A COMPARISON OF TWO TECHNIQUES FOR R-VALUE CALCULATION, USING WINTER IN-SITU DATA

Stephen N. Flanders André O. Desjarlais Timothy J. Kunz

ABSTRACT

This study employed winter in-situ temperature and heat flux data from a building in North Dakota and two buildings in upstate New York. The authors obtained the temperature and heat flux data according to ASTM Standard Practice C 1046-91. A proposed revision of ASTM Standard Practice C 1155 includes two calculational techniques, summation, and sum of least squares. These techniques were applied to the data obtained and the results compared. The comparison reported in this study was of the estimate of the R-value obtained, the speed at which a stable value was obtained, and an assessment of the conditions that provided the most reliable results from each calculation.

INTRODUCTION

Determination of In-Situ Thermal Resistance

Determination of thermal resistance or R-value of building envelope components is useful to ensure that construction standards have been met or as a tool to assess needed improvements in insulating levels. Such a determination is more difficult to accomplish in settings of actual use than in the laboratory because of the delays in thermal signals caused by thermal storage and insulation effects. This paper compares two techniques for calculating R-value from in-situ data.

In-Situ Data Two American Society for Testing and Materials (ASTM) standards are available for measuring in-situ temperature and heat flux data—C 1046-91 (ASTM 1991) and then for determining thermal resistance from them, C 1155-90 (ASTM 1990c). In Europe, a standard is under development to accomplish the same purpose (draft ISO Standard 9869). A variety of calculational techniques have been proposed and tried, including modified summation techniques (Anderson 1986), multiple linear regression (Anderlind 1992), sum-of-least-squares techniques (Beck et al. 1991; Bomberg et al. 1994), and Fourier analysis (draft ISO Standard 9869). This paper focuses on comparing the two procedures proposed for C 1155-90—the summation technique and the sum-of-least-squares technique.

Assumptions Both techniques place constraints on how the data were obtained. They require that the user understand the geometry of heat flow in the building component to be measured, sometimes using infrared thermography. The user then strives to place the instrumentation in areas with predominantly one-dimensional heat flow perpendicular to the surface of the component. The techniques are further limited to light- and medium-weight construction. Courville et al. (1990) found that agreement between the two techniques improved when the measured heat flux was greater than ±1.5 W/m^2 (0.5 Btu/h·ft^2).

Summation Technique The summation technique uses accumulated temperature and heat flux data to estimate thermal resistance as follows:

$$R(t) = \frac{\sum_{t=0} [T_{in}(t) - T_{out}(t)]}{\sum_{t=0} q(t)} \tag{1}$$

where t is time and T and q are the temperature and heat flux at a surface.

Sum-of-Least-Squares Technique The sum-of-least-squares technique adapts to multiple sensors placed at several boundaries between homogeneous layers within an insulated component. It assumes that one-dimensional, transient conduction is the heat transfer mechanism. The governing equation, allowing for variable-temperature thermal properties, is as follows:

$$\frac{\partial}{\partial x}\left(\lambda_s \frac{\partial T}{\partial x}\right) = (\rho \cdot C_p)\frac{\partial T}{\partial t} \text{ with } q = -\lambda_s \frac{\partial T}{\partial x} \tag{2}$$

Stephen N. Flanders is with the U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H. **André O. Desjarlais** is with Oak Ridge National Laboratory, Oak Ridge, Tenn. **Timothy J. Kunz** is with Holometrix, Inc., Bedford, Mass.

where λ is thermal conductivity and ρ and C_p are the material density and specific heat, respectively.

This technique solves Equation 2 numerically, using the Crank-Nicholson method, to obtain a finite-difference approximation. The measured temperature and/or heat flux histories on each side of the building component are the boundary conditions. One typically estimates apparent thermal conductivity as a function of temperature and a constant value of the product ρ and C_p for each layer described in the system.

To obtain the best estimates for as many parameters as required, one computes temperatures and heat fluxes with trial initial values of the parameters. Next, one compares them to measurements at the interior nodes, where independent measurements are available. Then one computes a weighted sum-of-squares function, Γ, from the differences between calculated and measured heat fluxes and temperatures, as follows:

$$\Gamma = \sum_{i=1}^{K} \sum_{m=1}^{M} (Y_{mi} - T_{mi})^2 \cdot W_{T_m} + \sum_{i=1}^{K} \sum_{n=1}^{N} (F_{ni} - q_{ni})^2 \cdot W_{q_n} \quad (3)$$

where each W is a weighting factor, T_{mi} and q_{ni} are the calculated temperature and heat flux at a node m or n, and a time i and F_{ni} are the measured temperature and heat flux at a node m or n and a time i.

