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Applications of Heat Flux Transducers: A Select and Annotated Bibliography

REFERENCE: Bomberg, M., "**Applications of Heat Flux Transducers: A Select and Annotated Bibliography**," *Building Applications of Heat Flux Transducers, ASTM STP 885*, E. Bales, M. Bomberg, and G. E. Courville, Eds., American Society for Testing and Materials, Philadelphia, 1985, pp. 223-236.

ABSTRACT: This paper is a select and annotated bibliography dealing with the construction of heat flux transducers, their calibration and error verification, and the methods used for thermal resistance determination.

KEY WORDS: heat flux transducers, annotated bibliography

The use of heat flux transducers (HFTs) for full-scale testing of the thermal resistance of walls started in Germany at the Thermal Protection Laboratory in Munich and in the United States at the Research Laboratory of the American Society of Heating and Ventilating Engineers in Pittsburgh, Pennsylvania, around 1924. The HFT slowly gained popularity until it became an integral part of different measuring systems used to evaluate the thermal performance of buildings. The papers published in this volume, which were presented at the Workshop on Building Applications of Heat Flow Sensors, held in Philadelphia, Pennsylvania, in September 1983, cover the topic well. However, they relate to only a small fraction of the industrial and research applications of HFTs. The following annotated bibliography is offered as a commentary on the development of the heat flux transducer. The bibliography is divided into three subject areas:

1. Construction of HFTs.
2. HFT calibration and error verification.
3. Methods for field determination of thermal resistance.

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Bibliography

Construction of Heat Flux Transducers

Andretta, A., Bartoli, B., Coluzzi, B., Cuomo, V., and De Stefano, S., "Simple Heat Flux Meter," *Review of Scientific Instruments*, Vol. 52, No. 2, 1981, pp. 223-224.

A 2-mm-thick Plexiglas disk with coils of resistor wire on each surface was built. It was calibrated by measuring the output of a heater guarded by an isothermal plate having the same temperature, with the radiative heat flowing through a narrow air gap.

Brown, G., "Heat Transfer at Exterior Surfaces of Buildings," in Swedish in *St. Nämnd för Byggforskning Transactions*, No. 27, 1956.

The paper discusses HFTs that integrate the rate of heat flow with respect to time, built and used for special applications where the cumulative rate of heat flow is of primary interest.

Cvetkovic, M., "Thermal Flux Measurements with a Compensated Heat Flow Meter," *Proceedings*, ASHRAE/DOE Conference on Thermal Performance of Exterior Envelopes of Buildings II, ASHRAE Special Publication 38, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA, 1983, pp. 749-766.

A theoretical analysis of the heat exchange between the metering and compensating (guarding) part of a zero-flow transducer is provided.

Degenne, M., Klarsfeld, S., and Barthe, M.-P., "Measurement of the Thermal Resistance of Thick Low-Density Mineral Fiber Insulation," *Thermal Transmission Measurements of Insulation, ASTM STP 660*, R. P. Tye, Ed., American Society for Testing and Materials, Philadelphia, 1978, pp. 130-144.

Another improvement in HFTs was effected in the manufacturing of thermopiles by photoetching techniques. This paper contains a description of the photoetched transducer developed by Degenne and its application. (See also the following entry.)

Degenne, M., "Thermal Flux Meter or Heat Flow Meter," U.S. Patent No. 4,197,738, 15 April 1980.

De Jong, J. and Marquenie, L., "Heat Flow Meters and Their Applications," *Instrument Practice*, January 1962, pp. 45-51.

This HFT follows the principle introduced by Schmidt and Hencky (see Schmidt, E.) but the thermopiles are manufactured in a different man-

ner. Constantan spirals with diameters of 2.5 mm and a wire gage of 0.15 mm are placed in a galvanic bath and partly covered with copper. Other types of HFTs contain constantan wire wound in rectangular fashion and partly coppered or silvered.

Devisme, J.-M. and Maréchal, J.-C., "Contribution aux mesures thermiques dans le bâtiment: Étude théorique et experimentale des fluxmètres de régime variable," *Annale de L'Institut Technique du Bâtiment et des Travaux Publics*, No. 369, 1979, pp. 55-70.

This paper and those by Ravalitera et al, Thery et al, and Devisme et al, as well as the paper by Degenne and Klarsfeld published in this publication, deal with new types of thermopiles developed by integrating a large number of thermoelements created on a thin conductor sheet covered with an electrolytic deposit. These transducers are usually manufactured by using printed circuit technology. (See also the following reference.)

