible], operating under ASTM Subcommittee C16.30, has prepared a draft "Practice on Thermographic Inspection of Insulation Installations in Envelope Cavities in Wood Frame Buildings" which specifies procedures that are applicable to quality control insulation installation inspections. Unlike ASHRAE Standard 101-1981 the ASTM proposed practice deals with the operator's level of knowledge. It states that "a trained thermographic [illegible] and data evaluator shall have knowledge and competence in principles of infrared theory, air movement, moisture migration, heat transfer, and a basic understanding of building enclosure theory in order to apply [illegible] techniques to diagnose defects in building envelope systems."

According to the proposed practice the following enviromental conditions are preferred for thermographic inspections:

1. Minimum temperature difference of 10°C between interior and exterior ambient for a period of 8 hours prior to the inspection.

2. No direct solar radiation on the surfaces for a previous 3 hours for wood frame with siding and a previous 8 hours for masonry and masonry veneer construction.

3. For exterior surveys, wind speed should be less than 15 mph and [illegible] should not be wet.

Although it is recommended that the above conditions prevail at the time of inspections, it is recognized that they can be performed under other conditions if sufficient knowledge is used in taking and interpreting

the thermal images. For example, a wall exposed to direct solar radiation will experience a temperature reversal - the studs and voids will appear warm and the insulated section cold on interior inspections. An exterior inspection will show the studs warmer than the insulated sections. On many veneer surfaces, interior surveys are technically possible one hour or two after sunrise.

The proposed practice states that in order to evaluate the structure for installation of insulation, certain preliminary data should be collected if possible:

1. Sketch or record of each type of anticipated wall cross section, noting age of construction, i.e., construction drawings and anticipated thermal pattern.

2. Additions or modifications to the structure.

3. Locations which the insulation contractor was contracted to insulate, the type of insulation (if known) and the anticipated R-value.

4. Difficulties encountered by the insulation contractor.

5. Thermal anomalies noted by the owner/occupant.

6. Type(s) of existing insulation(s).

7. Type(s) of exterior and interior surface finishing materials which might produce unwanted reflections.

8. Orientation of exterior walls.

9. Potential paths of air leakage into cavities.

10. Extraneous heat sources mounted on or close to the walls.

11. Time building is used.

With regard to information on the outdoor enviroment the practice states that the meteorological conditions which prevail during the inspec-

tion can greatly affect the thermal image. In conducting an inspection, the following locally measured interior and exterior environmental conditions should be recorded:

1. Exterior ambient temperature (on site).

2. Wind speed.

3. Wind direction.

4. Cloudiness.

5. Relative humidity.

6. Precipitation for previous twelve hours.

7. Maximum and minimum exterior ambient temperatures for a 24-hour period prior to the inspection.

8. Cloud cover estimates for a period of 12 hours prior to the inspection.

Inside the building, the air temperature should be measured in each room on each level and in the basement to an accuracy of 1°F or 0.5°C. Relative humidity should also be recorded for each level of the house. Unheated spaces should be noted and the interior temperature recorded. If certain rooms have temperatures differing by more than 4°F or 2°C from the temperature of the corresponding rooms on another level, those temperature should be reported.

As mentioned in a previous section, not all surfaces are accessible for inspection from the exterior and interior. Ideally, all movable obstacles blocking the view of the surface should be moved, and if they are in contact with the surface, they should be moved at least one hour before inspection.

The heating system should be left on unless turning it off will cause more than a 4°F or 2°C change in temperature. Operation of the heating system should not mask existing thermal anomalies.

In contrast with the ASHRAE standard the proposed ASTM practice is specific with regard to onsite equipment check and settings:

1. Verify that the system meets MRTD requirements for the temperature gradient through the wall.

2. Instrument gain or contrast should be set to allow (in the image) the operator to distinguish a stud from the wall around it. The brightness or level control should be set so that anomalies or their reference areas are not in saturation (maximum brightness or white) or in suppression (minimum brightness or black) on the display.

3. Verify proper operation of recording system (if any).

4. Produce hard copy of the thermal image of the wall.

Similarly the specifics of the inspection are outlined in the ASTM practice:

1. A complete quality control inspection of the building may consist of both an exterior and interior inspection of all surfaces which should have been insulated.

2. Inspections should be made of all surfaces which can be viewed with an angle of less than 30° from the normal to the surface. Inspections should be made from several angles to detect the presence of reflected radiation.

3. For an interior inspection, scans should be made from a position which allows a view of at least two horizontal and one vertical stud space.

4. For an exterior inspection, scans should be made from a position which allows a view of at least six horizontal and three vertical stud spaces.

5. Hard copies of each anomaly with notation of the location of all building characteristics (e.g., windows, doors, and vents) should be made. The quality of the hard copy should be based on the need for calculations of areas with insufficient insulation or for identification of cavities with varied defects. The primary purpose of the quality control inspection is to provide precise physical location information to allow for corrective retrofit.

It is not possible to provide a detailed interpretation of thermal patterns without some understanding of the construction of the building. It should be determined, if there are air spaces between the inspected surface and the insulation, whether there are heat sources in the cavity and the composition of the wall enclosing the cavity. In comparison with the studs, locations without insulation appear colder in interior inspections and warmer in exterior inspections. Air leakage between the insulation and the surface may cause a thermal pattern similar to a location without insulation. The interpretation of the thermal image or other hard copy allows determination of the following:

1. Total area and location where there is no insulation.

2. Total area and location where there is full insulation.

3. Total area and location where there is only existing insulation (for those applications where insulation is being added).

4. Location of cavities with improperly fitted insulation, or shrinkage.

5. Location and extent of air leakage or moisture damage.

Irregularities in the insulation and air tightness of a building will provide various apparent surface temperature patterns. Certain types of defects have characteristic shapes in a thermal image. In evaluating thermal patterns, the following characteristics are considered:

1. Relative uniformity of the thermal pattern.

2. Contours and characteristic shapes of the thermal patterns.

3. Irregular pattern shapes with uneven boundaries and large temperature variations produced by air leakage in the building enclosure.

4. Regular and well defined pattern shapes produced by missing insulation.

5. Mottled and diffused patterns produced by moisture in the structure where temperature variations are not extreme within the pattern.

6. Measured difference between the temperature at a location on the wall with full insulation and the temperature of the selected colder or warmer region.

7. Continuity and uniformity of the constant temperature region over the surface.

The type of defect can usually be determined by calculations, ancillary measurements, experience, or by comparing the actual thermal image with reference thermal images for structures with known insulation defects. Such determinations should be substantiated in the report.

The ASTM practice specifies that the report on a quality control inspection should contain, at a minimum, the items listed below:

1. Brief description of the construction features of the building. (This information should be based on drawings or other construction documents when available).

2. Types of surface materials used and their estimated spectral band emittance.

3. Orientation of the building with respect to the points of the compass and a description of the surrounding buildings, vegetation, landscape, and microclimate.

4. Equipment specifications, including model and serial number and any critical settings used during the measurement.

5. Date and hour of the inspection.

6. Outside air temperatures observed in the course of the twenty-four hours before and during the inspection.

7. Information about the solar radiation observed in the course of the twelve hours before and during the inspection.

8. Precipitation, direction, and velocity of the wind during the inspection.

9. Inside air temperature and air temperature drop across the enclosure.

10. Any other important factor influencing the results.

11. Sketches/photographs of the building showing the positions of the thermal images.

12. Thermal images with indications of their respective positions, and with comments on their appearance.

13. Results of the analysis dealing with the type and extent of each defect which has been observed.

14. Results of supplementary measurements and inspections.

15. Estimate of the total area and location where there is no insulation.

16. Estimate of the total area and location where there is full insulation.

17. Estimate of the total area and location where there is only existing insulation (for those applications where insulation is being added).

18. Names of numbers of inspection team and team leader.

NONDESTRUCTIVE SUBSURFACE MOISTURE TESTS

Thermal Imagers

The prevalent existing method of using visual means to detect moisture within the insulation of built-up roofing systems, and cutting into the membrane for verification has provided a useful but localized view of moisture damaged roofs. Experience has indicated that this procedure often leads to misinterpretation of roofing problems.

The development of roof inspection techniques using thermal imagers provided a means to quickly detect and accurately map subsurface roof moisture, and plays a significant role in non-destructive testing of roof assemblies. Due to the portability of imaging equipment, surveys can be performed by walking the roof or by scanning from the air. The method selected depends on the construction of the roof assembly, climatic conditions, the size of the roof, the number of roofs being surveyed, and the problems and the information desired. The best time to survey a roof is during the night. Certain problems can also be investigated from the interior and good results have been obtained using this technique with

adverse weather conditions. Information can be stored on video tape or film, depending on the future use of the information.

Although wet insulation is usually depicted as a bright area on the viewing screen of a thermal imager, not all brightness can be attributed to entrapped moisture. Exhaust from roof-mounted fans or heaters suspended below the roof, changes in construction, and repairs on areas that have been re-roofed, often resemble entrapped moisture on the thermal image.

The technique of thermal imaging senses variations in surface temperature, and only senses the effect of moisture as it relates to the surface temperature of the membrane. All materials between the interior and exterior of a building, including the ceiling and air spaces, are considered part of the roof assembly and all influence the thermal performance of the roof.

Moisture reduces the insulation's effectiveness and increases its conductivity. At night, during cool or cold months, this moisture can be depicted in a thermal image as warm zones on the roof's surface.

During warm or hot months, under conditions of intense solar radiation, the roof acts as a large thermal collector. Any insulation laden with moisture absorbs this radiation and acts as a heat sink. After sunset, especially on a clear night where there is good radiant cooling of the surface, the moist areas tend to hold their heat, forming warm zones. The amount of thermal energy stored by a roof is directly related to its construction and the volume of moisture trapped within it.

The period in which the inspection must be done begins after sunset when the wet insulation areas remain or become warmer than the dry areas to provide a detectable temperature differential. As the roof cools

throughout the night, the temperatures of the wet and dry insulation areas tend to equalize.

During the inspection procedure, thermal anomalies may appear. Because these anomalies may be associated with phenomena other than wet insulation, (e.g., interior heat sources, light fixtures, steam pipes, heavy gravel, etc.) they must be verified by taking roof cores. Other means of verification may also by used.

The use of thermal imagers for mapping subsurface roof moisture has one very significant advantage. Since these imagers can be used to quickly pinpoint the presence of subsurface moisture in insulated roof systems, only those locations which are suspect need be considered for maintenance action. This means that the "guesswork" of attempting to locate suspect subsurface moisture over large roof areas has been virtually eliminated from the process of visual inspections. Once moisture has been confirmed in those suspect locations the cost of reroofing will be limited to these specific areas. Before the advent of the use of thermal imaging techniques there was no way to quickly "see" the presence of subsurface moisture. Now that these techniques are readily available it is possible to quickly and precisely assess where maintenance action is required. The potential annual cost savings with this diagnostic technique can be enormous.

There are several limitations to the use of thermal imagers for roof subsurface moisture inspections. For proper interpretation of the thermal imagery there is no need for a thorough understanding of both infrared theory/applications and roof construction. The equipment must be capable of detecting relatively small temperature differentials which may occur with damp insulation or under less than optimal conditions. It must pro-

vide an image with sufficient clarity and contrast that will provide useful and readable information throughout the entire inspection period. The imager must be portable enough to permit the operator's access to all areas of the roofs to be inspected. Uninsulated roofs do not, in general, retain sufficient quantities of water for a long enough time to permit infrared inspections. The efficiency of visual inspections on uninsulated systems is such that the use of instrumented inspections is not required.

Environmental conditions must be near optimal for location of interply moisture. Since felt plies are highly porous to moisture, interply moisture is a transitory state and may be more readily and economically located by visual examination. For these reasons, the use of instrumented inspection for the location of interply moisture is of questionable value.

Lightweight concrete decks may be inspected, but care must be used in interpreting the data. These systems are poured in place and often retain a significant moisture content. Unless this is realized, the data may tend to indicate unacceptable moisture contents throughout the entire roof. Inspections of this type system are more difficult because the boundaries of the wet areas are indistinct and extensive verification is necessary.

Thick layers of insulation may mask the thermal loading effect on moisture retained in the lower layers and prevent its accurate location. A thermal insulator placed over a layer of wet insulation makes moisture detection more difficult.

An aluminized surface reduces the energy reradiated from the roof and increases the energy due to reflectance. Therefore, a newly aluminized roof surface may be impossible to inspect until the surface reflections have been reduced through oxidation or other contamination.

A surface with heavy gravel above the insulation will retain sufficient heat, preventing temperature differentials due to the moisture content of the insulation from being detected, making it difficult, if not impossible, to survey. Anything on the building interior or exterior that significantly affects the roof surface temperature may make accurate inspection results impossible to obtain.

When a roof inspection depends upon temperature differentials generated by solar radiation, a roof shadowed by clouds, trees, or building appurtenances may not receive sufficient solar energy to permit an inspection. The roof must be free from surface moisture or snow during the inspection. If the roof surface is wet the day of the inspection, the sun's energy will be spent drying the surface instead of warming the wet insulation. Inspection of the surface may be difficult.

Winds in excess of 15 mph will significantly increase the convective cooling effect on a roof and will cause the wet and dry areas to rapidly reach the same temperature. This effect shortens the time of inspection.

Although an infrared inspection of a roof is generally regarded as a nondestructive test, verification of the results may not be. Since thermal image interpretation cannot absolutely guarantee the presence of subsurface moisture, other means of verification must be used. Roof cuts are the most reliable form of verification. The use of thermal imaging techniques must be considered quasi-nondestructive until such time as a nondestructive verification technique has been developed.

The use of thermal imaging techniques for subsurface moisture inspections of roofs is a recent development. There have been no known recent significant advances in inspection techniques.

Spot Radiometers

Although theoretically a spot radiometer can be used in every application in which an imaging system is used, from a practical perspective, it would be difficult to justify its substitution in every instance because of the basic and significant difference in the characteristics of each device. Due to the localized measuring capability of the spot radiometer, the ASHRAE Standard 101-1981 recommends that that instrument be used for (1) interior measurements of wall segments to detect the presence of thermal anomalies, and (2) to determine the apparent range of thermal resistance of a building component utilizing the Temperature Index or similar technique. The use of the spot radiometer is not recommended by that standard for exclusive use in conducting surveys of total wall sections or for complete building surveys for the purpose of identifying all insulation voids and air leakage paths.

The ASHRAE Standard has established two classes of interior measurements: A and B. The Class A measurement is used to locate the presence of thermal anomalies and to determine the local range of apparent thermal resistance (R-value) of a building component while the Class B measurement is used only to detect the presence of thermal anomalies.

For Class A measurements, the Standard stipulates that (1) a spot radiometer be calibrated with a blackbody reference with a temperature accuracy within ± 0.3°C (0.5°F), (2)indoor ambient and outdoor air temperature be determined within an accuracy of ± 0.3°C (0.5°F), (3) outdoor air temperature be measured with a conventional thermometer, (4) indoor ambient temperature be measured with a spot radiometer by pointing it at an object having an emittance similar to the exterior wall and

thermally insulated from it, (5) spot checks to determine range of apparent thermal resistance be conducted no sooner than three hours after sunset, (6) the heating system be turned off one hour prior to measurement, (7) curtains and drapes by pulled closed, and (8) measurements not be made on reflective surfaces. For Class B measurements, the Standard states that (1) the indoor/outdoor ambient air temperature difference must exceed the appropriate value for a period of atleast two hours prior to any measurement, (2) spot checks in no case be made when the indoor/outdoor air temperature difference is less than 10°C (18°F), (3) exterior to interior surface measurements of building components exposed to solar loading must exceed the appropriate values, and (4) the heating system be turned off one hour prior to measurement. In actual use the spot radiometer is panned slowly across a wall section in order to allow for the instrument response time. Any significant temperature changes are noted by the operator.

The following data are recorded:

Date

Time of day

Indoor ambient temperature

Outdoor air temperature

Wind speed

Wind direction

Weather conditions

Surface finish and materials

Description of building construction

Window glazing

Orientation of surface

Other factors which might affect data

Range of apparent thermal resistance

Apparent outdoor/indoor temperature difference.

When making Class A measurements using the Temperature Index Method the range of apparent thermal resistance is determined using the procedure given in Section 3 of the Appendix of the ASHRAE Standard. When spot checks are conducted to determine the existence of cavity insulation, certain criteria are applied to determine if in fact that insulation is present: the wall is insulated if the apparent surface temperature between studs is greater than the apparent temperature of the studs and uninsulated when the apparent stud temperature is less.