Finally, one uses the Gauss linearization method (Beck and Arnold 1977) to minimize Γ as the analysis iterates with better and better estimates of the desired properties until the desired convergence is obtained. With only two surfaces instrumented, the assembly was approximated as a uniform slab and values were assumed for thermal conductivity, thickness, density, and specific heat as a starting point for the estimate. It was further assumed that thermal conductivity varies with temperature.

Comparison of Techniques

Previous experience with the summation and the sum-of-least-squares techniques (Courville et al. 1990) suggests that the latter technique is advantageous at times of low temperature difference (ΔT) between indoors and outdoors. The purpose of this study was to compare the two techniques at conditions with a higher ΔT. Three points of comparison are of interest: (1) whether they obtain the same correct answer, (2) how quickly they reach that answer, and (3) the sensitivity of each technique to temperature conditions such as ΔT and variations in ΔT.

R-Value Agreement The authors compared how closely the two techniques came to producing the same R-value. It was impossible to test independently for whether the value was correct; however, experience suggests that any biases due to calculation and not instrumentation become small with time in the presence of a significant ΔT. Therefore, long-term data sets were used wherever possible.

Speed of Determination Because of the delays in obtaining an output thermal signal of temperature or heat flux on one side of the construction when the opposite side has changes in temperature, it can take days to obtain a valid determination of R-value. If one technique is faster than the other in determining the final value reliably, it would be preferred. Consequently, the authors compared the time that elapsed before each technique began to stay within 10% of its final estimate of R-value.

Sensitivity to ΔT It was mentioned previously (Courville et al. 1990) that the sum-of-least-squares technique succeeds at low ΔTs, whereas the summation technique becomes unstable when the denominator of Equation 1 is near zero as a cumulative result of reversals of ΔT. The sum-of-least-squares technique works well during changing ΔT, even when ΔTs are small, because $\partial T/\partial t$ is the key variable in Equation 2. Does this or any other aspect of ΔT cause a more reliable or rapid solution for one technique or the other? Indications were sought that may have made one technique advantageous over the other.

Comparison of Measurement Sites

Table 1 summarizes the building locations and types. The climatic conditions, measurement duration, and building types are significant to the outcome of the measurements.

TABLE 1 Summary of R-Value Measurement Locations

Location	Type	Component Measured	Duration of Measurement
Riverdale, N.D.	Metal Insulated Panel	Walls	487 hours
Fort Drum, N.Y.	Metal Insulated Panel	Wall	331 hours
	Masonry	Wall, Attic	240 hours

Cold Climates The experience in previous work in a temperate climate (Courville et al. 1990) suggested choosing a colder climate to expand the understanding of the effects of ΔT on R-value measurements. Riverdale, N.D., and Fort Drum, N.Y., have temperatures that reach −20°C (−4°F) and below.

Building Types The building in Riverdale was a heated maintenance building serving the Corps of Engineers' Garrison Dam, with metal panels that sandwiched 51 mm (2 in.) of fiberglass insulation between steel skins. The buildings at Fort Drum serve military purposes. The metal-paneled building was a motor vehicle maintenance building, where the mechanical room was instrumented, which also had 51 mm (2 in.) of fiberglass insulation sandwiched between steel skins on the walls. The masonry building serves as a battalion headquarters. Its walls—which consisted of 102-mm (4-in.) brick, 25-mm (1-in.) air space, 51 mm (2 in.) of foil-faced polyisocyanurate insulation, and 203-mm (8-in.) concrete masonry units—were instrumented. Likewise, the attic, with its 254 mm (10 in.) of fiberglass insulation, was instrumented.

FIELD PROCEDURES

Heat flux and temperature data were obtained using the procedures in ASTM Standard Practice C 1046-91. In each case, a thermographic survey was performed using the techniques discussed in ASTM Standard Practice C 1060-90 (ASTM 1990a), which revealed no unexpected thermal anomalies.

Instrumentation The heat flux transducers (HFTs) used were 305 mm (12 in.) square, 0.81 mm (0.032 in.) thick, and had an active metering area of 152 mm (6 in.) square. These were calibrated according to ASTM C 1130-90 (ASTM 1990b). The temperature sensors were type K chromel/alumel thermocouples, calibrated according to the special limits of error specified in ASTM E 230-83 (ASTM 1983).

HFTs were placed on the indoor surface of the building construction at 10 sites. Each site had a pair of thermocouples, one on the inside and another on the outside surface of the construction. These sites were arranged in sensor groups of three or four. Each sensor group had a reference thermocouple in an isothermal box and an indoor and outdoor thermocouple mounted 152 mm (6 in.) from each surface.