Devisme, J.-M., Maréchal, J.-C., and Duthoit, B., "Détermination de la résistance thermique d'une paroi en régime quelconque," *Bulletin RILEM: Matériaux et Construction*, Vol. 15, No. 88, 1982, pp. 299-306.

See Devisme, J.-M., above.

Fischer-Hansen, J. P., "Evaporative Heat Meters in Practice," *Building Research and Practice*, May/June 1977, pp. 164-168.

See Brown, G.

Fuchs, M. and Hadas, A., "Analysis of the Performance of an Improved Soil Heat Flux Transducer," *Soil Science Society of America Proceedings*, Vol. 37, No. 2, 1973, pp. 173-175.

A transducer was made out of a thermopile wound on a glass microscope slide, sandwiched between two anodized aluminum sheets. Contact between the soil and the transducer appeared to be largest source of errors. Under different experimental conditions the error varied between 15 and 50%.

Gerashchenko, O. A., Iordanishvili, E. K., Gudkin, T. S., Fiskind, E. E., and Pogurskaya, Z. L., "Heat Flux Transducers Based on Artificially Anisotropic Thermoelectric Materials," English translation in *Journal of Engineering Physics*, Vol. 35, No. 2, 1978, pp. 908-911.

The use of an artificially anisotropic thermoelectric material for a core of a heat flux transducer, the method of selecting its components, and the optimization of the parameters are discussed.

Gilbo, C. F., "Conductimeters: Their Construction and Use," *A.S.T.M. Bulletin*, No. 212, 1956, pp. 68-74.

This paper discusses the utilization of heat flux transducers in laboratory apparatus for determining the thermal conductivity of materials. It also reviews the construction of other transducers, for example, those by Hatfield and Wilkins (*Journal of Scientific Instruments*, Vol. 27, No. 1, 1950, pp. 1-3), Zobel (*Journal of Scientific Instruments*, Vol. 14, 1927, pp. 409-427), Gier and Dunkle (*Refrigerating Engineering*, Vol. 62, October 1954, pp. 63-69), and Cammerer (Die Wärme, Vol. 60, 1937, pp. 765-767). For further discussion of HFT application to laboratory thermal resistance determinations see *Guarded Hot Plate and Heat Flow Meter Methodology, ASTM STP 879*, R. P. Tye and C. J. Shirtliffe, Eds., American Society for Testing and Materials, Philadelphia, 1985.

Heard, C. L. and Ward, I. C., "The Design and Use of Low-Cost Heat Flux Plates for the Measurement of Building Heat Transfer Rates," *Building and Environment*, Vol. 17, No. 3, 1982, pp. 229-233.

A copper-constantan thermopile was wound on a Perspex core with about 80 turns per 5-cm width; in this way inexpensive and reasonably quickly responding transducers were built.

Huebscher, R. G., Schutrum, L. F., and Paramalee, G. V., "A Low-Inertia Low-Resistance Heat Flow Meter," *American Society of Heating and Ventilating Engineers Transactions*, Paper No. 1453, June 1952, pp. 275-286.

The principal feature of this construction is the use of thermocouple chains made from copper-constantan foil or ribbon. A bar of constantan was welded to a bar of copper and rolled into a thin ribbon. Then notches were cut in the ribbon and the thermocouple chains were woven over and under strips of the core material providing the thermal resistance. Because of its ability to integrate heat flow over the entire metering area and the ease with which different shapes and sizes can be constructed, this design is still used in some research laboratories. It is interesting to note that this development, as well as the research of Lustig and Cammerer on foil HFTs (*Gesundheits-Ingenieur*, Vol. 76, 1955, pp. 289 ff.), was directed towards measuring the rate of heat exchange between mammals and their environment.

Klems, J. H., "Design and Construction of Large-Area Heat Flow Sensors for Measuring Building Heat Flows," *Proceedings*, ASHRAE/DOE Conference on Thermal Performance of Exterior Envelopes of Buildings II, ASHRAE Special Publication 38, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA, 1983, pp. 734-748.

The paper describes HFTs based on A-C resistance thermometry and built to integrate heat flows over a large area.