Virtually all of the same advantages and limitations of interior and exterior inspections are experiences by operators of spot radiometers and imaging systems. The additional limitations of a spot radiometer (nonimaging and nonscanning) create additional problems for an operator of that device. One of these problems is the time required to conduct a complete energy audit, quality control insulation installation inspection, or electrical/mechanical inspection. The other problem is the rapidly expanding field of view that occurs with increasing distance from the surface being measured (without benefit of an image that can be monitored). Without the benefit of an imaging capability, it would be almost impossible to use a spot radiometer in any application requiring pattern recognition (e.g., subsurface moisture tests of roofs and walls). Therefore, its use must be restricted to those applications requiring extremely localized surface temperature measurements.

The advantage of using a spot radiometer is that for extremely localized surface temperature measurements, it can be used to quickly measure them and infer a range of R-values for that particular locale.

Portable Line Scanners

The use of portable line scanners is not unlike that of a thermal imaging system. The significant difference between their use is that an imaging system automatically produces a thermal image of an object through a combination of optical and electronic components, while a portable line scanner produces a surface temperature profile superimposed on a visual image. A complete temperature map of a surface can only be made by manually scanning (moving it up or down in a manner that will produce temperature "lines" that are superimposed on the visual image of the surface being observed).

At the time the ASHRAE Standard was being drafted, no portable line scanners were being sold. Therefore, that standard does not cover the use of such a device.

Because the line scanner is not an imaging device, the time limitations for large scale surveying would be similar to the limitations of a spot radiometer. However, because a visual image can be produced, use of the line scanner generally has the advantage of taking less time to correlate a thermal anomaly (once its located) with its precise physical location.

For certain applications of electrical inspection, a portable line scanner has the advantage of not being affected by spurious electromagnetic fields produced by the electrical equipment itself. This means that if the components to be inspected are obstructed by other components, objects, or

equipment an operator can move in close with the line scanner to get an unobstructed view.

CHAPTER 2

NONCONTACT ELECTROMAGNETIC MEASUREMENTS

NUCLEAR METER

Measurement and Analysis. As early as 1941 a paper in the Oil and Gas Journal described the basic process used in the nuclear meter. The instrument was developed for use in petroleum exploration and consisted of a neutron source and ionization chamber.

The nuclear method for determining moisture content of a material is based on the principle of measuring the slowing of neutrons emitted into the material from a fast-neutron source. The collision of the fast neutrons with hydrogen atoms in the material slows those neutrons. The number of slow neutrons is detected by a counter tube and electronically counted. The slow neutron count is proportional to the amount of water in the material.

The nuclear meter has been used successfully to delineate entrapped moisture on a large number of built-up roofs. Use of the meter is reasonably simple, requiring only it and a calibration block. The work can be done by two people who are trained to use the instrument. An average of 400 readings (approximately 32,500 sq ft of roof area) can be surveyed per day.

Accuracy. Not determined for roof measurements.

Advantages

Nuclear meters can be used to detect entrapped roof moisture. The number of backscattered slow neutrons received (compared to a reference standard) is directly related to the number of hydrogen atoms present in the entire roof cross section under the meter from the surface to the

deck. A reference grid system will proivde an accurate location of entrapped moisture at the expense of increasing the time required to complete the job. The nuclear meter can also be used to check out and verify suspect locations found with an infrared scanner. Use of a nuclear meter provides contact with the roof during daylight hours when visual inspection of the roof materials can be made.

Limitations

The means of detecting entrapped moisture is direct in that the meter responds to hydrogen ion concentrations in the material. A grid system must be laid on the roof and readings need to be made at each grid intersection. This procedure slows down the survey, but provides an accurate map, since each reading is referenced to a position on the roof surface.

Cost. Instrument costs range from $2800 to $5500 and can be used for several years without extensive maintenance.

New Technology/Developments. None.

Manufacturers. Campbell Pacific Nuclear, 130 South Buchanan Circle, Pacheco, CA 94553, (415) 228-9770; Seaman Nuclear Corp., 3846 W. Wisconsin Ave., Milwaukee, WI 53208, (414) 762-5100; Troxler Electronic Labs, Inc., P.O. Box 12057, Cornwallis Rd., Research Triangle Park, NC 27709, (919) 549-8661.

CAPACITANCE SENSOR

Measurement and Analysis. The dielectric constant for a roof containing moisture will be significantly different than for a dry roof. For example, water has a dielctric constant of about 80 while dry roofing materials have a dielectric constant of approximately 4. This extreme

difference affords the use of an electronic capacitance sensor to detect moisture in both insulation and membrane.

Moisture readings taken from the capacitance system are plotted on a drawing of the roof to create a three dimensional representation of moisture content.

Accuracy. Not available.

Advantages

Sensor can detect moisture in both membrane and insulation.

Limitations

Sensors cannot give quantitative results. Grid has to be laid on roof, increasing moisture survey time.

Cost. $275 to $4200.

New Technology/Developments. None.

Manufacturers. A-Tech, P.O. Box 5576, Madison, WI 53705, (608) 831-5333; Tramex/United, 1300 Shoshone St., P.O. Box 4246, Denver, CO 80204, (303) 892-0400.

CHAPTER 3

CONTACT HEAT FLOW MEASUREMENTS

HEAT FLUX TRANSDUCERS

Measurement and Analysis. A heat flux transducer (HFT) is a thin wafer, either circular or rectangular in shape. The wafer contains an embedded thermopile (a series of pairs of thermocouple junctions placed across the wafer) which produces a signal proportional to the rate of heat flow passing through the wafer.

The constant relating the output to the heat flow rate is called the sensitivity of the device (expressed in millivolts per Btu/(hr/ft^2)) which is a slight function of its average temperature.

ASTM Standard Practice C 1046-85 for In-Situ Measurement of Heat Flux and Temperature on Building Envelope Components specifies the procedure outlined here more fully.

The output signals from heat flow sensors can be read out at any interval using data loggers, strip-chart recorders, or analog integrators. Any read-out device must have sufficient sensitivity to resolve a signal at its lowest level.

Manufacturer's calibrations of HFTs are seldom valid for use on buildings. Because HFTs distort the heat flow which they are intended to measure, a change of materials, temperatures or other factors may change the conversion factor significantly. Therefore, calibration of HFTs should duplicate the material and thermal surroundings in which they are to be used. If the sensor is to be permanently imbedded in the construction, then the calibration procedure should represent the materials on either side of the sensor. If the HFT is to be surface-mounted, then the calibra-

tion must occur in an apparatus which simulates this. In either case, the temperatures and heat flux during calibration should approximate the average temperature and heat flux which the sensor will likely encounter. ASTM Stnadard Practice C-1046-85 describes these requirementts in greater detail.

When HFTs and thermocouples are to be surface-mounted, masking tape usually provides good attachment, smoothing over the sensor to avoid disrupting air movement, and adequate matching of infrared absorptivity. The match of absorptivity is important so that the sensor will absorb heat in a manner similar to its surroundings. Surface-mounted HFTs should be on indoor surfaces only because of the strong influence of solar radiation. Curtains should be drawn to prevent sun from shining on measured surfaces. Gaps between the HFT and the surface of more than 0.5 mm (0.02 in.) can cause errors from 2 to 10% because of convection. A layer of gel tooth-paste or similar substance behind the HFT can improve thermal contact. Thermocouple leads should be attached to the surface for a foot or so behind the junction to ensure that the measurement represents the surface temperature.

Thermocouple junctions are mounted (using epoxy) to the inside and outside surface of the building component. After the epoxy dries, the junctions should be covered with the same paint as used on the wall in order to equalize the absorptance and emittance of the measuring location to that of the surface. Thermocouple leads should be run at least a couple of feet along the surface in order to minimize heat conductance along them.

Accuracy. When the HFT 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 using steady-state heat transfer theory has agreed to within 6 percent when the composition of the wall was known accurately. For the calculated values, heat transfer coefficients from engineering handbooks are used. Without a third means of verification, such as drilling an inspection hole, it cannot always be determined whether the difference between measurement and theory is due to the use of incorrect values of the material properties or to inaccuracies associated with the measurement.

Advantages

In attempting to assess the thermal performance of building components, it is necessary to determine the quantity of heat passing through that component in a given period of time. The result of this measurement, together with interior/exterior surface temperature data taken over a period of time, can be used to calculate the thermal resistance (R-value) of the component.

An HFT will produce a quantitative value.

The most important advantage of using HFTs for measurement and analysis is that they produce a signal output which is related to the heat flow through that particular location. The addition of contact temperature sensors to the inside and outside surfaces enables the calculation of the thermal resistance (R-value) of the building component at those specific locations.

Limitations

Since an HFT is a contact transducer, it must be mounted securely to the building component to insure the accuracy of the measurements. Thermo-

graphy is recommended to assure that sensor sites are appropriate. Once the sensor is placed, the results obtained are only applicable to that one spot.

An HFT with a relatively small thickness can have a fluctuating signal. This may require averaging.

Since the sensor contacts the surface, heat flow at that location is perturbed. If the heat flow is only in one dimension (i.e., through the surface) the sensor should be measuring the actual flow rate. However, if the heat flow is multi-dimensional (i.e., along and through the surface), the sensor will not be measuring the actual flow rate.

Setup time for a heat flow rate measurement can be somewhat long. If several (or many) locations are to be monitored, setup could become extremely time consuming.

Since careful calibration, detailed measurement preparation and proper data interpretation are necessary, qualified technicians are required to carry out this procedure. Field personnel should be experienced with proper low-level electrical measurement techniques and also have an understanding of the fundamentals of building heat transfer. If the dynamic response of a building component is to be determined, graduate level training in mathematics is required.

A minimum temperature difference between inside and outside air temperatures must be maintained in order for an HFT to respond with a measurable and useable output signal. Spurious voltage sources can induce fluctuations into the measurements; however, integration can be used to average out many of the fluctuations.

Mounting an HFT onto the exterior surface of a building component should be avoided since the sensitivity of the device will change with the change in the outside air temperature.

In order to obtain a representative R-value at any location, the sensor should remain at that location for at least one diurnal cycle, (24 hrs) (depending upon the thickness of the construction). Building enclosure systems consisting of masonry walls may require measurement over a period of many days.

Cost. The cost of a heat flow sensor depends upon its size. The approximate cost of most small to medium size sensors is in the range of [illegible]. Larger sensors will cost more. The total cost of a system (sensor and readout device) to monitor one location would be approximately $[illegible].

New Technology/Developments. In studying the performance of building enclosures to improve their energy efficiency, it is sometimes necessary to measure heat flows that are relatively small and spatially nonuniform. Multiple HFTs can usually determine the area-averaged heat flow.

The Lawrence Berkeley Laboratory has developed an HFT, based on ac resistance thermometry, that will accurately measure average heat flows over large areas. They have built several moderate-sized (0.09 m^2 or 1.0 ft^2) prototypes and are planning larger units (0.7 m^2 or 7.5 ft^2).

[illegible] techniques can be used to construct larger HFTs, and average heat flows over large areas may be measured with comparable sensitivity by piecing together HFTs of a convenient size. Their work has exposed no fundamental difficulty, and the major difficulties expected will be in [illegible] the wires in large units from strains and in developing a

convenient method of calibration. A lower sensitivity could be attained by improving the design of the amplifier.

The most recent development in the use of HFTs is that of combining their use with a thermal imager to determine the proper placement of the sensor in order to avoid locations (framing members, insulation voids) not required for monitoring.

Portable Calorimeter

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

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

Prior to a calorimeter box measurement of a building component, a representative measuring site should be selected. While thermal anomalies need to be located, there is usually more interest in the performance of a

building component in areas free of defects, unless the purpose is to measure the effect of thermal anomalies on the enclosure performance.

The calorimeter box is sealed to the measurement site. It is very important that a good seal is provided along the edge in order to prevent convective exchange between the calorimeter and the room air.

Required Measurement Periods for Various Building Components.

Component	Measurement Time 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

These measurement periods should insure an accuracy within 5 percent in determining the thermal resistance, R.

Calorimeter box measurements should be carried out only during periods when the outdoor and indoor temperature difference is greater than 10°F. Solar radiation on walls in the winter season may frequency produce temperature differences less than 10°F. During the measurement, the indoor temperature should be thermostatically controlled at a constant level in order to minimize differences in the temperature between the calorimeter box and the room. Solar radiation and conditioned air from supply vents should not contact the calorimeter box.

The methods for interpretation of data from HFTs are applicable to data produced by this technique. However, the results are applicable to larger areas of the building components.

This technique has been used only by the National Research Council of Canada. They have constructed 10 portable calorimeters and have had private contractors construct portable calorimeters using their specifica-

tion. 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 HFTs.

Envelope Thermal Testing Unit

The envelope thermal testing unit (ETTU) was developed by the Lawrence Berkeley Laboratory in order to evaluate the on-site 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. This unit was designed to overcome some of the difficulties in using HFTs and calorimeters for the on-site evaluation of building components. Unlike those devices, the ETTU controls variation in heat flow and not temperature.

The term "blankets" is used because they cover the test wall section and are slightly flexible so that they can be made to conform to slight irregularities on the wall surfaces. Placing the blankets in 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 electric heaters separated by an insulating layer in which is embedded an array of temperature sensors. Each heater is designed to provide a heat output that is uniform over the whole area.

A microprocessor-controlled data-acquisition system determines a planned variation in heat flow and records the wall's response.

After calibration of the unit, the thermal resistance of a building component can be determined within ± 5 percent.

This technique can be used where accurate determination of the thermal characteristics of the building enclosure are required. Its accuracy makes it suitable for the verification of thermal specifications in new and retrofit buildings. Since it requires the application of both an exterior and interior blanket, it may be difficult to use on the upper stories of tall buildings and 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.

CHAPTER 4

BUILDING ENCLOSURE SYSTEM EVALUATION

AIR LEAKAGE MEASUREMENT

DECAY (Tracer Gas)

Measurement and Analysis. The leakage of air into and out of a building is one of the major components of heat loss. Although recent advances in instrumentation have made it possible to measure the air leakage rate of a building automatically, the techniques to obtain these data are both expensive and time consuming. In attempting to assess the air leakage characteristics of a building, four questions must be answered: 1) what are the measured air leakage rates under various climatic conditions and usage patterns, 2) how tight is the building after retrofit measures are applied to it, 3) where are the leakage paths, and 4) what is the severity of each leakage path.

Air leakage is the uncontrolled entry of air into or out of a building. It can be measured under natural conditions by mixing indoor air with a gas not normally found in either outdoor or indoor air, (e.g., sulfur hexafluoride (SF_6)) or by measuring the excess (indoors over outdoors) of a naturally produced component (CO_2, CO or radon). This substance is called a tracer gas.

The infiltration rate of a building is usually determined by the tracer-gas dilution method. This method is very versatile, and the simplest of the tracer-gas measurement systems. It can be used for short- and long-term measurements, and the measuring equipment may be located on site or the samples may be collected in air bags and analyzed offsite.

The tracer-gas technique for measuring building air leakage consists of (1) injecting a quantity of tracer gas (e.g., sulfur hexafluoride (SF_6)) in such a manner that it is well mixed and (2) measuring the rate of decay of this gas.

After assuring that the initial quantity of gas is well mixed, concentration measurements are made at 5 to 15-minute intervals. The air leakage rate is then determined by a graph of the SF_6 concentration decay vs. time. The following instrumentation is used for these measurements.

1. Tracer gas monitor. The monitor should be calibrated by the manufacturer or on site with mixtures of at least two different concentrations used in the range of the test.
2. Sampling network. A network consisting of tubing, tubing junctions, a pump, and an aspirator. This network is used to draw samples from remote locations, blend them, and bring the blended sample to a convenient place for analysis.
3. Syringes.
4. Fans capable of circulating air throughout the building. The building's air handling system can also be used.
5. Meteorology stations that record wind speed and direction and outside temperature.
6. Indoor temperature monitor.

Automated equipment developed by researchers at the National Bureau of Standards (NBS) and Princeton University has been used in the United States since 1974. These system use an electron capture gas chromatograph that measures SF_6 in the parts per billion (ppb) range. The unit pumps air through an aluminum oxide column that separates SF_6 from oxygen (O_2), which

also captures electrons. The gases then pass through a detector containing a radioactive source of electrons. The decrease in the 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.