Data Acquisition The data acquisition system (DAS) comprised a personal computer with a 30-megabyte hard drive that obtained millivolt signals through a general-purpose interface bus. The DAS scanned the output of each sensor site 44 times per hour and calculated its value, using the appropriate conversion formula. At the end of the hour it would calculate an average value of the quantity measured at each sensor site and record it on the hard drive.

SENSOR SITES

Sensors were placed at each site in groups of three or four on walls and an attic as follows.

Metal Building—Riverdale, N.D.

Sensor groups 1 through 3 were installed on the Riverdale building as shown in Figure 1.

Sensor Group 1 Sensors 0, 1, and 2 were placed on a north-facing masonry wall that had insulated metal panels overlapping the outside to near ground level.

Sensor Group 2 Sensors 3, 4, 5, and 6 were placed on a south-facing wall comprising insulated metal panels.

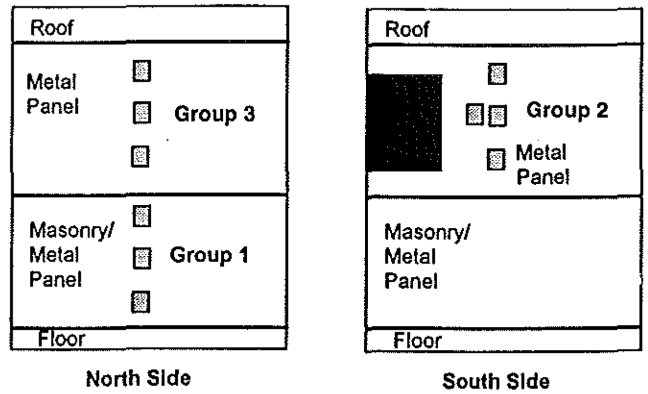

Figure 1 *Location of sensor sites at the Riverdale, ND, building. (Not to scale.)*

Sensor Group 3 - Sensors 7, 8, and 9 were placed on the same north-facing wall as sensor group 1, above the masonry block level on insulated metal panels.

Metal Building—Fort Drum, N.Y.

The evaluated building was designated P 10670. All sensors were placed on a south-facing wall that had a concrete masonry unit (CMU) block foundation that extended 1,220 mm (48 in.) up from a poured concrete slab floor and an insulated metal panel above that level. Sensor groups 1 through 3 were installed as shown in Figure 2.

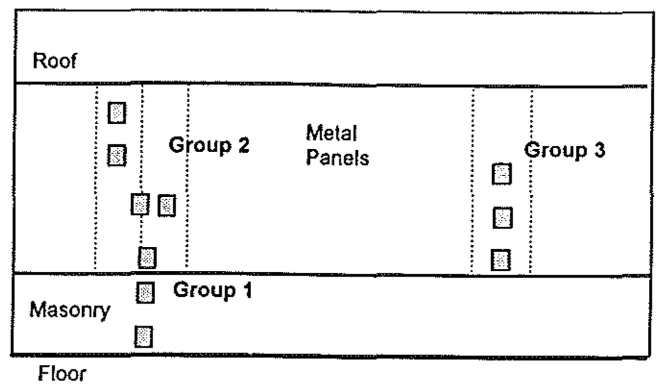

Figure 2 *Location of sensor sites at the Fort Drum, N.Y., metal building. (Not to scale.)*

Sensor Group 1 Sensors 0 and 1 were placed on the CMU foundation. Sensor 2 was placed over a seam on the metal panel.

Sensor Group 2 Sensor 3 was placed near a seam and just above the block wall. Sensors 4, 5, and 6 were midway between seams at various locations on the insulated metal panels.

Sensor Group 3 Sensors 7, 8, and 9 were placed midway between seams at various locations on the insulated metal panels.

Masonry Building—Fort Drum, N.Y.

The evaluated building was designated P 10630. The instrumented space was a heated telephone service room. The indoor surface of the wall consisted of CMUs. Sensor groups 1 and 3 were installed as shown in Figure 3 (sensor group 2 was installed in the attic, described later).

Sensor Group 1 Sensors 0 and 1 were placed on the portion of wall corresponding to the CMU. Sensor 2 was placed at a level corresponding to the masonry.

Sensor Group 3 Sensors 7, 8, and 9 were placed on the portion of wall corresponding to the masonry.