Klems, J. H. and DiBartolomeo, D., "Large-Area, High-Sensitivity Heat Flow Sensor," *Review of Scientific Instruments*, Vol. 53, No. 10, October 1982, pp. 1609-1612.

See Klems, J. H., above.

Kraabel, J. S., Baughn, J. W., and McKilip, A. A., "Isothermal Heat Flux Sensor," ASME Paper 78-WA/HT-14, American Society of Mechanical Engineers, New York, NY, 1978.

This heat flux transducer for local heat flux measurement contained a thermistor operated by a differential thermocouple and heated in such a way that the surface remained isothermal. (See also Tamura, T., et al.)

Nicholls, P., "Measuring Heat Transmission in Building Structures and a Heat Transmission Meter," *American Society of Heating and Ventilating Engineers Transactions*, Vol. 30, 1924, pp. 65-104.

This heat flux transducer has a copper-constantan thermopile penetrating through a core material. The metering area is 38 by 38 cm and the total area is 60 by 60 cm.

Nicholls, P., "Practical Applications of the Heat Flow Meter," *American Society of Heating and Ventilating Engineers Transactions*, Vol. 30, 1924, pp. 289-300.

See Nicholls, P., above.

Ravalitera, G., Cornet, M., Duthoit, B., and Thery, P., "Étude et description d'un nouveau thermofluxmètre permettant la mesure simultanée des flux thermiques et des variations de température," *Revue de Physique*, Vol. 17, 1982, pp. 177-185.

See Divisme, J.-M. and Maréchal, J.-C.

Schmidt, E., "Ein neuer Wärmeflussmesser und seine praktische Bedeutung in der Wärmeschutztechnik," *Mitteilungen Forschungsheim für Wärmeschutz* (Munich), Vol. 19, No. 3, 1923.

In 1923 Schmidt introduced a new heat flow meter or heat flux transducer. In contrast to Hencky's auxiliary wall (*Gesundheits-Ingenieur* 42, No. 43, October 1919, pp. 437-438), Schmidt's transducer was expected to produce a negligible disturbance in the pattern of heat flow through the wall, because it had low thermal resistance. However, the fact that the thermal resistance of the transducer was considerably lower than the resistance of the wall was not sufficient to guarantee the uniformity and unidirectional pattern of heat flow within the transducer. The situation was improved by applying a guard around the transducer made of a material with identical thermal resistance. This technique has been used in the

Thermal Protection Laboratory's transducers since 1923; they have a metering area of 0.5 by 0.5 m, but the guard extends the total area to 1 by 1 m or 1.5 by 1.5 m. (See also Schmidt, E., following.)

Schmidt, E., "Die Messung von Wärmeverlusten im Betriebe," *Archiv für Wärmewirtschaft*, 1924, pp. 9-11.

See Schmidt, E., above.

Schulte, E. H. and Kohl, R. F., "Low-Temperature, High-Sensitivity, Temperature-Compensated Heat Flux Sensor," *Review of Scientific Instruments*, Vol. 40, No. 11, November 1969, pp. 1420-1427.

The paper describes a miniature transducer used to measure heat transfer by conduction, convection, and radiation in the range of 75 to 300 K. The temperature compensation of the transducer is achieved by matching the changing properties of the insulating material with the changing properties of the semiconductor over a given temperature range. A testing apparatus operating under a vacuum of 10^{-1} Pa or less is described, as well as the construction of sensors and the test results obtained on semiconductors and resins suitable for HFT cores.

Tamura, T., Nemota, T., and Togawa, T., "A Zero HFT for Monitoring Perfusion Blood Temperature," *IEEE Transactions on Biomedical Engineering*, Vol. BME-26, No. 11, 1979, pp. 644-646.

See Kraabel, J. S., et al.

Thery, P., Farza, A., and Ravalitera, G., "Étude et caractérisation d'un nouveau fluxmètre calorifique," Société Francaise des Thermiciens, Congrès Mesucora, Session 7, 1979, pp. 23-38.

See Devisme, J.-M. and Maréchal, J.-C.

Yunkerov, Y. I., "Analysis of Measurement Errors of Convective Heat Transfer Coefficient Using a Thin-Walled Heat Flux Sensor," English translation in *Journal of Engineering Physics*, Vol. 35, No. 2, 1978, pp. 917-921.