Although exact SF_6 concentrations are not crucial to the method, it is important to calibrate the apparatus to ensure that operation is in the linear range. A linear response with a current corresponding to a potential of 70 V or higher indicates proper detector operation. Earlier versions of these systems used mechanical sequencing timers to control sampling and injection, and recorded the output on a chart recorder. The latest version consists of a 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 analog and digital data.

A less expensive method for obtaining these data consists of (1) using concentration monitoring equipment placed in the building and (2) analyzing air sample bags filled at intervals of one to two hours. Testing of a dwelling consists of the following steps.

1. Injection of SF_6

   A quantity of SF_6 is injected into the dwelling so that the initial concentration is 100 to 150 parts per billion (ppb) or approximately 10 to 15 mℓ per 1000 m^3 of living space. The gas is injected into each room in a quantity approximately proportional to the volume of the room.

2. Mixing of Tracer Gas

A period of approximately 1/2 hour to 1 hour is allowed for proper mixing of the gas. If the dwelling is heated by a forced air system, the fan can be turned on to assist in the mixing; however, convection currents will mix the tracer gas on each floor of the dwelling if the doors between rooms are open.

3. Filling Air Sample Bags

After adequate mixing of the tracer gas, one sample bag is filled (using a small pump) with air from each floor of living space. The air sample bags must be filled slowly to ensure the collection of representative samples.

4. Dissipation of Tracer Gas

One or two hours is allowed for the tracer gas to dissipate. The mechanical system is left in its normal operating mode during this time.

5. Filling Air Sample Bags (Repeat)

The procedure in the third step is repeated with a second sample bag of air from each floor of the dwelling.

6. Shipping Sample Bags to Analysis Center

The sample bags are shipped to a center for analysis and measurement of the tracer gas concentration. The air infiltration rate is then determined by computation.

According to some experts, a tracer gas should have the following attributes:

1. Content in air must be relatively small, and there must be no source of it in the building.
2. It must be possible for a low concentration to be accurately detected.
3. The density must be as near as possible to that of air.
4. It must not react with the constituents of air or be adsorbed onto the surfaces of walls, furniture, clothes, etc.
5. The gas must not be harmful to building occupants.
6. It must not be flammable.
7. The gas must be easy to handle, easily available and inexpensive.

Another purpose of air leakage tests is to measure whether ventilation is adequate. There have been numerous complaints in office buildings in both the U.S. and Canada of symptoms related to insufficient clean air supply: headaches, nausea, fatigue and respiratory symptoms. These complaints may be due to excessive concentrations of carbon monoxide, smoke, formaldehyde or other contaminants, or to excessive relative humidity, heat or insufficient air movement.

Failure to achieve specified building ventilation rates indicates a potential for employee complaints of symptoms and of contamination by such pollutants as radon daughters which cause no complaints. Ventilation may be more adequate in some parts of a building than in others. Insufficient air movement may occur even when ventilation is adequate; however, an excessively low air exchange rate is prima facie evidence of poor air quality.

Accuracy. Errors in tracer gas concentration measurements are approximately 2.5 percent. This negligible in comparison to the usual scatter caused by wind gusts, changing temperatures and furnace cycling.

Advantages

Tracer gas methods are an important aid in determining rate of air leakage or ventilation adequacy. The error rate is lower than with other air leakage measurement methods that rely on wind gusts, changing temperatures and HVAC system cycling.

Tracer gas can be used for both short and long-term measurement throughout the year. The injection and measurement may be done either manually or automatically, and a single detector can be used for a number of measurements.

With the air bag sampling method, operators need not be highly trained, and the measurement and analysis can either be done on or off sight, which gives the method great flexibility.

Limitations

Only long-term average results representing different climatic conditions are useful for comparison with other buildings.

Since most leakage occurs on windward and leeward faces of a building, poor construction may be missed by the tracer gas test. Tight control must be kept on the density of the tracer gas and the location of the detector, or spurious infiltration rates, high or low, could be registered. And, the method will not provide the precise location of air leakage paths.

In large buildings and those partitioned into many rooms, unless they have a central air handling system, uniform tracer gas distribution will be difficult to obtain.

The cost may be very high and operation may require highly trained technicians unless the air bag sampling modification is incorporated.

Cost. The chromatograph-detector unit is compact, simple to operate and costs approximately $6000 to $8000. It is portable but tanks of SF_6 and Ar or N_2 must be transported along with it. An attachment is available to enable ten sites to be automatically sampled almost simultaneously.

The complete automatic system costs approximately $20,000 and must be specially assembled. It has been used in air infiltration studies in large buildings.

New Technology/Developments. None.

CONSTANT CONCENTRATION (Tracer Gas)

Measurement and Analysis. This method is similar to the decay method except that time intervals between tracer injections are shorter. Currently all constant concentration injection techniques in use utilize automated systems.

British Gas Corporation Method

The British Gas Corporation air infiltration unit is based upon a microprocessor and rapid sample analysis. Gas is released to maintain constant concentration in each room of a house. Rooms are monitored in sequence for 6 seconds each, an injection valve is opened and the duration of injection is recorded.

The two most recent concentrations are used to vary the amount of N_2O injected prior to the next sampling with the concentration maintained at 50 ± 2 parts per million (ppm). Each of the injection lines is calibrated prior to the test so that the injection is suitable for each room.

This method has been used for almost 2 years with up to twelve rooms measured simultaneously. Six houses have been analyzed with an accuracy of 10 percent.

National Research Council of Canada (NRCC) Method

In this method, concentration is measured every 2 or 2 1/2 minutes. Fixed amounts of SF_6 can 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 for the tracer decay method. Since a level of 15 ppb SF_6 is generally maintained, the amount of tracer gas used during a test is very small.

The NRCC apparatus has been functioning for three years and is now available as a commerically packaged unit. This unit can hold SF_6 concentrations in a house constant to within 4 percent over 15-minute intervals and 2 percent over a one-hour interval.

Kumar et al., 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 thorough mixing in these houses, the furnace fan was operated continuously.

Danish Institute of Technology Method

The Danish Institute of Technology automated system is microcomputer-based. There are many similarities to the British Gas Corporation system. Injection of N_2O is essentially continuous. Small fans are located near the N_2O injection port in each room to promote rapid mixing. Ten solenoid valves are used to control injection and another ten control sampling to the infrared detector. The design also provides a tank of N_2O gas at 48

ppm to periodically check the design valve of 50 ± 2 ppm N_2O concentrations within the home. Temperature and humidity sensors are being added to further increase accuracy.

Metal tubes near door hinges are used to provide sampling paths so that door operation is unaffected. The N_2O injection orifices for each room are carefully designed and calibrated. The system can operate for up to six days unattended. Records are maintained on floppy discs, with a viewing screen provided to check on site operation.

Swedish National Testing Institute Method

The Swedish National Testing Institute automatic measurement method is similar to the previous one. The short response time of the N_2O analyzer allows collection of a large number of samples. Arrangement of 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 moves the samples to the analyzer through plastic tubes within the house. When operated from a van, special tubing is used to insulate the nine plastic tubes. Measurements are made at set intervals and used by the micro-processor to calculate air exchange rates for each room.

Advantages

Measurements may be taken over a long period and there is a task observable response to weather changes. Also, since the gas injection rate is directly proportional to the infiltration rate, data analysis is more direct. With this method, infiltration rates of buildings with spaces having separate air supply systems can be measured. Large air change rates can be generated with a measurement accuracy of 5 to 10 percent.

Limitations

Systems that use electron capture gas chromatography have a major weakness in that with heavy usage the column and detector require considerable maintenance, cleaning, and calibration. The switching value also requires maintenance. Additionally, with these systems, zero drift of the detector is a continuing problem.

In all systems of this type, measurement is always a response to a previous tracer concentration since the mixing of air and gas is not instantaneous.

The measurement system must always be automated and no precise air path leakages can be identified.

CONSTANT FLOW (Tracer Gas)

Measurement and Analysis. The constant flow method was developed at the Lawrence Berkeley Laboratory (LBL) to provide automated infiltration measurements in a test space at 30-minute intervals. The instrumentation originally used N_2O with an infrared analyzer but because of exposure limits was modified to use SF_6.

The system used was designed to permit researchers to examine the effects of weather and mechanical systems on infiltration. The instrumentation contains a microcomputer that (1) controls the injection rate of tracer gas, (2) selects the sampling port, (3) processes and records weather and system data, (4) calculates and records average infiltration values, and (5) computes a new injection rate based on the previously calculated infiltration rate to keep the concentration within a particular range. The average infiltration monitor, developed at LBL, permits simple unattended measurement of the long-term infiltration rate of a building.

The monitor minimizes both inconveniences to building components and the technical skills required to install the system. It consists of an injector and the sampler, each of which contains a small solenoid pump that is pulsed at a rate controlled by an internal timer. Each pump is either emptied by injecting tracer gas into the space or filled by sampling the mixture of tracer gas and room air in the space. The concentration is determined after the pump is emptied or filled.

Accuracy. Not available.

Advantages

This method permits continuous measurements of the ventilation rate.

No complex instrumentation feedback loops are required to maintain constant concentration.

The technique minimizes inconvenience to building occupants.

Limitations

The infiltration rate may drop considerably during changing weather conditions, causing the concentration to rise beyond the limit of the detector.

The technique must be automated in order to achieve maximum efficiency.

The method does not provide a precise location of individual air leakage paths.

Cost. Not available.

New Technology/Developments. None.

FAN PRESSURIZATION

Measurement and Analysis. Fan pressurization is used to measure building enclosure system tightness independent of weather conditions. The

building is pressurized or depressurized by a fan and the air flow is measured. Buildings can be compared by generating the air leakage at a standardized pressure difference. A fan mounted in an airtight assembly is mounted either in a window or doorway, and measurements are made in minutes. Inadequate mixing is not nearly as important a factor in fan measurements as it is in tracer gas measurements. In order to minimize natural pressure differences and to obtain measurable flow rates, large pressure differences are usually required. Use of a large fan or a number of smaller fans simultaneously may be required in medium-size buildings.

Tests are conducted as follows:

1. Make observations of the condition of the building, including windows, doors, walls, roof and floors. Measure and record the wind speed and outdoor and indoor temperatures. Place the air-moving apparatus near the structure and connect the duct or blower door assembly to the building enclosure, using a window, door, or vent opening. Seal or tape openings to prevent leakage.
2. Calibrate the fan to obtain air flow rates if no other flow meters will be used.
3. Measure flow rates at pressure differences from 10 to 70 Pa at 10 Pa increments.
4. Calculate airflow rates.

A uniform pressure is maintained in the building that is within 20 percent of the indoor-outdoor pressure difference. The maximum variation from stack or wind effect should be no more than 10 percent of the pressure difference. Tests are usually not made when wind speeds are above 15 km/h.

The thermal stack effect is usually disregarded for one-story buildings. For two or more stories the stack effect usually results in a pressure difference of approximately 0.1 Pa/C° (or 0.056 Pa/F°) per story. At a temperature difference of 20 C° (36°F), the stack effect in a 10-story building results in a pressure difference of approximately 20 Pa.

An alternative pressurization technique uses the air handling system of the building to pressurize it; however, this method cannot be used to measure permeabilities of individual components such as windows or doors.

The following instrumentation is required.

1. Fan, blower, or blower door assembly, capable of establishing indoor-outdoor pressure differences in the range 10-70 Pa.
2. Manometer or pressure indicator capable of measuring pressure differences to within 2.5 Pa.
3. Air flow or velocity measuring system capable of measuring flow 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 (60 ft/min).
5. Temperature measuring device accurate to 1°C (2°F).
6. Air flow regulating system, e.g., a damper, or variable motor speed control, that will regulate and maintain air flow within specific limits.
7. Ductwork able to accommodate both pressurization and depressurization.

Accuracy. ASTM estimates the uncertainty of the measurements to be approximately 10 percent.

Advantages

The method is simple and can be used to compare air leakage rates of buildings at various times (e.g., before and after retrofit).

No reference to wind and outside air temperature is required for data analysis.

The method can be used in conjunction with infrared thermography to locate leakage paths precisely.

The effectiveness of retrofit measures applied one at a time can be assessed.

Limitations

Under some circumstances the pressure differences generated are so great that the leakage paths may be quite different from those that occur under normal conditions.

It is difficult to isolate one pressurized space from an adjoining space.

It is difficult to pressurize adjoining spaces to maintain a uniform pressure difference.

Cost. $2500 - $10,000

New Technology/Developments. Pressure differences induced by fans are so large that wind has little effect by comparison. An alternative pressurization technique that uses pressures close to naturally occurring ones is the infrasonic or "AC fan" method. A piston inside the building or mounted in a wall alternately causes air to leak in and out. If the frequency is low enough, there is little compression and decompression. The

frequency provides a means of distinguishing induced from natural pressurization; the latter can be electronically filtered. This method has not been widely used and it may prove as difficult to apply to large buildings as the 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.

Manufacturers. Manufacturers include: Infiltec, Division of Saum Enterprises, Inc., PO Box 1533, Falls Church, VA 22041, (703) 820-7696; Retrotec USA, Inc., 6215 Morenci Trail, Indianapolis, IN 46268, (317) 297-1927.

INFRASONIC SYSTEM

Measurement and Analysis. In the frequency range (0.1-7 Hz) small buildings are characterized by one acoustic capacitance and one nonlinear leakage resistance. Infrasonic apparatus comprising a motor-driven source of known output, a pressure pickup and a signal processor is used to measure air leakage.

The infrasonic system is composed of a portable source and a pressure sensor that are set up inside the building. The fixed displacement source alternately compresses and rarifies the air above a moveable piston. The bottom of the piston supplies an alternating volume of air to the enclosed space. The piston has a peak-to-peak displacement of only 3.81 cm (1.5 in), making its action more like a bellows.

The pressure sensor has a very thin plastic membrane across its opening. As the pressure and the space vary (due to the source), the membrane deflection is measured with an optical instrument.

The infrasonic system generates a very low frequency (approx. 1 Hz) of known magnitude. The source frequency is applied to the building interior, and the alternating component of inside pressure is a function of the type and size of leakage paths.

The pressure variations that must be detected are such that the sensor must be able to resolve 0.1 to 0.01 Pa. In order to prevent normal barometric pressure fluctuations from interfering with the measurements, the sensor chamber is provided with a very small slow leak.

The signal from the sensor is processed before it is passed to a chart recorder. The system also uses a sharp cut-off filter to attenuate ordinary acoustic noise above 7 Hz.

Accuracy. When compared with a blower door system, the air leakage data agree within 200%.

Advantages

Setup time is minimal since no pressure taps or through-the-wall vents are required.

Limitations

Accuracy is low. Poor agreement is due to wind gusts and instrument calibration.

Calculations of air leakage from an infrasonic test requires using the building volume and the measured frequency response curve.

Cost. Not yet available commercially.

New Technology/Developments. Sound generation is provided by a number of sources. These include: tape player/speaker system, siren, horn, bells, etc. Numerous sound detection systems include a doctor's stethoscope and a small microphone attached to earphones with appropriate elec-

tronics. Both allow local sensing to pinpoint the leak. One approach that has proven effective is a white noise tape recording and a rising-falling tone recording. The white noise sound is useful outside where other noise generation may prove objectionable.

SMOKE TRACERS

Measurement and Analysis. Commercial smoke tracer units are available. These units provide smoke at a well-defined location so that in the presence of an air leakage site a stream of smoke extends to or from the opening.

Smoke tracer techniques employ both pressurization and depressurization of the building. Building depressurization/pressurization is effected by a fan, blower, blower door assembly, or mechanical ventilating system of the building that can be used to move air through the conditioned space at flow rates so that leakage sites will flow air to meet the depressurization/pressurization requirement. The system is normally adjusted to provide steady air flow rates during the leak site detection procedure.

Accuracy. Not applicable.

Advantages

Easy to use. Visual sighting of smoke flow provides instant analysis of leakage sites.

Limitations

Gives no quantitative information. Building may have to be evacuated before use. Smoke moving through the enclosure system in a twisted path may be absorbed in the insulation or other materials.

Cost. $100 to $10,000.

New Technology/Developments. None.