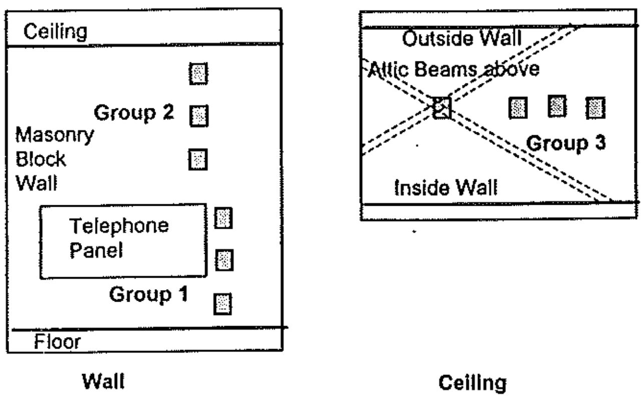

Figure 3 Location of sensor sites at the Fort Drum, N.Y., masonry building. (Not to scale.)

Attic—Fort Drum, N.Y.

The attic was also in building P 10630. The space that was instrumented was the same heated telephone service room.The indoor surface was the ceiling adjacent to the attic over the room. Sensor group 2 was installed as follows (sensor groups 1 and 3 were installed on the wall, described previously).

Sensor Group 2 Sensors 3, 4, 5, and 6 were placed on the ceiling. The thermocouples for the outside measurement were placed in the attic space on the top surface of the insulation. Sensor location 3 coincided with a steel beam under the insulation. The other three locations coincided with fiberglass batt only.

ANALYSIS

Thermal resistance was calculated from the heat flux and temperature data, using the procedures in ASTM Standard Practice C 1155-90. When there were gaps in the data due to lapses in power to the DAS, those blocks of continuous data were used as independent sets for comparison.

Calculation of In-Situ Thermal Resistance

Averaged Data The ΔT and q for each group of sensors were averaged prior to calculation of the R-value. This smoothed out spatial variations in data across the building component.

Spatial Variation The standard deviation, s, of the readings for like sensors was calculated in the group at each time period. That is, for a given time period, s was determined for the outdoor surface temperature readings, the indoor surface temperature readings, and the heat flux readings. This value was expressed as a coefficient of variation—the ratio of s to the mean as a percentage. The authors looked for variations among sensors that would suggest thermal anomalies. Finally, the coefficients of variation were averaged over the measurement period for each type of sensor to obtain s_{mean}.

Summation Technique A spreadsheet was used to calculate the R-value according to Equation 1. The convergence of the calculation of the R-value and the standard deviation of separate data sets was confirmed, according to C 1155-90.

Sum-of-Least-Squares Technique A proprietary Fortran program was used; it was developed to calculate thermal conductivity using the sum of least squares. In order to calculate thermal conductivity, assumptions must be made about the composition of the building element measured. For ΔT and q data, an equivalent homogeneous slab was assumed. In order to calculate thermal resistance, the assumed dimensions were used to convert thermal conductivity to the R-value. For comparison purposes, 4°C (40°F) was chosen as a temperature at which to calculate R-value.

The program incorporates a number of statistical tests for the goodness of fit between the data and the model that estimates thermal conductivity. It offers confidence intervals for thermal conductivity at the temperatures of interest. The residual values that represent the differences between model and data are an important indicator of goodness of fit.

Comparison of Techniques

R-Value Agreement The authors compared how closely the two techniques came to having the same value by calculating the converged value for thermal resistance for each data set and comparing the values.

Speed of Determination Bounds that were 10% above and below the final estimate of R-value for each data set were calculated both for the summation and the sum-of-least-squares techniques. For both techniques the R-value was calculated for data sets in incremental blocks of 24 hours. It was then established which was the last block of 24 hours during which each technique calculated an R-value that was outside the 10% bounds. Lastly, the authors compared which technique stayed within the 10% bounds the soonest.

Sensitivity to ΔT The authors examined the speed of determination for each technique in light of the prevailing average ΔT and the magnitude of the daily changes of ΔT.

RESULTS

Metal Building—Riverdale, N.D.

The measurements at Garrison Dam lasted 487 hours with three interruptions (Figures 4 and 5), resulting in a loss of 8% of the possible data. To obtain substantial blocks of data, the periods of 0 to 120 hours and 313 to 487 hours were chosen.

Spatial Variation During the first period of 0 to 120 hours, the average coefficient of variation (s_{mean}) among thermocouples was less than 2%. At the same time, the s_{mean} for the HFT readings was less than 7%. For the second period of 313 to 487 hours, the s_{mean} among thermocouples was between 1% and 8% and that among HFT readings was between 2% and 20%.