The sensor (often called a Gardon transducer) is built in the form of a disk of constantan foil, 0.05 mm thick, soldered into a cylindrical copper case with a 5-mm-diameter hole. A copper thermoelectrode, 0.05 mm in diameter, is welded to the center of the thin element. The interior of the case is filled with insulation and closed by a copper lug. A wire is connected to the case. Between this wire and the thermoelectrode in the center, a differential thermocouple is created.

Heat Flux Transducer Calibration and Error Verification

Ash, R. L., Weller, W. T., and Wright, R. E., Jr., "Sources of Error in Vacuum Calibration of Heat Flux Sensors," *Review of Scientific Instruments*, Vol. 41, No. 7, 1970, pp. 1112-1114.

Thin-foil heat flux sensors were coated with camphor black soot and exposed to radiative heat fluxes. Errors were shown to be caused by changes in the physical properties of the coating under varied levels of vacuum and free convection between the window and the sensor.

Bainbridge, B. L., "Results of Solar Testing of Circular Foil Heat Flux Sensors at the White Sands Solar Furnace," Report Sand-81-2390C, Sandia National Laboratory, Albuquerque, NM, 1982.

A pair of novel circular foil heat flux sensors was tested against a Kendall radiometer. An error analysis performed on the data indicates that atmospheric conditions and limitations of the facility preclude accurate comparison of the heat flux sensors with the Kendall radiometer. Details about the data acquisition and error analysis, as well as considerations about the proper gage calibration, are included.

Baumeister, K. J. and Papell, S. S., "Effect of Gauge Size on the Measurement of Local Heat Flux," *NASA Technical Memorandum*, No. TM-X-2943, National Aeronautics and Space Administration, Washington, DC, 1973.

In order to estimate the optimum size of a transducer, the averaging error, $e(x)$, for one-dimensional heat flux distribution must be known. This paper presents $e(x)$ functions for a dimensionless distance in cases of heat flux distributions, such as polynomial exponential peaks and general formulas based on the Taylor expansion series.

Bernstein, F. V. and Kinchen, B., "The Development and Evaluation of a Radiative Heat Source for the Calibration of Transient and Steady-State Heat Flux Sensors," *I.S.A. Transactions* (Instrument Society of America), Vol. 8, No. 2, 1969, pp. 110-116.

A heat flux source capable of producing levels up to 1 MW/m^2 and a calibration technique were developed for use in the calibration of heat flux sensors.

Bomberg, M. and Solvason, K. R., "Comments on Calibration and Design of a Heat Flow Meter," *Thermal Insulation, Materials, and Systems for Energy Conservation in the '80s, ASTM STP 789*, F. A. Govan, D. M. Greason, and J. D. McAllister, Eds., American Society for Testing and Materials, Philadelphia, 1983, pp. 277-292.

The calibration of the HFT used in the apparatus for determination of thermal conductivity was performed with mineral fiber insulation of different densities and polystyrene. The calibration procedures gave different results, depending on the insulating materials. A difference was also observed between the heat flux measured by the guarded hot plate apparatus and that calculated from the transfer standards. By rebuilding the transducers, more constant results were obtained with different calibration procedures.

Burryt, P. E., "A Calibrator for Heat Flow Meters," *Proceedings*, Sixth International Aerospace Instrument Symposium, Paper 8, Royal Aircraft Establishment, Farnborough, England, 1970.

The transducer was mounted between two sections of a copper bar. The upper section was provided with a heater operated by a differential thermocouple, and the lower section contained a liquid coolant and was insulated. The whole assembly was placed in a chamber evacuated to 10^{-2} Pa.

The paper describes briefly some problems caused by the non-uniformity of the transducer, the effect of the clamping pressure, and the fact that the calibration obtained with a conductive calibrator may differ from that obtained with a radiative calibrator.

Dul'nev, G. N., Pilipenko, N. V., and Kuz'min, V. A., "Inertia of Measurements with 'Auxiliary-Wall' Type Heat Meters," English translation in *Journal of Engineering Physics*, Vol. 39, No. 2, 1980, pp. 889-894.

Assuming that the thermal inertia is usually determined experimentally by suddenly exposing the transducer to a constant heat flux, and, further, that the time required to achieve 63% of the change on the transducer is known as the thermal inertia parameter, η, the paper presents an analytical method for determining this parameter. It also gives the boundaries of applicability of the approximate relationship for calculating the non-steady-state heat fluxes.