CHAPTER 5

HVAC SYSTEM EVALUATION

TEMPERATURE MEASUREMENTS

LIQUID-IN-GLASS THERMOMETERS

Measurement and Analysis. Any device that indicates temperature is a thermometer; however, in common usage the term signifies the oridnary liquid in glass indicating device. Mercury-filled thermometers have a useful range from -40°F (freezing point of mercury) to approximately 1000°F (softening point of glass). Thermometers are usually calibrated during manufacture at the freezing and boiling points of water, and the space between those points is evenly divided by scale divisions. The liquid-in-glass thermometers are calibrated for either full or partial immersion. If a thermometer is calibrated at full immersion and used at partial immersion then a correction factor must be applied to account for the temperature difference between the two.

Accuracy. The probable error for etched stem stem liquid-in-glass thermometers is ± [illegible] scale division.

Limitations

A thermomenter used to measure gas temperatures can be significantly affected by radiation from the surrounding environment; therefore, it is necessary to minimize these radiation effects by shielding. All thermometers must come in contact with the medium which they are measuring; their limitations are similar to those that measure surface temperature. They can measure actual temprature without complex corections for the characteristics of the medium; however, the measurement is only valid for that single location.

Cost. Liquid-in-glass thermometers can usually be purchased for a few dollars each in small lots or possibly less in larger quantities.

New Technology/Developments. None.

THERMOCOUPLES

Measurement and Analysis. When two wires made of dissimilar metals are joined, a thermocouple junction is formed. A voltage which depends upon the materials of the wires and the temperature of the junction exists between the wires. When the wires are joined at two points, a circuit is formed. If one junction is kept at a temperature different from the other, an electric current flows through the circuit. This phenomenon is used for temperature measurements in thermocouple systems, a reference junction being kept at a constant known temperature, while the other is at the point at which the temperature measurement is required. Advances in solid state circuitry have made possible digital readout devices, made both as a straight millivolt or microvolt meter and as a packaged thermocouple readout. The latter instrument only requires attachment of a thermocouple of proper composition to provide direct meter reading of temperature. Accuracies approaching or even surpassing those of the commonly used potentiometers can be attained, depending on the quality of the instrument.

The choice of materials for thermocouple wire is determined by the temperature to be measured, the protection from corrosion, and the precision and service required. In general, copper vs constantan is suitable for temperatures up to 700°F, iron vs constantan up to 1500°F, and chromel vs alumel up to 2200°F.

For use in heated air or gases, thermocouples are often shielded, as are thermometers, and aspirated thermocouples are sometime used.

With the use of thermocouples, temperatures at remote points may be indicated or recorded and may be obtained within thin materials, narrow spaces, or otherwise inaccessible locations.

A series arrangement of thermocouples, often called a thermopile, can have extreme sensitivity and is useful in detecting very small changes and differences in temperature. The thermocouple is particularly useful in determining a surface temperature and may be attached to a metal surface in one of several ways. For temporary arrangements, couples may be attached by means of tape, adhesive, or putty-like material. To minimize the possibility of error due to heat conduction along the wires, a surface thermocouple should be made of fine wires that are held in contact with the surface for an inch or so from the junction. The wires must be insulated except at the junction.

Accuracy. Accuracy is dependent upon the choice of materials used for the thermocouple wire which in turn is dependent upon the temperature to be measured. Generally for temperatures up to 2200°F the accuracy can vary from .1°F to 15°F. For temperatures from 500°F to 3000°F the accuracy can vary from .1°F to 5°F.

The thermocouple material used for standardizing other thermocouple measurements is accurate but expensive and requires expensive measuring devices. Other materials are less accurate and are subject to oxidation.

Advantages Limitations

[illegible] thermocouples are used in the probes of surface temperature measurements the advantages and limitations discussed in that section are applicable here.

Cost. A typical cost for a thermocouple assembly is $100 or less. This does not include the cost of the measuring device.

New Technology/Developments. Thermocouple assemblies feature quick disconnect plugs, miniature all-purpose heads, very high temperature probes, extremely flexible probes for bending around inaccessible corners and very thin diameter, low thermal inertia, fast response thermocouples (used for measurements in gas flow systems).

RESISTANCE THERMOMETERS

Measurement and Analysis. Resistance thermometers depend for their operation upon the increase of resistance of a sensing element (usually metal) with an increase in temperature. Their temperaure range parallels that of thermocouples, although readings tend to be unstable above 950°F. For accurate results the entire thermometer coil must be exposed to the temperature to be measured.

Thermistors (semiconductor compounds) are a special class of resistance thermometers that exhibit large changes in resistance with temperature, usually decreasing with temperature increase. Small formed shapes of compound, selected for a particular application and temperature range, are made and heat-cured. The thermistor element is connected by lead wires to a digital ohmmeter or special wheatstone bridge for readout. Thermistors can be purchased with a known temperature vs resistance curve or as uncalibrated units.

Accuracy. In the range of -320°F to 1800°F the accuracy of a resistance thermometer ranges between 0.02° to 5°F. When measuring gas temperatures its accuracy is affected by radiation from surrounding surfaces.

Advantages

Compared to the thermocouple, the resistance thermometer does not require a cold junction, and it can be scaled for more accurate measurements. It gives best results when used to measure steady or slowly changing temperatures. Of all usable metals, platinum best meets the requirements of thermometry because it can be highly refined, resists contamination and is mechanically and electrically stable. The relationship between temperature and resistance is nearly linear and drift and error with age and use are negligible. Production units can be closely matched in calibration.

Cost. Depending upon the material used in the sensing element the cost of a resistance thermometer can be up to and slightly over $100. Thermistors are available at $10 and up.

New Technology/Devlopments. A major advance has been the development of thin film sensing elements for platinum resistance thermometers which combines the precision measuring capability of platinum with the rapid response time of a thermocouple.

GLOBE THERMOMETER

Measurement and Analysis. Measurement of the radiant temperature in [illegible] spaces is required to determine comfort levels, as well as [illegible] electronic instrumentation.

[illegible] thermometer is commonly used to measure mean radiant tempera- [illegible] instrument consists of a 6-in. diameter hollow copper [illegible] flat black paint and has a temperature probe at its [illegible] ture in the globe at equilibrium is the result of a

balance between the heat gained or lost by radiation and the loss or gain by convection.

A two-sphere radiometer may also be used for the measurement of MRT. This instrument uses two spheres approximately 2 in. in diameter, one is gold-plated, and the other black. The two spheres are heated elecrically to the same temperature, eliminating differences in convection. The difference in energy to maintain temperature equilibrium is measured, and the MRT of the space can be calculated.

Accuracy. The accuracy would be determined in general by the type of temperature probe used in the sphere.

Limitations

Time constant is long, approximately 10-15 minutes. Correction for air temperature and local air speed must be made for accurate determination of temperature.

Cost. No data available.

New Technology/Developments. Plane Radiant Thermometer: An electronic device which determines the radiant temperature in one (or two opposite) directions(s).

- Several commercial devices recently available.
- May be determined from detailed surface temperature measurements.
- Occupant response should be gathered, but only carefully.

LIQUID CRYSTAL DISPLAY (LCD) THERMOMETERS

Measurement and Analysis. These heat sensitive indicators turn color through a chemical reaction as the temperature changes. They can be used to measure both air and surface temperature.

Accuracy. Accuracy of a typical single temperature rating is within 1% of that rating.

Advantages

LCD's are low cost. They will adhere to most surfaces.

Limitations

Remote temperature cannot be measured, they are capable of measuring localized temperatures only.

The user must be close to observe temperature change.

Cost. Depending upon quantity, cost varies from less than one dollar to less than ten dollars.

New Technology/Developments. None.

HUMIDITY MEASUREMENTS

PSYCHROMETER

Measurement and Analysis. Any instrument capable of measuring the humidity or psychrometric state of the air is a hygrometer. A psychrometer is a particular kind of hygrometer which consists of two temperature sensors, one of which has a cloth wick applied to it. The wick is wetted with distilled water and ventilated with air moving at a sufficient rate, relative to the instrument. The evaporative cooling has been found by experiment to produce a wet-bulb temperature approximately equal to the thermodynamic wet-bulb temperature. The difference between the dry-bulb temperature and the wet-bulb temperature is known as the wet-bulb depression. In the sling psychrometer, two thermometers are mounted side by side in a frame fitted with a handle by which the device can be whirled through the air. The motion is continued until the thermometer readings become steady. In the ventilated aspirated psychrometer, the thermometers remain

stationary and a small fan or blower, or a syringe, is used to move the air across the thermometer bulbs.

Other temperature sensors, such as thermocouples and thermistors, are also used and can be adapted for recording of the temperatures or for use where a small instrument is required.

Charts and tables are available showing the relation between the temperatures and humidity. Data are usually based on a barometric pressure equal to one standard atmosphere. A correction must be included for variations in barometric pressure.

For air temperatures below 32°F, the water on the wick may either freeze or supercool, and its state must be known and a proper table or chart used, since the wet-bulb temperature is different for ice than for water.

Accuracy. In the range from 0-500°F the accuracy is 0.3 to 3% of the relative humidity.

Advantages

Psychrometers are used as a standard for humidity measurement.

Limitations

Psychrometers are sensitive to air moving across the thermometer bulbs. The accuracy decreases as humidity increases. They are temperature dependent and difficult to use at sub-freezing temperaures. They do require a moderate amount of maintenance. The wick must be kept clean and the wet bulb should have distilled water.

Cost. up to $100. Increases with accuracy.

New Technology/Developments. None.

DEWPOINT HYGROMETER

Measurement and Analysis. In the most common form of these instruments, means are provided for cooling and observing the temperature of a surface exposed to the air. The highest temperature at which condensation occurs on the surface is taken as the dewpoint temperature of the air. This temperature may be used with charts and tables to determine the relative humidity of the air. A bright surface or metallic mirror is usually used with various methods to cool it, including evaporation of a refrigerant, or a stream of air passed through dry ice. In some systems, the presence of condensation is detected visually. Thermoelectric cooling is used in automated systems with photoelectric cells to detect the presence of a moisture deposit and accurately control the mirror at the dewpoint temperature. In automated systems, the dewpoint temperature is displayed on a dial, and provision is usually made for recording.

An instrument, in which the temperature varies with the ambient dewpoint temperature, is designated as a heated electrical hygrometer. This device usually consists of a substrate covered by glass fiber fabric, with a spiral winding for electrodes. The surface is covered with a salt solution, usually lithium chloride. When in operation, the flow of electrical current through the salt film heats the sensor. The resistance characteristics of the salt are such that a balance is reached with the salt and its critical moisture content, corresponding to a saturated solution. The temperature of the sensor then adjusts automatically so that the water vapor pressure of the salt film is equal to that of the ambient air.

Accuracy

Type	Range (depression °F)	Accuracy (depression °F)
Condensation	(-180) - 200	0.2 - 2
Salt-phase transition	0 - 160	1 - 2

Limitations

The condensation or chilled mirror hygrometer is delicate, expensive and must remain clean in order to provide accurate readings. Some difficulty can be expected with the supercooling effect. When lithium chloride is used in the salt-phase transition type hygrometer, it cannot be used to measure relative humidity below approximately 15% and it has an upper dew-point temperature limit of about 160°F.

Cost. No data available.

New Technology/Developments. None.

DIMENSIONAL CHANGE HYGROMETERS

Measurement and Analysis. Many organic materials change in dimension with changes in humidity, and this action has been used in a number of simple and effective humidity indicators, recorders, and controllers. Motion caused by changes in dimension through a linkage causes a pointer to move across an indicating dial, moves a pen across a recording chart, or actuates a pneumatic or electric control mechanism.

Organic materials commonly employed are human hair and animal membrane, animal horn and wood. Other organic based material like paper, nylon and dacron are also used.

Accuracy. In the temperature range betwen -40°F to 150°F and humidity range from 0 - 100% relative, a typical accuracy for a dimensional change hygrometer is 3% relative humidity.

Advantages

They can read directly in relative humidity, and they are simple and inexpensive by comparison with most other types.

Limitations

No organic material has been found which can be relied upon to consistently reproduce its action over an extended period of time, and the responses may be significantly affected by exposure to extremes of humidity. Such devices require initial calibration and frequent recalibration or setting; especially when going from one humidity extreme to another.

Cost. No data available.

New Technology/Developments. None.

ELECTRICAL IMPEDANCE

Measurement and Analysis. Any substances absorb or give up moisture with changing relative humidity, and exhibit corresponding changes in the electrical impedance. The sensor in this type of hygrometer consists of dual electrodes on a substrate. It is coated with a film, usually containing a salt, in a binder to form an electrical connection between the windings. Means are provided for determining the resistance of the film. The relation of sensor resistance to humidity is represented by graphs. Since the sensor displays a sensitivity to temperature, these graphs consist of a series of curves, each one being suitable for a given temperature.

Accuracy. In the range from -40°F to 150°F, the accuracy varies from [illegible] to [illegible] rh.

Advantages

Is susceptible to excessive humidities and to a variety of vapors. Should be calibrated periodically.

Limitations

Displays a high sensitivity to humidity change.

Cost. No data available.

New Technology/Developments. None.

ELECTROLYTIC HYGROMETER

Measurement and Analysis. Air is commonly passed through a tube where the moisture is absorbed by a desiccant, and electrolyzed. The air flow is regulated, commonly at 100 cc per minute, STP. The electrical current required for electrolysis can be related to the humidity level. The instrument is commonly designed for use with moisture-air ratios in the range of 1 to 1000 parts per million, but can be obtained for use with higher humidities.

Accuracy. In the range from -100°F to -5°F depression, the accuracy is 3% of the scale range.

Limitations

Ordinarily limited to low humidities.

Cost. No data available.

New Technology/Developments. None.

GRAVIMETRIC HYGROMETER

Measurement and Analysis. The humidity level can be measured by extracting and weighing the water vapor in a known quantity of air. For precise laboratory work, powerful desiccants, such as phosphorus pentoxide and magnesium perchlorate, are used for the extraction process, while for

some purposes calcium chloride or silica gel may be satisfactory. Freezing the water vapor out of a measured stream of air with solid carbon dioxide, and weighing the ice, is a similar operation.

A commercial system for continuous measurement of humidity uses piezoelectric crystals coated with an absorbent material which reaches a moisture content that is dependent on the ambient humidity. The natural frequency of the crystal varies with the mass of coating and the moisture.

Accuracy. 0.1 to 2%.

Limitations

Special equipment and extreme care required for high accuracy.

Cost. No data available.

New Technology/Developments. None.

VELOCITY MEASUREMENTS

ANEMOMETERS

Measurement and Analysis. Heating and air-conditioning engineers are called upon to measure the flow of air more often than that of other gases, and usually the air is measured at or near atmospheric pressure. Under this condition, the air can be treated substantially as an incompressible fluid.

A detecting vane anemometer consists of a pivoted vane enclosed in a [illegible]. Air exerts a pressure on the vane as it passes through the instrument and the movement of the vane is resisted by a spring and a magnet. The instrument gives instantaneous readings of directional velocities. With fluctuating velocities, it is necessary to average swingsof the needle.

The propeller or revolving vane anemometer consists of a wind-driven wheel connected through a gear train to a set of recording dials that read the linear feet of air passing in a measured length of time. Each instrument requires individual calibration. At low velocities the friction drag of the mechanism is considerable. In order to compensate for this, a gear train that overspeeds is commonly used.

A cup anemometer is almost universally used for measuring wind speeds. It consists of three or four hemispherical cups mounted radially from a vertical shaft. Wind from any point of the compass will cause the cups and shaft to rotate. The instrument is so constructed that wind speeds may be recorded or indicated electrically at some remote point.

Measurement of low air velocities (0-100 fpm) is particularly difficult for the instruments mentioned above. The flow pattern is very unstable, causing the turbulence level to be of the same order of magnitude as the velocity. Useful data can be obtained with any of several instruments, if they are maintained in calibration and the user understands their operation and limitations. Several types of thermal anemometers (directional and nondirectional), are applicable to this range, but have questionable accuracy at the lower end.

If a suitable sensing element is heated electrically at a fixed rate and exposed to an air stream, its temperature is determined by how fast the air stream is conducting heat away from it. Therefore, its temperature is a measure of air velocity. In the hot-wire anemometer, a very thin heated wire is used as a resistance-thermometer element whose temperature may be determined accurately.