Statistical Tests of Solutions Table 2 illustrates the 95% confidence intervals for the sum-of-least-squares technique and the coefficient of variation for the summation technique for the periods of 0 to 120 hours and 313 to 487 hours. The values for the lower CMU/panel portion of the north wall reflect the fact that this portion of wall was relatively massive and had probable heat paths to the ground. The northern exposures have less variation than the southern exposures.

R-Value Agreement The R-values obtained from averaged data from the summation and the sum-of-least-squares techniques are summarized in Table 2. The agreement was within 10%, except for the CMU/metal panel portion of the wall.

Speed of Determination In all cases, the solution of R-value remained within 10% of its final value within one day for each method.

Sensitivity to Temperature Figure 5 illustrates that the ΔTs for the metals on the north and south sides follow the same trends. Note that those during the period of 0 to 120 hours are lower and more steady than those for the period of 313 to 487 hours. Furthermore, the south side experiences much wider diurnal swings under the influence of solar gain.

Heat fluxes are much higher for the metal panel/masonry wall than for the metal panels (Figure 4). For the metal panels, they are similar (Figure 5).

Metal Building—Fort Drum, N.Y.

The measurements at Building 10670, the metal building at Fort Drum, lasted 330 hours with two interruptions (Figure 6), resulting in a loss of 27% of the possible data. To obtain substantial blocks of data, the periods of 52 to 189 hours and 248 to 330 hours were

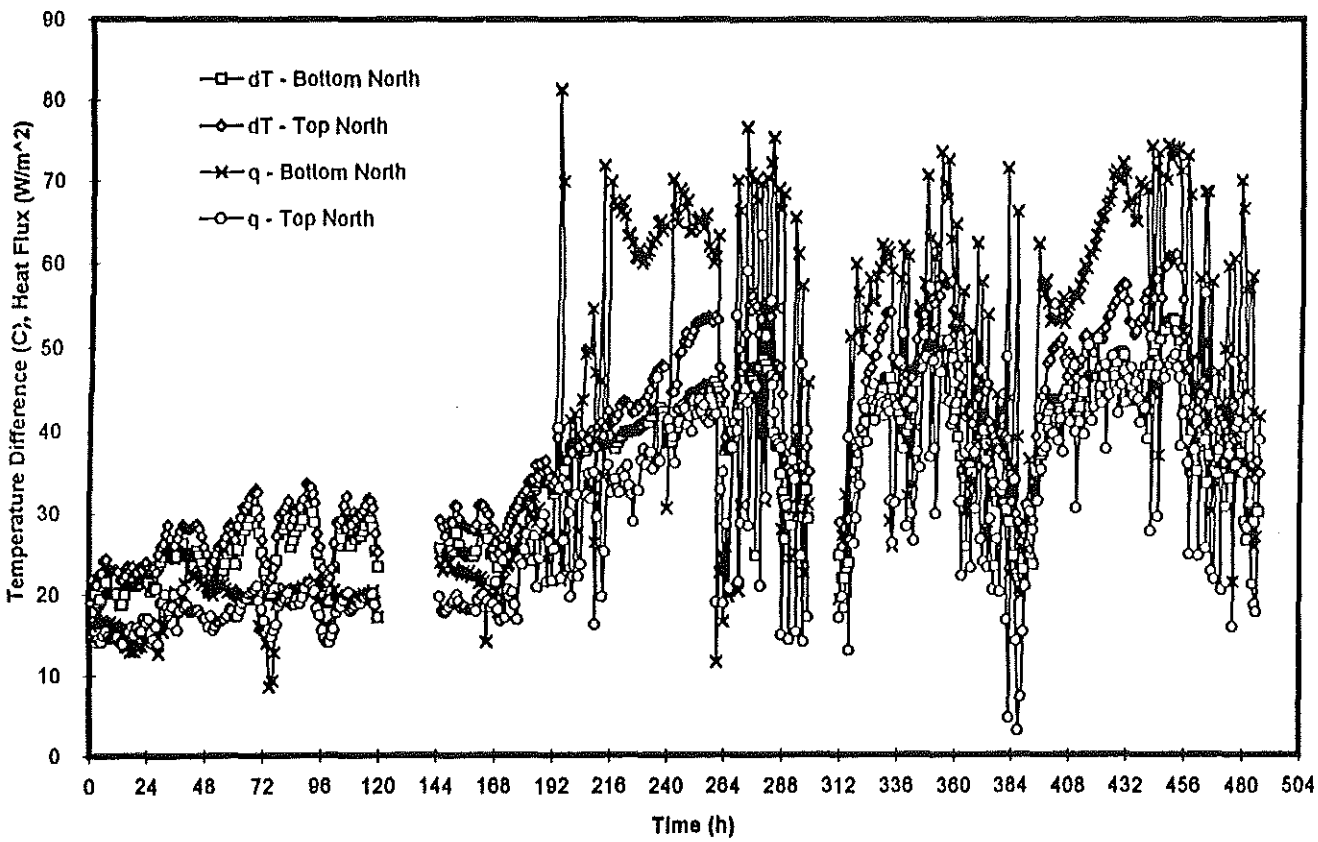

Figure 4 ΔT and q for the sensors on the north side of the heated maintenance building at Riverdale, N.D., with metal panels (top) and masonry/metal panels (bottom).