Gerashchenko, O. A., "Fundamentals of Heat Measurement," English translation in *NASA Technical Memorandum*, No. TM-75490, National Aeronautics and Space Administration, Washington, DC, 1979.

The monograph presents basic information on the theory, design, and application of devices for measuring heat fluxes over a wide range of temperatures. The main chapters deal with methods of heat flow measurements, self-contained HFTs, banked HFTs, calibration of radiative fluxes at low and moderate temperatures, calibration of conductive fluxes up to 600°C, and other applications of HFTs.

Gerashchenko, O. A. and Gorshunova, N. N., "High-Temperature Calibration of Heat Flux Transducers," *Heat Transfer—Soviet Research*, Vol. 5, No. 1, 1973, pp. 141-144.

The calibration is performed under vacuum on a setup consisting of transducers alternating with heaters. The balance of heat transfer involves two transducers and the power output of a heater.

Haupin, W. E. and Luffy, J. W., "Construction and Calibration of Rugged Heat Flow Meters," *Proceedings*, 106th Annual Meeting of the American Institute of Mining, Metallurgical, and Petroleum Engineers, Vol. 6, The Metallurgical Society, New York, 1977, pp. 125-132.

Several short, heavy gage constantan wires bridging a narrow air gap between two parallel steel plates create an iron constantan thermopile. An insulating cord and ceramic seal are used to maintain the position of the plates and to enclose the air gap space.

The calibration was performed in the furnace with the calibrated transducer on top of the furnace transducer. The calibrated transducer acted as a small fin, which increased the heat flux and affected the calibration coefficient. To correct this, master curves were prepared for different temperatures and locations in the furnace.

Johannesson, G., "Heat Flow Measurements: Thermoelectrical Meters: Function, Principles, and Sources of Error," Report Rap TVBH 3003, Lund (in Swedish), English translation available from the Division of Building Technology, Lund Institute of Technology, Sweden or the U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, 1979.

The paper lists the sources of errors that can influence measurements in the field or laboratory testing, as well as the design criteria for the transducers and the basic elements of HFT calibration and application.

Karpov, B. J., "Behavior of Heat Flow Meters Under Operating Conditions," *Bulletin of the International Institute of Refrigeration*, Annex 1, 1957, pp. 73-78.

To determine the measurement error of HFTs under non-steady-state conditions, an equation for damping temperature waves in the multilayer construction was applied. Graphs are provided for maximum error as a function of the measured heat flux and the amplitude of 2-h oscillations, linear changes in temperature, and different thicknesses of damping layer applied to the metering section of the transducer.

Nuckols, M. L., "Heat Flow Transducer Responses to Hyperbaric Environments," *Journal of Engineering for Industry*, Vol. 102, No. 3, 1980, pp. 247-252.

Heat flow transducers were used in the evaluation of convective body heat losses in hyperbaric environments. Environmental conditions were varied to observe the HFT responses. When the appropriate temperature correction was made, the ambient pressure variations were found to have only little effect. However, a significant change in HFT response was observed when the environmental gas composition varied, probably because of a slight porosity of the material used in the core of the HFT.

Polyakov, U. A., Degtyarev, S. A., and Ivanov, A. E., "A Thin-Film Impulse Energy Flux Thermotransducer," English translation in *Power Engineering*, Vol. 20, No. 3, 1982, pp. 127-131.

The influence of the protective insulation coating on the dynamic characteristics of a thin-film impulse energy flux thermotransducer is investigated. Recommendations based on an analysis of amplitude-phase frequency characteristics are given for the development of an optimal fast-response film sensor. Results are reported for an experimental investigation of heat-impulse fluctuations in the combustion chamber of a diesel engine; they confirm the possibility of reproducing the high-frequency portion of the pulsation spectrum without distortion.

Schwerdtfeger, P., "The Measurement of Heat Flow in the Ground and the Theory of Heat Flux Meters," CRREL Technical Report 232, U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, NH, 1970.

Assuming that the mean temperature gradient established between the sensing surfaces of the heat flow transducer may be equal, smaller, or larger than the one existing in the thermally undisturbed region of the surroundings, Schwerdtfeger defined the geometric parameter of the transducer, after analyzing the HFT temperature response and the heat flux response. The report also discusses the use of pairs of HFTs and different calibrating techniques such as the one making use of a novel radiation enclosure in which meters are temporarily tested as net radiometers. (See also Tuck, E. O.)