The hot wire anemometer is a general purpose instrument for air flow measurements. Typical applications are:

- troubleshooting and the balancing of heating, ventilating, and air conditioning systems by measuring duct air velocities
- monitoring outdoor air movements
- flow measurements for performance tests on ventilation fans
- velocity profiles in large ducts
- calibration of other air flow meters.

The anemometer can be conveniently used to measure the total mass flow of air in a pipe or duct. Generally, it is necessary to take measurements at various points in the duct to determine a velocity profile. Then the best placement of the sensor can be made to achieve the desired relationship of mass flow rate and velocity.

A hot-wire anemometer system consists of a hot-wire sensor, an electronic module containing a power supply, amplifiers, and feedback circuits, and a suitable data recorder. A voltmeter and an electronic filter are often used in turbulence studies.

Sensors for anemometer systems are available in a wide assortment of types and sizes. Specifications for a typical hot-wire sensor are as follows: (a) length, 1 to 2 millimeters; (b) diameter, 5 microns; and (c) material, platinum coated tungsten. The sensor completes one arm of a Wheatstone bridge circuit and is heated to a temperature which is significantly higher than the fluid temperature. The electrical power which is supplied by the anemometer to the hot-wire, and which is dissipated into the fluid, is related to the instantaneous velocity of the fluid over the wire.

Two basic types of anemometer systems are used, constant current and constant temperature. In the constant current anemometer, the electrical current supplied to the sensor is kept constant and any temperature change is a measure of air flow. In the constant temperature anemometer, the temperature of the hot-wire sensor is kept constant and the electrical energy needed to hold this temperature constant is a measure of air flow. For either system, the voltage drop across the wire is proportional to the instantaneous fluid velocity over the wire. The relationship between sensor voltage drop and fluid velocity must be carefully determined by calibration. The calibration process should be conducted in a suitable device (miniature wind tunnel, water tunnel, etc.), using the fluid of interest at the temperature of interest.

The useful frequency response of an anemomenter system can be as high as 45 KHz. A hot-wire anemometer is capable of measuring very rapid velocity fluctuations.

The heated-thermocouple anemometer is calibrated to give velocity in terms of the differential voltage between heated and unheated thermo-junctions exposed to an air stream.

In the heated-bulb anemometer, a heating wire is wound around a mercury-in-glass thermometer, and the temperature difference between this thermometer and a similar unheated one serves as an index of air speed.

Accuracy

Instrument	Range (fpm)	Accuracy (%)
Deflecting-vane type anemometer	30-24,000	5
Revolving-vane anemometer	100-3000	5-20
Heated thermocouple anemometer	10-2000	3-20
Hot-wire anemometer	1-1000	1-20
	up to 60,000	1-10

Characteristics of specific anemometers.

Instrument	Limitations
Deflecting-vane type anemometer	Large 1/2 - 3/4 inch diameter probe. Tubes connecting sensor head to body somewhat awkward.
Revolving-vane type anemometer	Subject to error with variations n velocities with space or time; easily damaged;
Heated thermocouple anemometer	Accuracy of some types not good at lower end of range. Steady state measurements only.

The hot-wire anemometer is a sophisticated, complex, delicate and costly instrument. Principal advantages of hot-wire anemometer systems are: (a) high frequency response suitable for transient velocity and turbulence measurements; (b) ability to accurately measure very low velocities in gases and liquids; (c) availability of specialized sensors and accessories; and (d) small diameter probe with flexible connection to instrument body.

All anemometers need periodic calibration.

Cost. $150-$2200.

New Technology/Developments. Devices have been developed which are compact enough to fit in a shirt pocket, have retractable self stowing probe, are ultra low powered (AAA cells) and extremely rugged.

Manufacturers. Manufacturers include: Alnor Instrument Co., 7555 North Linder Ave., Skokie, IL 60077, (312) 647-7866; Kurz Instrument, Inc., PO Drawer 849, Carmel Valley, CA 93924, (800) 424-7356 or (408) 659-3421.

PITOT TUBE

Measurement and Analysis. The Pitot tube, used in conjunction with a manometer, provides a simple method of determining the air velocity at a point in a flow field.

The type of manometer to be used with a Pitot tube depends upon the magnitude of the velocity pressure being measured and the accuracy desired. At velocities greater than 1500 feet per minute, a draft gage is usually satisfactory. If the Pitot tube is being used to measure low air velocities, a precision manometer is essential.

Many forms of Pitot tubes have been used and calibrated. To meet special conditions, different sized Pitot tubes which are geometrically similar to the standard tube can be used.

Accuracy

Range, fpm	Accuracy
180-10,000 with micromanomter; 600-10,000 with draft gages; 10,000 up with manometer	1-5%

Limitations

In order to obtain a velocity profile across a duct, a traverse of many readings must be taken. Pulsating or disturbed flow in a duct will result in erroneous readings; therefore a Pitot tube must be located sufficiently far from that disturbance to avoid those errors. This method is inapplicable in many cases because of its lack of precision at low velocities or the impracticability of taking traverses where many tests are in prospect.

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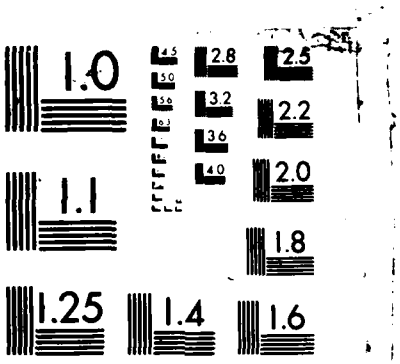

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS 1963 A

Cost. No available data.

New Technology/Developments. None.

AIRBORNE TRACERS (see also section on leakage measurements)

Measurement and Analysis. Tracer techniques are suited to making velocity measurements in an open space. Typical tracers include smoke, feathers, pieces of lint, radioactive and nonradioactive gases. Measurements are made by timing the rate of movement of the tracers or by monitoring the change in their concentration level.

Smoke is very useful in studying air movements and can be obtained from titanium tetrachloride or by mixing potassium chlorate and powdered sugar and firing the mixture with a match. Titanium tetrachloride smoke can be easily handled in a small pistol-like ejector. Smoke tubes, candles, and bombs are available for studying airflow patterns. Gas tracers are a useful method for studying complex ventilation problems.

Accuracy

Range, fpm	Accuracy
5-50	10-20%

Advantages and Limitations. See section on air leakage measurements.

Cost. $20 - $5000.

New Technology/Developments. An infrared radiation absorbing tracer gas technique using nitrous oxide (N_2O) and a thermal imaging system has been developed by the Architectural and Building Sciences Division of Public Works Canada (PWC) to illustrate patterns of air flow from air-conditioning supply diffusers. Air flow patterns are recorded in real time on video tape through use of an infrared camera and N_2O.

A typical diffuser test setup contains a screen that is heated and located some distance behind the diffuser. The space partitioning arrangement is not changed from that found in actual practice, and thermographic scanner is located at as high an elevation as is practicable. N_2O is then introduced into the diffuser air stream where it appears as a smoke-like image to the scanner. The images can be enhanced by the use of a computer; the background may or may not be removed during this process in order to provide a clear image of the exact path of the tracer. The PWC data indicate that some types of air diffusers will provide good penetration of supply air into the work area under almost any conditions. These diffusers, however, are generally considered to be less desirable because they create strong downdrafts of cooled air and cause discomfort. The "draftless" diffusers, on the other hand, are affected by furniture layouts and diffuser flow rates. When air flow rates are high there is good penetration of supply air in variable air volume systems. When air flow rates are decreased according to lower cooling requirements, up to 90 percent of supply air does not reach the occupant.

VOLUME MEASUREMENTS

VENTURI, NOZZLE AND ORIFICE FLOW METERS

Measurement and Analysis. Air volume in HVAC systems may be determined by several methods. Some methods require in-place sensors, others may be performed in installed systems. Unlike balance measurements, which are often made at terminal units, some volume measurements may be required in system ducts for optimal load management, or for performance analysis.

Gas and liquid mass or volume flow rates are most often determined by measurement of the pressure difference across an orifice, nozzle, or

Venturi tube. The orifice is more easily changed than the nozzle or Venturi tube and is less affected by change of Reynolds number. The nozzle is often preferred to the orifice because of its relative freedom from the influence of approach conditions and accurate predictability of its coefficient. The Venturi tube is in essence a nozzle followed by an expanding recovery section to reduce the net pressure drop.

The flow meters are usually used to measure fluid flow through pipes, ducts and plenums.

Accuracy. One percent accuracy above a Reynolds number of 5000.

Limitations

Accuracy is affected by approach conditions.

Cost. $1500-$3000.

New Technology/Developments. None.

Manufacturers. See Chapter 6, Energy Metering

DISPLACEMENT METERS

Measurement and Analysis. For measuring liquid or gas flow, many types of displacement meters are available. The two types are the gas meters, which employ leather bellows, and the wet test meters, which use a water displacement principle. The Thomas meter has been used in the laboratory for measurement of high gas flow rates with a small pressure drop. The gas is heated and the temperature rise measured by two resistance thermometer grids. Knowing the heat input and temperature rise, the flow is calculated as the quantity of gas that will remove the equivalent heat at the same temperature rise.

Accuracy

Instrument	Accuracy
Displacement meter	0.1 - 2% up to 1000 cfm (depending on type).
Gasometer	0.5 - 1.0%
Thomas meter	1% over any range.

Limitations

Some displacement meters require calibration and are used in applications where relatively small volume flows at high pressure drops ocur. Gasometers are used in short duration tests and also for calibrating other flow methods. The Thomas meter is usually used only to measure the flow of gases and usually can only be justified where an elaborate setup is required by high accuracy.

Cost. $100 - $2000.

New Technology/Developments. None.

Manufacturers. See Chapter 6, Energy Metering

ROTAMETER

Measurement and Analysis. The rotameter is used for permanent installations where high precision, ruggedness, and ease of operation are important. Its most frequent use is in measurement of liquids or gases in small diameter pipes. For ducts or pipes over 6 in. in diameter, the expense of this meter may not be warranted. In large systems, however, the meter might be placed in a bypass line and used in conjunction with an orifice.

In its most common form, the rotametr consists of a float which is free to move vertically in a transparent tapered tube. The fluid enters at the narrow bottom end of the tube and moves upward, passing through the

annulus formed between the float and inside wall of the tube. At any particular rate of flow, the float assumes a definite position in the tube, its location indicated by means of a calibrated scale on the tube.

This type of flow meter is usually furnished in standard sizes calibrated for specific fluids by the manufacturer. The compactness, reliability, and ease of installation are particularly advantageous when many measurements of the same type are to be made.

Accuracy. One percent accuracy over any range of measurements.

Advantages

Compact, reliable and relatively easy to install.

Limitations

Must be calibrted for each specific fluid by the manufacturer.

Cost. $300 - $3000

New Technology/Developments. None.

Manufactureres. See Chapter 6, Energy Metering.

TURBINE FLOW METERS

Measurement and Analysis. Turbine flow meters are volumetric sensing meters having a magnetic turbine rotor suspended in the flow stream in a nonmagnetic meter body. The fluid steam exerts a force on the blades of the rotor, setting it in motion and converting the linear velocity of the fluid to an equivalent angular velocity. The rotational speed of the turbine is proportional to the fluid velocity and to the volume rate of flow of the fluid.

The speed of the rotor is monitored by an externally mounted pickoff assembly. Two types of pickoffs are used: magnetic and radio frequency.

Since the output frequency of the turbine flowmeter is proportional to flow rate, every pulse from the meter is equivalent to a known volume of fluid that has passed through it; adding these pulses yields total volumetric flow.

Accuracy. Accuracy is 0.5% over any range of flow.

Advantages

Some meters may be used in bidirectional flow applications.

Cost. $2000 - $3500.

New Technology/Developments. None.

Manufacturers. See Chapter 6, Energy Metering.

POSITIVE DISPLACEMENT METERS

Measurement and Analysis. For measuring total liquid or gas flow rates, many types of positive displacement meters are available. In this type of meter, the fluid flows into compartments of definite size. As the compartments are filled, they are rotated so that the fluid discharges from the meter. The rate of flow through the meter is equal to the product of the size of the compartments, the number of compartments, and the rate of rotation of the rotor. Most of these meters have a mechanical register which is calibrated to show total flow.

Novel and more sophisticated positive displacement flow meters have become commercially available. These meters use a metering gear pump (or a special blower), a transducer which senses the pressure difference across the pump, and a feedback system which controls the speed of the pump and maintains a zero pressure drop across the pump.

Accuracy. Using positive displacement meters with electro-mechanical feedback, fluid flow rates from 0.10 to 150 gpm have been measured with

accuracies of better than 0.10 percent. Because of the zero pressure drop across the meter, accurate measurements near the boiling point of liquids can be made.

Cost. $500 - $2500.

New Technology/Developments. None.

Manufacturers. See Chapter 6, Energy Metering.

CHAPTER 6

ENERGY METERING

ENERGY MANAGEMENT OBJECTIVES

Energy management includes energy metering. The type of energy metering system required will depend on the functions the metering must serve to meet the energy management system needs. For instance, if the only need for energy metering is for billing on a facility wide basis, then only a centrally located metering system is needed at the heating plant or substation. On the other hand, if energy useage is to be paid for by many different users within a facility, then each energy accountability unit needs a metering system so that the information needed for user motivated conservation and billing is generated.

Energy conservation is often most effectively pursued if a small user group - an individual, a family or a small office - is metered and billed for the energy it uses and there is direct feedback to the individuals who control the energy use. At the other end of the spectrum, if metering is facility wide and large numbers of users are contributing to a very large total energy consumption, individuals or small unit users have little feedback on the effectiveness of their conservation measures, and often the tendency is for individuals to become insensitive to energy use and the need for conservation.

Energy metering is expensive. So is energy use. A balance must be reached so that the metering installed produces savings in energy use equal to or greater than the cost of installing and operating meters. Utility

companies install meters on each user unit whether it be a family, an office, or a factory. They must install meters for each user because they need the information for billing purposes. The cost of metering is built into the cost of service to the customer. But for a large facility which either generates its own energy or distributes purchased energy to many user groups within it, the situation appears different. Bills are not usually sent out to each user group. Instead, the cost of energy is totalled and all users share equally. In this system, individual user group energy use is not known. Thus, inappropriate or wasteful energy use is difficult to pinpoint and correct.

Energy use meters provide information which may be used in several ways to help reduce energy usage.

1. Providing information for Usage Centers.

Where energy use responsibility is tied to payment and comes out of each usage units annual budget, where there is consumer accountability, the energy meter provides necessary information to allow local usage units to monitor, control, and assess their own energy conservation measures.

2. Monitoring Energy Use to Determine Equipment Malfunction.

Some equipment malfunctions are not obvious and are often detected through observing energy usage over a period of time. Inefficiencies due to equipment malfunction often go undetected for months unless increased energy usage is measured, observed and investigated. Ideally it should never be necessary to find out about malfunctions this way because preventive maintenance should keep equipment operating so that this does

not occur. However, many facilities are not able to sustain an effective preventive maintenance program and malfunctions do occur.

3. Monitoring Energy to Measure Conservation Effectiveness.
The effect of conservation measures on energy use can be observed with the information gained from energy metering. This allows the energy manager to compare predicted energy savings with actual energy saved. By substantiating the cost-effectivenss of energy conservation measures, the energy manager builds a data base for the facility which makes future predictions more accurate and new programs easier to sell.

4. Monitoring Energy to Measure the Impact of New Users.
When new systems are installed, new departments added, new managers put in place, or new operating procedures adopted, the energy monitoring system can help the energy manager evaluate the impact of these changes. Energy use requirements can then be planned more effectively.

5. Long- Versus Short-Term Energy Monitoring.
Where energy is being billed to user groups, long-term energy monitoring is required. In this way energy use is totaled in the form of kilowatt hours, pounds of steam, BTU's or gallons of oil and is used to allocate the cost of energy to the users. However, if the user is very large and sub-units are not to be held directly accountable for their usage or billed for it, then sub-unit system efficiency can often be monitored with short-term energy meters which are installed temporarily in the energy line to monitor energy use for a day, a week, a month, or whatever length of time is required to accommodate the energy manager's needs.

From these considerations, it can be seen that the energy manager must decide what overall energy management strategy is to be employed before deciding on energy metering equipment.