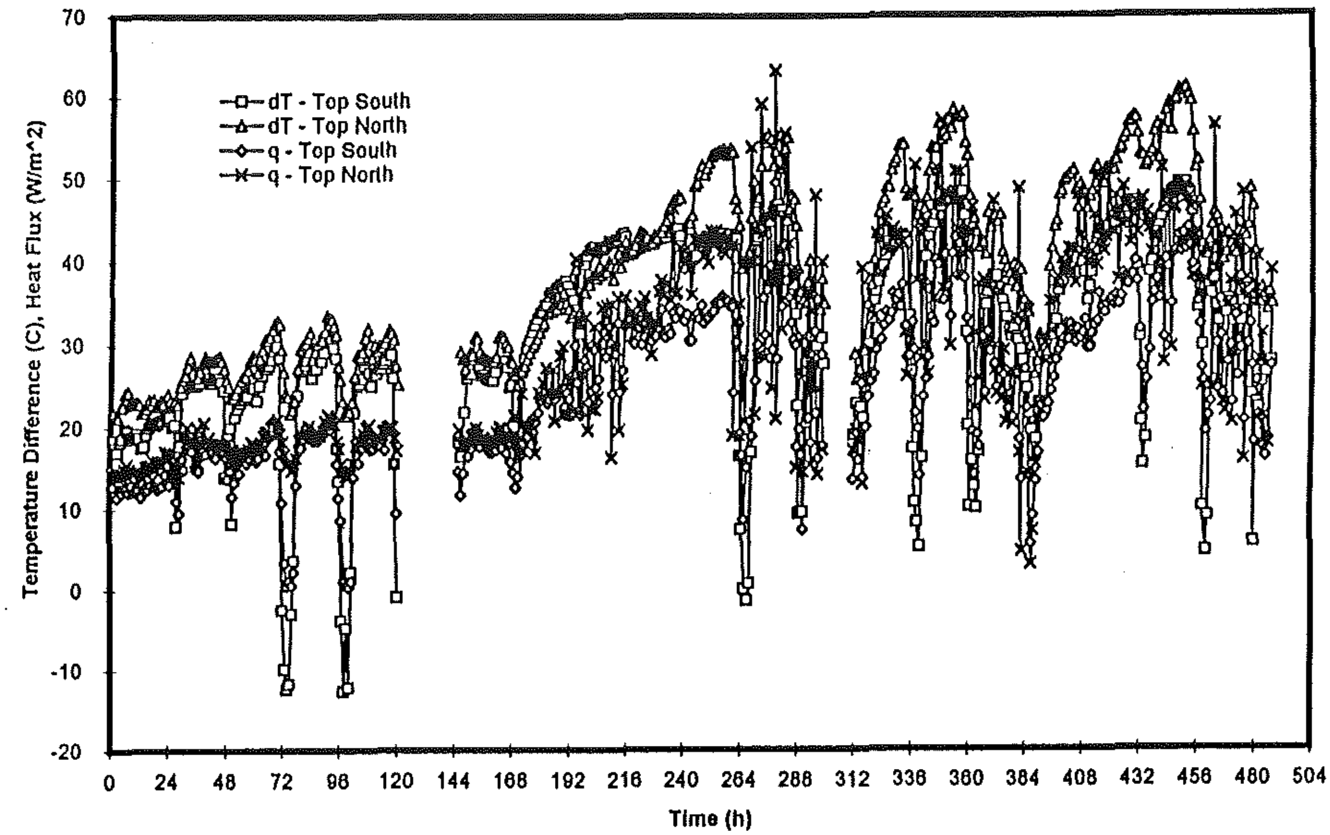

Figure 5 *ΔT and q for the sensors on metal panels of the building at Riverdale, N.D., with north or south exposures.*

TABLE 2 **Precision of R-Value Measurements for the Riverdale, N.D., Building**
Time Period **A** = 0 to 120 Hours, **B** = 313 to 487 Hours.