Tuck, E. O., "A Theory for the Design of Thin Heat Flux Meters," *Journal of Engineering Mathematics*, Vol. 6, No. 4, 1972, pp. 355-368.

See Schwerdtfeger, P., above.

Methods for Field Determination of Thermal Resistance Based on Steady-State Approximation

Anderson, B. R. and Ward, T. I., "Measurements of the Heat Loss Through an Insulated Roof," *Building Services Engineering Research and Technology*, Vol. 2, No. 2, 1981, pp. 65-72.

The dependence of the thermal resistance of attic insulation on the air speed at its exposed upper surface has been measured *in situ*. This paper represents one of several field studies that illustrate applications of HFTs. (See also Becker, R.; Larson, D. C.; Roberts, C. C.; Reinke, K. , Jr.; and Shuman, E. C.)

Becker, R., "Resistance to Heat-Flow Built-up Sections by Means of the Heat-Flow-Meter Test Method," *RILEM Bulletin, Materials and Structures*, Vol. 16, No. 94, 1983, pp. 275–283.

See Anderson, B. R. and Ward, T. I., above.

Brown, W. C. and Schuyler, G. D., "In Situ Measurements of Frame Wall Thermal Resistance," *ASHRAE Transactions*, Vol. 88, Part 1, 1982, pp. 667–676.

In this field study of the thermal resistance of a wood-frame wall, two methods were utilized: the portable wall calorimeter and embedded heat flux transducers. The study was designed to compare the measured thermal resistance with that which had been predicted and to determine the effect of factors such as the wall orientation, the duration of the measurement, the thermal lag, and the mean temperature.

By analyzing the heat flux delay versus the temperature difference across the south-facing wall, and by cross-correlating these data with those collected for walls having different orientations, a thermal lag was determined. The values of the thermal resistance were then calculated for a seven-day period, making use of two different procedures, with and without thermal lag. The results showed in each case a common R-value within a range of $\pm 5\%$. The comparison over a 24-h period, starting at different times of the day, showed that the starting time for integration had less of an effect on the apparent R-value than the use of shorter integration periods (for example, 4 h).

Flanders, S. N., "Time Constraints on Measuring Building R-Values," CRREL Report 80-14, U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, NH, 1980.

The report discusses the measurement error resulting from a variety of changes (cyclical, step, and random change) in temperature for walls of different time constraints.

In view of this report, as well as research reported in the entries for Brown and Schuyler, Flanders and Marshall, Hedlin et al, Orlandi et al, Siviour and McIntyre, and Treado, S. J., it is generally agreed that a 24-h integration period should be used for the steady-state evaluation of the R-value under field conditions. If the thermal lag and the thermal resistance as a function of temperature are known, and, further, if the temperature difference across the wall is steadily between 15 and 20 K, at least, one 24-h period can be sufficient for testing wood-frame or masonry walls. On the other hand, if the thermal lag is unknown or if the temperature difference is less than 10 to 15 K, a much longer measuring period will be required. This was the case in the survey performed in New Zealand (discussed by Trethowen in this publication), in which a 72-h period of testing was used. Finally, it should also be noted that, in cases where there are concrete walls and roofs or when a moisture movement occurs in the building construction, the field testing period will be prolonged for a total of seven to ten days.

Flanders, S. N. and Marshall, S. J., "In Situ Measurement of Masonry Wall Thermal Resistance," *ASHRAE Transactions*, Vol. 88, Part 1, 1982, pp. 677-688.

The presence of a high temperature difference, ΔT, is the most powerful factor assuring convergence on the thermal resistance measured, the R-value. The results of measurements at quadruple the average ΔT converged very closely with the ultimate value within 24 h, whereas measurements related to the average ΔT did not converge until a week had passed.

This investigation demonstrated that the technique employed is adequate to obtain precise measurements of thermal resistance with at least a 6-K average ΔT, which was the lowest utilized.

The measurements were repeatable at a given location within a standard deviation of 10% of the mean. Two fully insulated areas, far removed from each other, were measured at different times of the year by different researchers, yet the differences were only 2%.

Grot, R. A., Bruch, D. M., Siberstein, S., and Glowin, L. S., "Measurement Methods for Evaluation of Thermal Integrity of Building Envelopes," NBSIR-82-2605, National Bureau of Standards, Washington, DC, 1982.

See Treado, S. J.