OPERATION AND USE OF ENERGY METERS

Energy supplied in the form of gas or liquid such as steam, air, water or oil is usually measured by a device which measures the volume of material as it flows through pipes from its source to its point of use. The volume measurement may be direct, as in the case of steam condensate meter which takes all the condensate passing through it and measures its volume; or calculated, based on the measurement of pressure or velocity in a pipe of known dimensions and flow characteristics, as in the case of a turbine meter in a hot water or steam line.

The volume flow measured or computed is then converted to mass flow, usually in terms of pounds or kilograms. This conversion is simple for liquids and for gases at constant known conditions of temperature and pressure. But for gases with varying conditions, temperature and pressure need to be monitored to accurately convert the meters' volumetric readings to mass flow and finally to energy flow.

The useable energy stored in a non-fuel gas or liquid depends on its beginning and ending temperature and its phase change characteristics. For instance, if the temperature of one pound of water drops one degree Farenheit, it gives off one BTU (British Thermal Unit) of energy. On the other hand if one pound of steam changes phase and condenses to water with no temperature change, it gives off approximately 1000 BTU. Thus, to find the energy flow of a gas or liquid, one needs to determine the beginning and ending temperatures and, if a phase change (gas to liquid or liquid to

solid) is involved in the process, the phase change characteristics of the material.

Electrical metering is available to measure both kilowatt-hours and kilowatt demand. The kilowatt-hour is a unit of electrical energy. The kilowatt is a unit of electrical power, the rate of use of electrical energy, or kilowatt-hours per unit time. In alternating (AC) currents the measure of electrical power and energy is complicated by a factor known as power factor. Normally one thinks of electrical power, the kilowatt, as EI, a product of the voltage, E, and the current, I. Because of what is called reactance in an AC circuit, caused by motors, transformers and other electrical equipment, the current gets out of phase with the voltage. If one takes the product of EI in an AC circuit, one will obtain the apparent power of the system. The apparent power is always equal to or greater than the real power of the system. The real power is the product of the voltage and that component of the current which is in phase with the voltage. This is computed by taking the product of the voltage, E, the current, I, and the cosine of the angle of phase lag or lead which is always equal to or less than one.

Meters by themselves do little good. To be useful, they must be read, maintained and their information organized for use. Many meters are now available with both direct readout capability as well as with a signal input to a digital processor for use in automatic data processing. This means tht they may be ordered for use in a strictly manual operation, or for a highly automated system with central control, monitoring and data processing.

METER TYPES AND THEIR CHARACTERISTICS

Many different types of meters exist, each having its own special application advantages. None are perfect and each choice will represent a compromise involving cost, performance and complexity. The following discussion is meant to introduce the readers to some of the more general characteristics of various types of meters. As the facility engineer investigates the facilities own special requirements and begins the process of obtaining detailed specifications and installation, operating and maintenance information from manufacturers and users in the field, it will become much more clear what type of meter best meets the requirements of a particular application.

1. Condensate Meter - This meter measures the volume of steam condensate. It consists of a drum designed to rotate as the condensate flows through it. Because it is mounted in the condensate line, installation does not need to interrupt service. It is regarded by users as reliable, relatively simple to install, easy to maintain and accurate (± 0.5 to 1.0%). Accuracy is maintained at all flow rates from zero to maximum rated. Cost of equipment and installation run between $300-$3,000.

Manufacturers include Cadillac Meter Company, P.O. Box 1175, Port Townsend, Washington 98368, (206) 385-5500.

2. Differential Pressure - Orifice Plate - This meter is used for gas, liquid, or steam and is the most common type of steam meter used in direct line metering. It is mounted directly in the line, which must be shut down for installation or replacement. Because it is mounted directly in the line and gets its pressure differential by restricting the flow, it produces a large unrecovered pressure drop in the line. This in itself can

be a costly operating factor and should be assessed. Accuracy is ± 1 to 1-1/2% of maximum flow and is good down to flow rates only as low as 25% of maximum (turn down ratio of 4:1) or 10% (turn down ratio of 10:1) with a span adjustment. Cost of equipment and installation run between $2500 and $5500.

Manufacturers Include: American Meter Co., Division of Singer, 1350 Philmont Ave., Philadelphia, PA 19116, (215)673-2100.

3. Differential Pressure - Averaging Pitot Tube - This meter may be used for gas, liquid, or steam. It may be installed either permanently or as an insertion type. As an insertion type, it permits checking line flow periodically and using the same meter to check different lines of the same size. It does not sample the full stream flow. Dirty flow may clog probe openings. Its useful pressure range is about 2-10 inches of water with an accuracy estimated at ± 1% of full scale. Turn down ratio is about 4:1 or up to 12:1 with a span adjustment. Line pressure drop due to meter is low. Cost of equipment and installation is $2,000 to $6,000.

Manufacturers include: Annubar, Ellison Instrument Division, Dieterich Standard Corporation, Boulder, Colorado 80302, (303) 449-9000.

4. Turbine-Insertion Type - This meter may be used for gas, liquid or steam. It may be permanently or temporarily mounted. One size will measure several pipe sizes. Relatively simple maintenance may be required on turbine every 1 or 1-1/2 years. Turn down ratio runs from 10:1 to 50:1. Flow straightness may be required, requiring streight pipe approximately ten pipe diameters upstream and four diameters downstream from the turbine. It does not sample the full stream flow. Turbine blades are delicate and may be damaged by trash in flow or by frequent startup.

Turbine bearings may fail. Accuracy is approximately ± 1% of reading. Cost of equipment and installation is $2,000 to $6,000.

Manufacturers include: Engineering Measurements Company, 600 Diagonal Highway, Longmont, Colorado 80501, (303)651-0550; Electronic Flo-Meters Inc., P.O. Box 38269, Dallas Texas 75238, (214)349-1982.

5. Vortex Shedding - The vortex shedding meter creates a disturbance in the flow and uses a sensor to measure the frequency of fluctuations in pressure produced by vortexes which occur at a rate proportional to the rate of flow. These pressure fluctuations are measured and translated to flow rate. The vortex shedding meter can be used in steam, liquid or gas. Accuracy is reported to be ± 1% of reading. Turndown ratio is from 8:1 to 30:1. Insertion models are under development. Cost of equipment and installation is estimated at between $1500 and $6000.

Manufacturers include: Eastech Inc., 26 West Highland Ave., Atlantic Island, NH 07716, (201)291-3500; Fischer & Porter Co., County Line Road, Warminster, PA 18974, (215)674-6000; Fisher Control Co., 205 South Center Street, P.O. Box 190, Marshalltown, Iowa 50158, (515)754-3011.

6. Target - This meter may require a straight run of pipe for twenty (20) diameters upstream and ten diameters downstream. It produces a low pressure drop and its turn down ratio is 10:1. It is used in difficult service applications such as viscous or dirty flow and for steam. Its accuracy is ± 1/2% of full scale. Estimated cost of equipment and installation is $1500 to $3000.

Manufacturers include Hersey Products Inc., P.O. Box 4585, Spartanburg, SC 29305, (803) 578-1005.

7. Rotary Shunt - The rotary shunt meter diverts part of the flow through a turbine. The rotation of the turbine is picked up magnetically and its RPM is proportional to the rate of flow. It is used for steam, air or gas. Its turn down ratio is 10:1 to 60:1 and its accuracy is ± 2% of reading. Estimated cost of equipment and installation is $1800 to $6000.

Manufacturer include: Cadillac Meter Division, Control Station Steam Co., P.O. Box 1175, Port Townsend, WA 98368, (206)385-5500 or (800) 426-5611; Kent Process Control, P.O. Box 6494, Edison, NJ 08818, (201) 225-1717; BIF, 1600 Division Rd., West Warwick, RI 02910, (401) 885-1000.

8. Condensate Return - Run Time Totalizer on Condensate Pump - This is similar to the condensate meter in that it measures steam flow by measuring the condensate. However, it simply times the run time of the condensate pump. It requires that there be a condensate pump, and that the flow characteristics of the pump be known (or measured in the system). Its accuracy is ± 1% of reading and estimated cost of equipment and installation is between $300 to $1500. This system would probably be facility installed by purchasing a condensate pump (if needed) and a run time totalizer.

9. Positive Displacement Water Meters - These meters are positive displacement meters which use a magnetic pick up. They are made for hot, warm and cold water measurements including boiler feed, condensate and similar services. Accuracy is approximately ± 1% of reading. Estimated cost of equipment and installation is between $300 and $3000.

Manufacturer include: Kent Meter Sales, Inc., 903 N.E. Osceola, Ocala, FL 32670, (904)732-4670; Neptune Water Meter Co., Box 458,

Tallassee, AL 39078, (205)283-6555; Hersey Products Inc., Hersey Division, 250 Elm Street, Dedham, MA 02026, (617)326-9400.

10. Turbine Water Meter - This water meter is often used for larger sized pipes and flows. It consists of a turbine driven shaft and a magnetic pick up. Accuracy is approximately ± 2% of reading. Estimated cost for equipment and installation is $300 to $6000.

Manufacturers include: Kent Meter Sales, Inc., 903 N.E. Osceola, Ocala, FL 32670, (904)732-4670; Hersey Products Inc., Water Meter and Controls Division, 250 Elm St., Dedham, MA 02026, (617)326-9400.

11. Oil Meters - Several types of oil meters are available for high temperature, high viscosity, multi-viscosity flows and a wide range of flow rates. Turn down ratios run from approximately 15:1 at an accuracy of ± 1% to 100:1 at ± 2%. These include oscillating piston and turbine meters. Estimated cost of equipment and installation is $100 to $2000.

Manufacturers include: Kent Meter Sales, Inc., 903 N.E. Osceola, Ocala, FL 32670, (904)732-4670; Engineering Measurements Co., 600 Diagonal Highway, Longmont, CO 80501, (303)651-0550; Electronic Flo-Meters, Inc., PO Box 38269, Dallas, TX 75238, (214)349-1982.

12. Gas Meters - Several gas meters, in addition to the types cited above, include diaphram, positive displacement, full flow turbine and orifice meters. These meters operate with an accuracy of approximately ± 1% of capacity. Turn down ratios vary from 3:1 to 1000:1 depending on type and conditions. Estimated cost of equipment and installation is from $100 to $3000.

Manufacturer include: American Meter Co., Division of Singer, 13500 Philmont Ave., Philadelphia, PA 19116, (215)673-2100; Rockwell International, Measurement and Control Division, 400 North Lexington Ave., Pittsburgh, PA 15208, (412)247-3000; and Sprague Meter Co., 35 South Ave., Bridgeport, Conn. 06601, (203)333-4172.

13. Electric Meters - Electric meters measure kilowatt-hours, a unit of electrical energy. The industry standard watt hour meters, often referred to as wattmeters, take the power factor into account and measure real energy used. These meters totalize electrical energy used and show their results on readout dials. They may be equipped with a digital impulse generator for demand metering and for information processing and central readout. Accuracy is approximately ± 0.25% of readings. These meters are extremely reliable with maintenance intervals of approximately 15 years. Estimated cost of equipment and installation is between $300 and $3000.

Manufacturers include: General Electric, Meter Business Department, 130 Main St., Somersworth, NH 03878, (603)692-2100; Westinghouse Electric Corp., 2728 North Boulevard, Raleigh, NC 27611, (919)834-5271; Landis and Gyr Metering Inc., P.O. Box 7180, Lafayette, Ind. 47903, (317)742-1001.

14. Analog Power Meters - Analog watt transducers with both induction coil and Hall effect pickups are available. These are watt meters which provide a DC current or voltage output proportional to an AC power input and are corrected for power factor. They are totally electric and, unlike industry standard watt hour meters, have no moving parts. Interface with an energy management system microprocessor can be provided by an analog-to-

digital converter which should be located as close to the transducer as possible. Demand power readings are taken by sampling the wattage output from the transducer at one second intervals, and averaging over a 15 minute period. If the induction coil pickup type is used, and it uses a split ferro-magnetic core sensor, it will be capable of use on existing conductors without breaking into the line. Accuracy of these meters is about ± 1% of reading. Estimated cost of equipment and installation is $300 to $1000.

Manufacturers include: Yokogawa Corp. of America, 2 Dart Rd., Shenandoah, GA 30265, (404)253-7000; Crompton Instruments, 2763 Old Higgins Rd., Elkgrove Village, IL 60007, (312)593-1107; Weschler Co., 4000 Northwest 121st Ave., Coral Springs, FL 33065, (305)755-7111.

15. BTU meters - This category is meant to include both simple and complex integrated systems which employ meters, electronics and sometimes special equipment that makes moving the system from building to building possible. Some of these systems use microcomputers. Some use simple analog devices. They are often designed to read out in terms of BTUs of energy use. Costs can vary from $500 to $15,000 and up depending on type and application. This category is included to bring in some reference to the electronic side of energy metering.

Manufacturers include: Foxboro/Adec Inc., 1421 E. Pomona St., Santa Anna, CA 92705, (714)540-8863; Engineering Measurements Co., 600 Diagonal Highway, Longmont, CO 80501, (303)651-0550; American Meter Co., Division of Singer, 1350 Philmont Ave., Philadelphia, PA 19116, (215)673-2100.

CHAPTER 7

STACK GAS ANALYSIS

Efficiency of furnaces and boilers is determined through stack gas analysis. Both portable and fixed equipment is available. Portable analyzers are used primarily for spot checks in small furnaces and boilers where the firing rate is fixed. They are often used to check the efficiency of combustion, to show what changes might be made to improve efficiency, and to check the result of changes after they are made. Fixed analyzers, on the other hand, are usually used in large boilers or process combustion systems where the firing rate may be variable or the process so critical that precise control of conditions is required. Fixed analyzers are used to both provide the operator with continuous information on combustion system performance and also to actually control the combustion process itself. Changing conditions in fuel heating value, viscosity and temperature, along with variations in ambient air temperature and humidity, result in continuous changes in combustion conditions. These changes along with changing load conditions often make continuous monitoring and control cost effective.

PORTABLE EQUIPMENT

There are two commonly used types of portable stack gas analysis systems. One is the Orsat "Dumbell" system and the other is an electronic analyzer. Both show approximately equivalent accuracies. Accuracy on overall combustion efficiency is not usually given by the manufacturers

because there are too many factors in the computation of efficiency. However, the O_2 (oxygen) measurement accuracy is about ± 1/2% O_2 for both systems. If the reading were 3% O_2, a tolerance of ± 1/2% O_2 would be ± 17% measurement error. For this reason, it is usually recommended that several Orsat readings be taken and averaged.

The Orsat "Dumbell" system uses chemical CO_2 or O_2 analysis, stack gas temperature probe and a smoke tester or CO measurement depending on whether the fuel is oil or gas. With the information derived from this analysis, the efficiency of the combustion and heat exchange process can be determined. Some skill and experience is required to take the measurements and make the calculations necessary to determine combustion efficiency. Costs for complete combustion analysis kits run from $250 to $500. The Bacharach Instrument Co. of Pittsburgh, PA (412) 963-2000 is the only U.S. producer of the Orsat "Dumbell" system.

Electronic analyzers have the advantage of being easier to operate than the Orsat system, and, as a result, might be considered more accurate, although in skilled hands the Orsat system has the capability of roughly equivalent accuracy. The portable electronic stack gas analysis measures the stack gas parameters and uses a microprocessor to make its calculations. It has a digital read out. Two types are available. One is for individual read outs and ranges in cost from $400 to $700. The other is designed to measure continuously over a short period, say fifteen minutes, to allow continuous monitoring of efficiency while adjustments are made and conditions change in an industrial boiler. The cost of these systems range from $1800 to $3000. Manufacturers include the Bacharach Instrument Co. of

Pittsburgh, PA (412) 963-2000, the Teledyne Corp. of San Gabriel, CA (213) 283-7181; and the Lynn Products Co. of Lynn, MA (617) 593-2500.

FIXED EQUIPMENT

The two basic types of fixed systems for stack gas analysis are in-situ and extractive. Both use a zirconium oxide cell coated on both sides with porous platinum. One side of the cell is exposed to air and the other to stack gas. When heated to about 1200° the cell causes oxygen molecules coming in contact with the platinum to pick up four extra electrons. And when there is a difference in the oxygen partial pressures between the two sides of the cell, there is a flow of oxygen molecules from the high to the low pressure side. Because these molecules are ionized, a voltage difference between the two sides is established which is proportional to the difference in oxygen partial pressure between the air and the flue gas. From this voltage difference, the oxygen content of the flue gas is calculated.