Orientation	Construction	Time Period	Sum of Least Squares 95% Confidence Interval	Summation Coefficient of Variation
North	CMU/metal panel	A	18%	1%
		B	16%	5%
North	Metal panel	A	2%	1%
		B	11%	1%
South	Metal panel	A	3%	3%
		B	11%	3%

TABLE 3 **Summary of R-Value Measurements in $m^2 \cdot K/W$ ($ft^2 \cdot °F \cdot h/Btu$) on the Riverdale, N.D., Building**
Time Period **A** = 0 to 120 Hours, **B** = 313 to 487 Hours.

Orientation	Construction	Time Period	Sum of Least Squares R-Value (R_{SLS})	Summation R-Value (R_{SUM})	Ratio of R_{SLS} to R_{SUM}
North	CMU/metal panel	A	0.63 (3.6)	0.72 (4.1)	88%
		B	0.44 (2.5)	0.46 (2.6)	96%
North	Metal panel	A	1.51 (8.6)	1.53 (8.7)	99%
		B	1.25 (7.1)	1.27 (7.2)	99%
South	Metal panel	A	1.51 (8.6)	1.55 (8.8)	97%
		B	1.46 (8.3)	1.48 (8.4)	99%

chosen. The data from sensor group 1 represented a variety of different conditions that were not analyzed as a block.

Spatial Variation of Readings During both periods, s_{mean} among thermocouples was between 2% and 6%. At the same time, s_{mean} for the HFT readings was between 2% and 9%.

Statistical Tests of Solutions Table 4 illustrates the 95% confidence intervals for the sum-of-least-squares technique and the coefficient of variation for the summation technique for the periods of 52 to 189 hours and 248 to 330 hours.

R-Value Agreement The R-values obtained from averaged data from the summation and the sum-of-least-squares techniques are summarized in Table 5. The agreement was within 10%, except for the CMU/metal panel portion of the wall.

Speed of Determination In the period of 52 to 189 hours, sensor groups 2 and 3 required only one day of data until the solution of the R-value remained within 10% of its final value for each method. In the period of 248 to 330 hours, sensor groups 2 and 3 required two days of data until the solution of the R-value remained within 10% of its final value for each method.

Sensitivity to Temperature Figure 6 illustrates that the ΔTs and q for sensor groups 2 and 3 followed each other closely.

Masonry Building—Fort Drum, N.Y.

The measurements at Building P 10630, the masonry building at Fort Drum, lasted 240 hours without interruption (Figure 7).

Spatial Variation of Readings During the period, s_{mean} among thermocouples was less than 3%. At the same time, the s_{mean} for the HFT readings was 5% at sensor group 1 and 15% at sensor group 3.

Statistical Tests of Solutions Table 6 illustrates the 95% confidence intervals for the sum-of-least-squares technique and the coefficient of variation for the summation technique for the period of measurement.

R-Value Agreement The R-values obtained from averaged data from the summation and the sum-of-least-squares techniques are summarized in Table 7. The agreement was 100%.

Speed of Determination The data in Table 8 summarize for how long data had to be obtained before the solution of the R-value remained within 10% of its final value for each method. On the massive walls, the sum-of-least-squares technique was somewhat faster than the summation technique.

Sensitivity to Temperature Figure 7 illustrates that the ΔTs and q for sensor groups 1 and 3 followed each other closely.

Attic—Fort Drum, N.Y.

The measurements in the attic of Building P 10630 lasted 240 hours without interruption (Figure 8).

Spatial Variation of Readings During the period, s_{mean} among thermocouples was less than 2%. At the same time the s_{mean} for the HFT readings was 11%.

Statistical Tests of Solutions Table 9 illustrates the 95% confidence intervals for the sum-of-least-squares technique and the coefficient of variation for the summation technique for the period of measurement.

R-Value Agreement The R-values obtained from averaged data from the summation and the sum-of-least-squares techniques are summarized in Table 10. The agreement was 100%.

Speed of Determination The authors obtained a solution of R-value within 10% of its final value for each method within one day for both techniques.

Sensitivity to Temperature Figure 8 illustrates that the ΔTs for all sensors follow each other closely and agree with those in Figure 7. Note that the center period represents a ΔT that is about 50% higher than that of the beginning and ending periods, which are about equal.

TABLE 4 **Precision of R-Value Measurements for the Metal Building at Fort Drum, N.Y.**
Time Period **A** = 52 to 189 Hours, **B** = 248 to 330 Hours.