Hedlin, C. P., Orr, H. W., and Tao, S. S., "A Method for Determining the Thermal Resistances of Experimental Flat Roof Systems Using Heat Flow Meters," *Thermal Insulation Performance, ASTM STP 718*, D. L. McElroy and R. P. Tye, Eds., American Society for Testing and Materials, Philadelphia, 1980, pp. 307-321.

Heat flow rates and temperatures were measured with heat flow meters and thermocouples. The values were recorded and averaged over 24-h periods.

Thermal resistances of systems and individual components were found using two analytical methods. In the first, the ratio of the heat flow to the temperature difference was calculated. This method was unreliable at low heat flow rates. In the second method, the slope of the heat flow versus the temperature difference was used. Hedlin et al reject data with temperature difference of less than 4 K but recommend a ΔT of not less than 10 K.

The thermal resistances of several pieces of insulation found by this method were compared with results obtained using laboratory equipment. The differences ranged from about 0.5 to 5%.

Larson, D. C., "Field Measurements of Steady-State Thermal Transfer Properties of Insulation Systems," in *Guarded Hot Plate and Heat Flow Meter Methodology, ASTM STP 879*, in press.

See Anderson, B. R. and Ward, T. I.

Orlandi, R. D., Shu, L. S., Derderian, G. D., and Siadat, B., "A Field Thermal Measurement Technique for Building Envelope Systems," *Proceedings* ASHRAE/DOE Conference on Thermal Performance of Exterior Envelopes of Buildings II, ASHRAE Special Publication 38, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA, 1983, pp. 703-719.

As the convection and radiation factors are specific to the particular environment in which measurements are carried out, *in situ* calibration precedes the use of HFTs to determine the thermal resistance of building envelope systems. During the calibration, the HFTs are attached to the substrate of the portable calibrator, which is built as a replica of the building envelope substrate. The calibration is performed with careful consideration of convective and radiative factors, as well as lateral heat flow in the substrate.

Roberts, C. C. and Reinke, K., Jr., "Thermal Measurements of Building Envelope Components in the Field," *ASHRAE Transactions*, Vol. 88, Part 1, 1982, pp. 733-743.

See Anderson, B. R. and Ward, T. I.

Shuman, E. C., "Field Measurements of Heat Flow Through a Roof with Saturated Thermal Insulation and Covered with Black and White Granules," *Thermal Insulation Performance, ASTM STP 718*, D. L. McElroy and R. P. Tye, Eds., American Society for Testing and Materials, Philadelphia, 1980, pp. 519-539.

See Anderson, B. R. and Ward, T. I.

Siviour, J. B., "Theoretical and Experimental Heat Losses of a Well-Insulated House," *Proceedings*, Eighth CIB Triennial Congress, Vol. 1A, International Council for Building Research Studies and Documentation, Oslo, Norway, 1980, pp. 329-332.

See Siviour, J. B. and McIntyre, D. A., below.

Siviour, J. B. and McIntyre, D. A., "U-Value Meters in Theory and Practice," *Building Services Engineering Research and Technology*, Vol. 3, No. 2, 1982, pp. 61-69.

The thermal resistance established by field testing can differ from the mean value for a number of reasons, including the external temperature variation, sunshine, the internal temperature variation, the position of the transducer, the contact between the transducer and the wall surface, and the temperature difference across the wall. (See also Siviour, J. B., above.)

Treado, S. J., "Thermal Resistance Measurements of a Built-up System," NBSIR-80-2100, National Bureau of Standards, Washington, DC, 1980.

The objective of this report is to identify factors affecting thermal performance of existing built-up roof systems and to describe a technique for determination of thermal resistance which uses thermography heat flux transducers and thermocouples. A field validation of the measurement system was performed and reported. (See also Grot, R. A., et al.)

Wright, R. E., Jr., Kantsios, A. G., and Henley, W. C., "Effect of Mounting on the Performance of Surface Heat Flow Meters Used to Evaluate Building Heat Losses," *Thermal Insulation, Materials, and Systems for Energy Conservation in the '80s, ASTM STP 789*, F. A. Govan, D. M. Greason, and J. D. McAllister, Eds., American Society for Testing and Materials, Philadelphia, 1983, pp. 293-317.

This paper discusses an experimental evaluation of the effect of the resistance of a thermal contact, which demonstrates a possibility of substantial errors in the heat flux measurement.

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