An excellent booklet, Flue Gas Measurement - A Guide to Maximizing Combustion Efficiency, is available from Ametek, Thermox Instruments Division, 150 Freeport Road, Pittsburg, PA 15238.

1) In-Situ Systems

The in-situ system utilizes a probe with a small zirconium oxide cell which includes a filter for the stack gas and a supply of clean dry instrument air supplied through the probe. Maximum stack gas temperature allowable for the in-situ analyzer is about 1100°F which permits its use in most boiler/furnace applications. Exceptions would be special process applications where very high stack gas temperatures may be required.

The life expectancy of an in-situ zirconium oxide cell is from one to five years depending on the corrosiveness of the stack gas constituents. Calibration should be done every one or two months on a general purpose boiler and as often as every week if used on a critical process. All in-situ probes should employ flame arrestors so that, in the event of a burner malfunction producing a fuel air mixture in the stack, the heated zirconium oxide cell will not cause an explosion. Accuracy of the in-situ system is about ± 6% of the reading. Cost of an in-situ system is $2700 to $4000.

Electronics connections to the in-situ probe are limited to a maximum of about 20 feet.

2) Extraction Systems

Although the principles of operation of the in-situ and extraction analyzers are the same, the extraction system extracts a stack gas sample and removes it to a large zirconium oxide cell outside the stack. This system permits its use with stack gas temperatures up to 3200°F and, because the cell is larger and produces a stronger signal, the electronics of the system may be located further away than is possible with the in-situ system. In addition, extraction system analyzers are available which can measure carbon monoxide and hydrogen combustibles.

Calibration requirements are about the same for in-situ and extraction systems. Accuracy of the extraction systems is ± 2% of the measured value. Perhaps more important is that the repeatability of readings for an extraction system can be excellent, with variations between readings less than 1%, where for the in-situ system, because of the varying flue gas conditions, variation between readings can be up to 5 or 6%.

Cost of an extractive O_2 analyzer varies from about \$3000-\$7000. Cost of an extractive O_2 plus combustibles (CO and H_2) analyzer varies from \$4000 - \$8000.

Manufacturers of in-situ and extraction analyzers include Thermox Division of Ametek, Westinghouse Combustion Controls Division, Bailey Division of Babcock and Wilcox, and Cleveland Controls.

CHAPTER 8

ENERGY MANAGEMENT AND CONTROL SYSTEMS (EMCS)

Energy management and control systems (EMCS) can be used for both energy and maintenance management. Most EMCS systems employ off-the-shelf minicomputer/microcomputers, instrumentation and equipment configured into a network with control monitoring functions at multiple locations for heating, ventilating, air conditioning, process equipment, lighting, chillers, and boilers.

The capacity of an EMCS system to effect energy savings and optimize energy use will depend on the number, type and location of sensing and control points as well as on the type of equipment and controls being managed.

Many energy using systems in our current building inventory were originally designed and operated with little concern for energy conservation. EMCS systems were extensively employed in the late 1970's as a means of reducing energy usage in fundamentally inefficient systems. In many cases these EMCS systems were able to assist in reducing energy costs by as much as 40%. They accomplished this in several ways:

1) Duty Cycling - Uses EMCS to start and stop HVAC equipment based on a preset schedule to reduce unnecessary run times on electric motors [illegible] blowers, chillers, pumps, and on other energy consuming HVAC equipment.

2) Central Sensor Temperature Control and Night Set-Back - Uses EMCS to control an HVAC system on or off to satisfy a centrally located sensor -

positioned to provide approximately average temperatures in the area served by that system. This takes control out of the hands of individual users who may not observe the required maximum heating or minimum air conditioned temperature established by the government or agency in control. The EMCS can usually be programmed to use different temperatures for night or long-term shut down. In cold regions, to avoid freeze ups, it is important to place sensors for long-term shut down (where 45°F or 50°F might be used to save energy) in locations expected to be the coldest. This is often difficult as the coldest location in a building will depend on wind speed and direction. So often more than one sensor is used for this type of low temperature control and the system is designed to use the sensor exhibiting the lowest temperature. Building occupants cannot adjust these sensors as they might a thermostat. The control function remains in the EMCS and is adjustable only from the central or local control console.

3) Demand Limiting - uses EMCS to selectively shut down users of electricity to avoid total momentary electric usage exceeding a pre-established peak above which the facility will be assessed a rate penalty by the utility.

4) Monitoring and Alarming - Uses EMCS to monitor space temperatures and equipment operation and alarms the central control operator when preset values are exceeded or critical equipment fails. This saves energy when a failed system would tend to increase temperatures, or cause systems to run unnecessarily.

5) Monitoring Motor Run Time - Uses EMCS to monitor and record run time on electric motors. This can provide necessary information to deter-

mine potential cost savings and payback for replacing existing motors with new high efficiency motors.

6) Controlling Motor Stop/Start Times - Uses EMCS to avoid too close stop/start cycling which would significantly reduce motor life. This would result in maintenance cost savings.

One of the most difficult problems in attempting to make existing HVAC equipment energy efficient is that the controls used, particularly the most prevelent pneumatic controls, are not precise, are difficult if not impossible to keep calibrated and consequently are prone to out-of-balance operation. Most controls in existing buildings were designed in the days when energy costs were very low and when HVAC systems were designed to heat and cool at the same time. During times of relatively low cost energy, reheating cooled air to get proper room temperaure was common. Today, except where significant dehumidification is required, reheat systems are seldom used. Some of the greatest savings achieved, as energy conservation became important, were realized as a result of changing the operation of building HVAC systems to prevent them from reheating previously cooled air - from heating and cooling at the same time. However, this required a finer control function which most controls and most systems were not able to provide. As a result, much time and effort has gone into adjusting and maintaining controls; and even with increased maintenance, complex buildings modified in operation to be energy conserving often do not function very well, at least not to the satisfaction of many of the users. Thus, the ability of EMCS to provide both energy savings and user satisfaction depends a great deal on the HVAC equipment, system control design, the way

the EMCS is integrated into the system, and the types of sensors and controls the EMCS integrates.

The heart of an EMCS is a digital computer fed by analogue sensors which control certain HVAC system functions. The quality of the information available to the energy manager is a function of sensor accuracy and reliability, sensor location, and choice of measured system parameters. The ability to minimize energy use while still providing user comfort and utility depends on the quality of information fed to the EMCS, the inherent ability of the HVAC system to modulate its energy usage, and the characteristics of the EMCS-HVAC control linkages.

Both sensing and control portions of an EMCS are crucial to its ability to help the energy manager conserve energy. At the present time most EMCS do not employ energy flow sensing. They measure temperature and sometimes pressure but almost never measure flow. Thus, current EMCS will not give an energy manager all that is required to measure actual energy consumption. The energy manager can use the EMCS to reduce energy useage by controlling blower run times, assuring against over-temperature operation, and other techniques made available by having an EMCS monitor energy related system parameters. The manager knows that if temperature in a heated building is reduced 5 degrees, or increased 5 degrees in an air conditioned building, the building energy usage will drop. But at present most EMCS will not actually monitor the energy flow and the manager only receives this information indirectly by reading steam or electric meters, or waiting for the utility bill.

The technology in HVAC controls is gradually changing. Some work on development of digital controls is underway and some have been used by

innovative users of complex systems. Several manufacturers are producing or are about to produce direct digital control (DDC) systems. DDC systems promise accuracy and reliability. Resistance to their development has been due to both inertia on the part of the large control manufacturers, and cost. Often first cost is what controls building equipment decisions. Life cycle costs, which would include energy use, are more often talked about than used, both inside and outside the Government, and when energy costing is used outside the Government, one to three year energy paybacks on equipment are usually required. In non-government retrofit, where energy payback is most often used, a short one to three year payback predominates. Thus the development of accurate HVAC controls has been slow.

To employ an EMCS successfully, the facility engineer may wish to consider the following steps:

1. Identify and understand the important energy using systems within the facility. Complex buildings and the major energy users within those buildings must be identified.

2. Evaluate existing controls. Determine the characteristics and capabilities of existing controls. An EMCS will be limited by local controls on energy using equipment. Determine the ability of existing controls to maintain calibration.

3. Consider what is needed to upgrade control and HVAC equipment components to provide satisfactory control and operation and to provide a well integrated system with candidate EMCSs.

4. Determine information needed to monitor and manage energy use.

5. Determine number, location and type of sensing devices needed to provide necessary information.

6. Estimate growth potential of individual buildings and the potential for new facilities. Determine contemplated changes and estimate potential additional servicing points which might be required over the next ten years.

7. Investigate EMCS candidates to determine which types fit the needs of the facility. Provide potential EMCS suppliers with detailed needs and work with EMCS manufacturer specifications to optimize system utility. Check to be sure that the EMCS has enough capacity to monitor all sensing points with enough room for anticipated expansion. Keep in mind the needs for flexibility and the possibility of incorporating new components as the technology changes. Energy managers usually find out a great deal more about their equipment after an EMCS has been installed. As more is understood, more is seen that may need to be changed. So system flexibility is important.

8. For large or complex installations, simulated equipment operation on the EMCS is very useful. This allows the EMCS manager to program the characteristics of various HVAC systems and to then, at any time in the future, see what result a change in operating parameters will have in system operation. This can be done very quickly if the simulation capability is included. If it is not, the EMCS manager will have to make changes using the HVAC systems and then watch the results. A change will be made, and then, using a printout at set time intervals, the manager will see how the system responds in real time. In this way what could take a few minutes with simulated runs, could take days and significant amounts of energy using the actual HVAC systems in real time.

9. Consider distributed versus centralized EMCS. For large facilities with several complex energy using building, distributed control systems may be useful. Distributed processing allows for varying amounts of programming and spot monitoring at the distributed field locations. The heart of the distributed control concept is the intelligent Field Interface Device or "smart FID." FIDs are termed "smart" because each has the capacity to continue performing energy management functions in the event that the central unit or any FID in the network should fail. As distributed control becomes better developed, it allows the use of more units networked together with the ability to exchange information between controllers without going through the central computer.

Although EMCS was originally used as a central monitoring system with limited control functions, its use as a controller is now expanding significantly. The new digital control technology initiated by EMCS has placed increased emphasis on direct digital control (DDC). These controls combine a microprocessor with sensors and electric actuators and represent a new controls technology alternative to the old pneumatic thermostats, receiver/controllers and activators. DDC has several advantages over the old pneumatic controls:

1. Creates more accurate and sophisticated control.

2. Reduced maintenance due to fewer parts, greatly reduced calibration requirements, and the avoidance of a complex compressor driven pneumatic system prone to compressor oil contamination.

3. The ability to communicate directly with the EMCS.

4. Lower building life cycle cost.

Item 3 above opens the door to using the EMCS with DDC as an energy flow measuring device, since if the flow characteristics of water, steam, or air duct valves and dampers used for heating or cooling are known and are part of the EMCS algorithms, the DDC can provide feedback to the EMCS on valve or damper position and flow temperature, velocity and pressure to provide energy flow information for use in allocating energy use to specific areas.

At the present time (1986) DDC has a higher first cost than pneumatic systems and is relatively new in the market place with a limited number of suppliers. However, the number of suppliers is increasing, with several just about to release new DDC equipment in 1986. The cost of DDC equipment is likely to come down as usage increases.

An extensive list of approximately 100 EMCS suppliers can be found in Energy User News, Vol. 11, No. 8, February 24, 1986, page 8.

Cost of EMCS varies widely depending on size and complexity.

CHAPTER 9

ILLUMINATION MEASUREMENT

LIGHTING SYSTEM EVALUATION

LIGHT METERS

Measurement and Analysis. One of the most widely used devices for measurement of light is the selenium cell. This cell when coupled with a microammeter, corrected filters, and multirange switches is used in hand-held light meters and other more precise instruments. For multirange use in precision meters, different cell heads are used. Cadmium sulfide photocells, in which the resistance varies with the illumination, are also used in light meters.

The small survey-type meters do not have the accuracy of laboratory meters, and readings should be considered approximate, although the readings are quite consistent for a given condition. Their range is usually from about 5 to 5,000 footcandles. Precision low level meters have cell heads with ranges down to 0 to 2 footcandles.

If light meters are used to measure the number of lumens per square foot leaving a surface, foot lamberts (brightness), instead of footcandles (illumination), are being measured. Light meters can be used for measurement of brightness, but electronic brightness meters containing a photocell, amplifier, and microammeter can read brightness more directly. Typical ranges are from 0.0001 to 100×10^6 foot lamberts on a single meter.

Those light meters that incorporate a spherical diffuser can be used to measure incident light on a surface. For a reflected light measurement the meter is pointed toward the subject without the diffuser over the

photocell. Usually light meters are used in walk-through type lighting audits of a building where both natural light from windows and artificial illumination from lighting fixtures can be measured. The measured light levels are then compared with standardized levels and recommendations made with respect to effective cost reduction.

Accuracy - Not available.

Advantages

Light meters can be used to measure the combined illumination in a space that results from natural light (windows) as well as from the artificial light (lighting fixtures). They can also be used to measure the actual illumination in situations where the measurement would be preferable to the calculated value (e.g. reduced illumination due to soiled bulbs).

Multipoint lighting analysis is required for a true picture of light levels. This requires a great deal of time, or multiple sensors if many tests are to be run. Measurement of equivalent sphere illumination, one measure of lighting effectiveness, requires a special overlay for the light meter, and a computer analysis of the data. Light measuring equipment can be expensive, depending on accuracy and complexity.

Using measured bright levels, it is possible to get a more accurate level of lighting availability than using the technique of adding the total electrical input (watts) to all the lighting fixtures in a space and dividing by the illuminated area of the space. The measured light levels take into consideration the availability of natural light as well as the actual light levels incident upon individual work surfaces (tables, desks, computer terminals, etc.).

Limitations

The disadvantage of measuring light levels is that it is more time consuming than a walk-through audit based on calculations.

Cost. Depending upon complexity cost can range from $25-$200.

New Technology/Developments. Light meters are available which incorporate a memory for storing light values, instantaneous readings, programmable exposure changes, a spherical diffuser for incident footcandle readings, and various other accessories.

With the development of the portable computer terminal, results of a walk-through lighting audit can be processed on-site by keying all data into a central computer over telephone lines. Such data includes (but is not limited to) heating and air conditioning costs, type of fuel, number of lamps, mounting height of lamps, lamp life and usage, maintenance and installation costs, and lighted areas.

CHAPTER 10

ELECTRICAL SYSTEM EVALUATION

ELECTRICAL MEASUREMENTS

METERS (VOLT, AMP, WATT, OHM)

Measurement and Analysis. Over a period of about 150 years many persons have contributed to the art of measuring electrical quantities, such as volts, amperes and ohms. Through most of this period of history the principal effort of making instruments react to electricity was aimed at the perfection of pointer deflecting instruments. In these, the deflection angle of the pointer is proportional to the value of the electrical quantity measured. The name analog instruments has been coined to distinguish these instruments from a completely different type in which the value of the quantity measured is displayed in numerals. These newer instruments are called digital instruments. Digital electrical instruments owe their existence to the ability of electronic devices to create electrical pulses, perform rapid switching operations, produce precisely predictable time functions of voltage, make voltage comparisons, amplify and to perform the fundamental operations of addition, multiplication, differentiation and integration.

The distinction between analog and digital instruments is perhaps less significant than the basic approach to electrical measurements. Just as we weigh objects against a standard weight on a calibrated spring, so can we measure electrical quantities such as voltage or current, by balancing the torque they produce in an electromagnetic system against a calibrated

spring. Or, we can balance the electrical quantity itself against a standard value of that quantty, as in a potentiometric system.

Styling of analog instruments has produced a multiple-range, table-top instrument containing a permanent-magnet, moving-coil instrument with a variety of circuits and transducers for measuring many electrical functions in one modular housing. With a permanent-magnet, moving-coil mechanism, this instrument measures direct current and voltage; with a moving iron vane mechanism, it measures alternating current and voltage.

A digital voltmeter converts the analog input into digital logic and displays it in decimal form. Solid state electronics perform many functions at high speed and with great accuracy. Digital instruments use electrical and electronic means to convert electrical quantities into digital outputs and readings. Almost always the input quantity is a voltage, other quantities being easily converted into voltage before being processed by the instrument.

Accuracy. Electrical instruments may be calibrated against the prime standards of the quantity measured. However, most are calibrated against secondary standards whose calibrations are traceable to the primary standards. All primary standards in the United States are established and maintained by the National Bureau of Standards.

Alternating current voltmeters and ammeters are usually calibrated against electrodynamic voltmeters and ammeters which have been calibrated on direct current and have a known accuracy on alternating current.

The finest analog instruments are rated to be accurate to within ± 0.1% of full scale. Digital instruments can be made 50 to 100 times more accurate.

Advantages and Limitations. Comparative rate of change of the quantity measured can be judged more easily when observing the motion of a pointer on an analog meter than a change in the value of a digital readout. Analog instruments are prefered when a visual indication of rate is important.

Analog instruments are relatively simple in construction and can be made to perform under very unfavorable environmental conditions. However, they contain moving parts.

Digital instruments are relatively complex and made of parts and components whose reaction to environmental condition varies. However, digital instruments can be made without moving parts.

Diagnostic electrical measuring meters are in general relatively inexpensive and do not require extensive training for their proper use.

Cost. Depending upon accuracy desired cost can range from $25 to several hundred dollars.

New Technology/Developments. meters are being manufactured that will communicate directly with a computer. The use of thermal scanning techniques to determine the temperature rise in an electrical conductor is a relatively recent development and is worth describing in detail.

Failure mechanisms in current-carrying equipment usually develop as a result of overheating, caused by high resistance connections of circuit conductors. Overheating causes the deterioration of electrical and mechanical components, as well as the insulation. Factors which contribute to the formation of high resistance connections include: loose connections, improper equipment design and installation, vibration, expansion and

contraction of circuit parts due to load cycling, deterioration of mechanical components, and oxidation of conducting surfaces. Overheating of high resistance connections is a self-compounding problem. The temperature increases with the resistance of the connection. The greater the temperature rise the more pronounced the effects of forces that further increase the resistance. The problem becomes progressively worse until a failure causes a short circuit which damages or destroys the device. Using a thermal imager the resistance of circuit connections can be checked by evaluating the thermal image of the device's terminals. Temperature differences between various loctions in a terminal can be measured with a differential temperature measuring imager. However, only qualitative comparisons (intensity differences of bright locations) can be obtained with an imager that does not have the capacity to measure temperature differentials.

The basic method in the inspection of electrical/mechanical components is to observe the thermal operating characteristics of the equipment to discern if any abnormalities exist. These abnormalities can be analyzed to determine the severity and the cause of the problem. There are three comparisons that can be made with a thermal imager in order to observe the operating characteristics of an electrical device. Parts of the device can be compared with itself, with an adjacent device, or with the ambient air temperature. Each comparison provides a different reference for obtaining an overview of the operating conditions. The speed at which the inspection is performed will depend on several factors including the complexity of the electrical/mechanical equipment, the operators skill and technique in

operating the thermal imager, and the number and nature of the problems that are detected. Simple distribution equipment can usually be inspected in a few seconds. More complex apparatus may take several minutes. Since there are circuit components that normally operate hotter than ambient temperature, thermal patterns can be very complex. Experience and knowledge of electrical equipment and distribution systems are very important to the results of an inspection.

When a problem is detected, a more detailed summary is done to pinpoint the location and to analyze the nature of the problem. Photographs and thermograms are then taken to record both the thermal data and the visual scene. Notes are taken to record the information necessary to identify the location and describe the nature of the problem. These notes are used later in the preparation of a written report.

There are some failure mechanisms inherent in current-carrying equipment which are indicated by "cold spots." As mentioned earlier, some electrical devices normally operate much hotter than ambient temperature. A problem is indicated if they are observed to be operating at ambient or a colder than normal temperature. There are failure mechanisms other than high resistance connections that show up as hot spots. A severely unbalanced condition could cause the failure of a motor, generator, or transformer. Unbalanced currents in a three-phase system can also be detected. The temperature of those conductors carrying more current will be higher than those conductors carrying less current. In this situation, the imager will indicate two phases that are operating at equally higher temperatures than the third phase. This indication of an unbalanced

current can be confirmed by measuring the currents flowing in each phase with a clamp-on ammeter.

A good electrical connection is characterized by very low resistance. A low resistance ohmmeter can be used to measure the resistance of circuit connections, but the circuit must be de-energized. It would be very time consuming to measure the resistance of every connection in an electrical system. It is usually difficult to schedule a power shutdown for that purpose.

A quantitative thermal imager can be used to remotely and quickly monitor the relative apparent temperatures of all conducting/insulating surfaces without the need to disrupt normal system operations. With this information decisions can be made to establish priorities for making repairs.

However, a nonquantitative imager can only be used to make a qualitative comparison (extremely hot, hot, warm not hot) between two or more conducting/insulating surfaces.

If true temperatures are required of a conducting/insulating surface, then system calibration curves and surface emittances are required. This procedure requires somewhat more time and effort than that required for differential measurements.

CHAPTER 11

INDOOR AIR QUALITY MEASUREMENTS

CARBON MONOXIDE (CO) MONITOR

Measurement and Analysis. Although long term health effects from exposure to low levels of CO are suspected, exposure to high levels of CO for a shorter period of time can cause more serious immediate health problems including death. Typically, CO levels high enough to cause "short term" health effects are generated by a blocked combustion flue, a faulty or poorly tuned combustion source, or a car with its engine on in a garage. There are several commercially available continuous real-time monitors that can reliably measure CO levels through a electrochemical oxidation/diffusion process. Indoor CO problems can be detected by turning on the combustion sources for a specified time interval and measuring the CO levels.

An alternative to monitoring the continuous CO concentration is to measure the average CO levels over a longer period of time. From the long term CO concentrations it should be possible to identify a residence that has high intermittent CO levels. In general, a home with a higher average CO concentration will have high CO peaks. One approach is to use a passive monitor which requires no external power and usually measures an integrated pollutant concentration over a period of 24 hours to 7 days. One passive technique available is to expose a tube of silica gel beads impregnated with potassium pallado sulfite (PPS) which changes color from yellow to brown in the presence of CO.

Accuracy: Active: ±1 - ±15%

Passive: ±2 - ±5%.

Advantages

Active/Passive: No training required for sampling operation. Real-time monitor data doesn't require laboratory analysis and the results can be made available immediately.

Limitations

The field reliability and accuracy of PPS indicators for spot or average measurements on a large scale audit has not been established. For spot measurements, there is no guarantee that a single measurement is representative of normal furnace, stove, or other combustion activities. For average measurements, the diffusion characteristics of CO through silica gel beads are not adequately defined for making quantitative measurements.

Cost: Active: $1700 - $2500

Passive: $ 700 - $1400

Potassium pallado sulfite (PPS) beads (passive) $1.50 each in lots of 100.

New Technology/Developments. None.

FIBROUS AEROSOL MONITOR

Measurement and Analysis. Sample air passes through a chamber and enters a sensing region illuminated with a He-Ne laser. The light scattered out of the laser beam by the oscillating fibrous aerosols is detected by a photomultiplier tube.

Accuracy. Equal to reproducibility when calibrated for specific fibers.

Advantages

Can operate for indefinite unattended period of time. May be operated off battery pack. Has recorder output. A standard membrane filter permits a concurrent collection of fiber samples.

Limitations

Requires occasional cleaning of optics.

Cost. $12K-$13K with battery pack and digital to analog interface.

New Technology/Developments. None.

FORMALDEHYDE (HCHO) MONITORS (active/passive)

Measurement and Analysis. The passive monitors operate by a process where the formaldehyde diffuses into the monitor and is collected by a sorption process. They can be left unattended from 2 hours to approximately one week. The shelf life of these devices ranges from a few weeks to approximately one year depending on whether or not they have been previously exposed to formaldehyde.

The principle of operation of the active formaldehyde analyzer is that sample air is drawn through a solution that contains a fixed quantity of sodium sulfite. After the addition of pararosaniline the intensity of the color is measured in the yellow part of the spectrum.

Accuracy: Active: ±3%

Passive: ±13 - 25%.

Advantages and Limitations

Active: 98% collection efficiency. Can be used over a range of 5-95% relative humidity. No training required for sampling.

Passive: Requires no power. Requires no specialized training. Low accuracy, low reproducibility. Inexpensive. Laboratory analysis must be used to obtain quantitative results.

Cost: Active: $5K-$6K

Passive: $7-$35 depending on lot size and analysis requirements.

New Technology/Developments. None.

PARTICULATE MONITOR (active and passive)

Measurement and Analysis. A pulsed infrared laser, in combination with detector, senses the forward light scattered by the particulate matter. In the passive device the air flows freely while the active device uses a pump to pull the air through the sensing volume.

Accuracy. Equal to the reproducibility for specific aerosols.

Advantages

Can be operated over humidity range form 0-95%. No training required for sampling.

Cost. Passive: Approximately $2K without recorder

Active: $6.5K - $8.0K without recorder.

New Technology/Developments. None.

PARTICULATE SAMPLER/IMPACTOR

Measurement and Analysis. Air is accelerated through nozzles or slots designed to pass or reject particles of various sizes. The particles are then collected and analyzed.

Accuracy. Accuracy is specified at certain flow rates and pressure drops and varies between ±3% - ±10%.

Advantages and Limitations. Training required. Will sample any ambient particulate concentration.

PARTICULATE ANALYZER

Measurement and Analysis. The sample air stream is passed through an impactor to remove nonrespirable particles. The particles that exit the impactor are precipitated onto an oscillatory quartz crystal sensor. The change in frequency of the sensor is proportional to the particulate mass that has collected there.

Accuracy. Accuracy is ±10% - ±0.01 mg/m^3.

Advantages

Relatively high collection efficiency. No training required for sampling.

Limitations

Annual calibration recommended. Maintenance required. Changes in relative humidity during a measurement can cause error. Some particles (e.g. dry diesel exhaust) are not sensed accurately.

Cost. $5K - $17K depending upon model.

New Technology/Developments. None.

NITROGEN DIOXIDE (NO_2) ANALYZERS (active)

Measurement and Analysis. The principle of operation of one analyzer is based on a chemiluminescent reaction with ozone which is detected by a photomultiplier tube. Another analyzer uses a dye-forming reagent to continuously absorb the sample air. The intensity of the dye is measured at a specific wavelength in the yellow spectrum to obtain the NO_2 concentration.

Accuracy. Instrument accuracy is dependent upon calibration source accuracy.

Advantages

Training not required. Both can be used over a wide range of humidity (5-95%).

Cost. Chemiluminescent - $7.3K (without recorder and battery pack).

Chemistry/colorimetry - $5.8K.

New Technology/Developments. None.

NITROGEN DIOXIDE (NO_2) SAMPLERS (passive)

Measurement and Analysis. The basic principle of operation in three commercially available devices is diffusion/sorption. In the dosimeter the collection relies upon molecular diffusion to deliver sample air to a liquid sorbent solution at a constant rate. After exposure the sorbent is analyzed in a laboratory spectrophotometer. In the Palmes tube the cap is removed during sampling and NO_2 diffuses to a collector at a rate determined by the tube geometry and ambient NO_2 concentration. At the termination of the sampling period the collector substrate is analyzed to obtain a quantitative value for the time weighted average concentration. The NO_2 filter badge basically uses the same principle of operation as the Palmes tube.

Accuracy. Accuracy ±18 - ±20%.

Advantages

No training required for sampling. No maintenance required.

Cost.

Device	Amt.
Dosimeter approximately	$ 1.00 each in lots of 260 or more
Palmes	$ 8.00 - $10.00 per tube
Filter Badge -	$11.65 each

New Technology/Developments. None.

OZONE METER

Measurements and Analysis. The basic principle of operation is the photometric detection of the flameless reaction of ethylene gas with ozone.

Accuracy. Not available.

Limitations

Training recommended.

Cost. $6-$7K.

New Technology/Developments. None.

RADON COLLECTOR (passive)

Measurement and Analysis. Ambient radon diffuses into a chamber where the subsequent disintegration of particles are electrostatistically focused onto a dosimeter chip. Each particle striking the chip creates defects which can be related to the integrated radon concentration. The instrument is based upon the Passive Environmental Radon Monitor.

Accuracy. Not available.

Advantages

Can operate up to 1 year unattended. Can operate over a wide range of ambient temperatures and humidity. No training required for sampling.

Cost. $600 (includes batteries).

New Technology/Developments. None.

RADON MONITOR (active)

Measurement and Analysis. Radon daughters are collected on a filter and particle activity is measured with a detector. A microprocessor counts and stores detector pulses.

Accuracy. Typical accuracy is ±5%.

Limitations

Requires some maintenance. No training required for sampling.

Cost. $2-$3K depending upon model.

New Technology/Developments. None.

RADON/RADON DAUGHTER DETECTOR (active)

Measurement and Analysis. A known volume of sample air is drawn through a filter and a gas scintillation cell. Radon daughter products collect in the filter while the gas cell retains a sample of radon.

Accuracy. Not available.

Advantages

Useable over a wide ambient temperature range.

Cost. Approximately $8K with optional accessories.

New Technology/Developments. None.

RADON GAS MONITOR (active)

Measurement and Analysis. Three measuring ranges. Selectable sampling intervals. Contains sample chamber, solid state detectors and microprocessor to control operation. Ambient air is drawn through a pre-filter which collects daughter products of two radon isotopes. Air enters a sample chamber and the decay particles are deposited on a solid state detector. The decay particles are analyzed to discriminate between the two radon isotopes. Daughter products captured on the prefilter are also analyzed. All information is stored in memory.

Accuracy. Accuracy ±10%.

Advantages

Useable over wide ambient temperature and humidity range. No field calibration or training required.

Cost. Approximately $35K with optional accessories.

New Technology/Developments. A humidity sensor has been incorporated to monitor the relative humidity level of the prefiltered ambient air.

RADON DAUGHTER ANALYZER (active)

Measurement and Analysis. The analyzer contains a filter for the incoming sample air. A computer that plugs into the analyzer computes the radium concentration automatically. Sample air is drawn through a filter for two minutes while simultaneous measurements of alpha and beta particle backgrounds are measured. The sample deposit on the filter is transported to the detector where all counts are registered for two minutes.

Accuracy. Not available.

Advantages

Useable over a wide range of ambient temperatures. Humidity levels do not affect operation. No warmup time required. Automatic calculations of radium levels. No training required for sampling.

Limitations

Periodic maintenance required.

Cost. $17,000.

New Technology/Developments. None.

RADON TRACK DETECTOR (passive)

Measurement and Analysis. A card of negligible weight that integrates radon exposure. Alpha particles from radon in air penetrate the detector and cause damage tracks. The tracks are chemically etched at the end of

the exposure interval and counted. Average exposure is proportional to the counted tracks per unit area.

Accuracy. 1-3%.

Advantages

Useable over wide range of ambient temperatures and humidities. Good reproducibility. No calibration required. Simple to use. No maintenance required. No training required for sampling.

Cost. $16-$66 depending upon lot size and sensitivity required.

New Technology/Developments. None.

SULPHUR DIOXIDE (SO_2) ANALYZER (active)

Measurement/Analysis. Contains a sensing electrode that generates an electric current through electrochemical reaction. The analyzer has three measuring ranges and can provide a continuous sampling rate. Audible and visual alarms are optional features.

Accuracy. ±2% of full scale.

Advantages

Requires three different types of battery (total of 7 units).

Cost. $1.7K-$1.9K depending upon model.

New Technology/Developments. None.

SULPHUR DIOXIDE (SO_2) ANALYZER (active)

Measurement and Analysis. The unit contains an electrochemical cell, a digitizer, and a separate data reader. SO_2 diffuses into an electrochemical cell that produces a signal proportional to SO_2 concentration. The signal is digitized and stored.

Accuracy. Accuracy is ±2% of reading + one least significant digit.

Advantages

Uses one long life 9v battery. Useable over wide range of humidity.

Limitations

Requires maintenance.

Cost. $1.1-$1.2K.

New Technology/Developments. Latest model features an LCD display instead of data logging.

SULPHUR DIOXIDE (SO_2) ANALYZER (active)

Measurement and Analysis. The analyzer samples 250 ml/min continuously. Sample air is drawn through distilled water. Absorbed sample reacts with parasosaniline and formaldehyde to form a parasosaniline methyl sulfuric acid. The intensity of this acid is measured in the yellow spectrum.

Accuracy. Not available.

Advantages

No training required for sampling.

Limitations

Monthly maintenance required.

Cost. $5.7K with optional accessory.

New Technology/Developments. No.

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