Sensor Group	Construction	Time Period	Sum of Least Squares 95% Confidence Interval	Summation Coefficient of Variation
2	Metal panel	A	4%	5%
		B	9%	7%
3	Metal panel	A	4%	2%
		B	11%	6%

TABLE 5 **Summary of R-Value Measurements in $m^2 \cdot K/W$ ($ft^2 \cdot {}^\circ F \cdot h/Btu$) on the Metal Building at Fort Drum, N.Y.**
Time Period **A** = 52 to 189 Hours, **B** = 248 to 330 Hours.

Sensor Group	Construction	Time Period	Sum-of-Least-Squares R-Value (R_{SLS})	Summation R-Value (R_{SUM})	Ratio of R_{SLS} to R_{SUM}
2	Metal panel	A	1.05 (6.0)	1.07 (6.1)	98%
		B	1.1 (6.3)	1.1 (6.3)	100%
3	Metal panel	A	0.93 (5.3)	0.93 (5.3)	100%
		B	0.95 (5.4)	0.97 (5.5)	98%

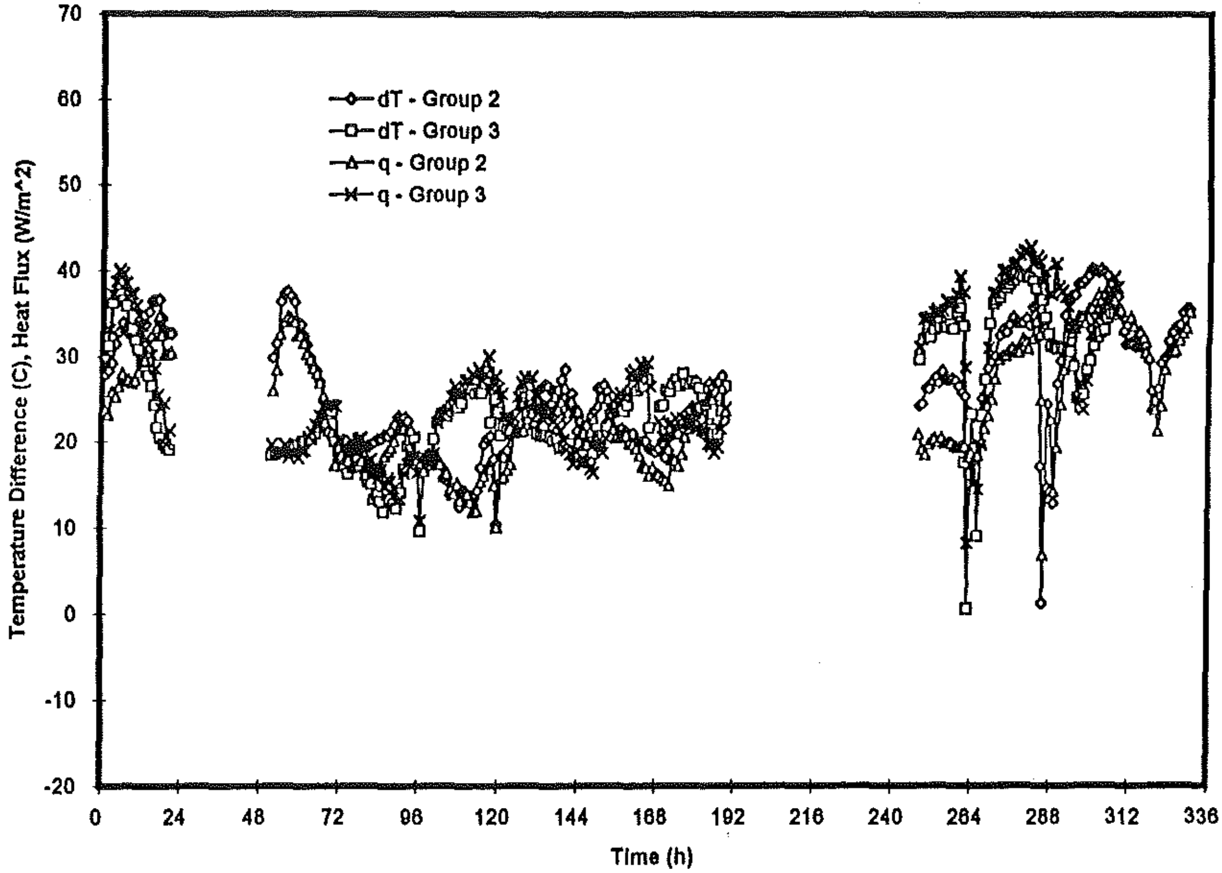

Figure 6 ΔT and q or the sensors on metal panels in the mechanical room of building P 10670 at Fort Drum, N.Y.

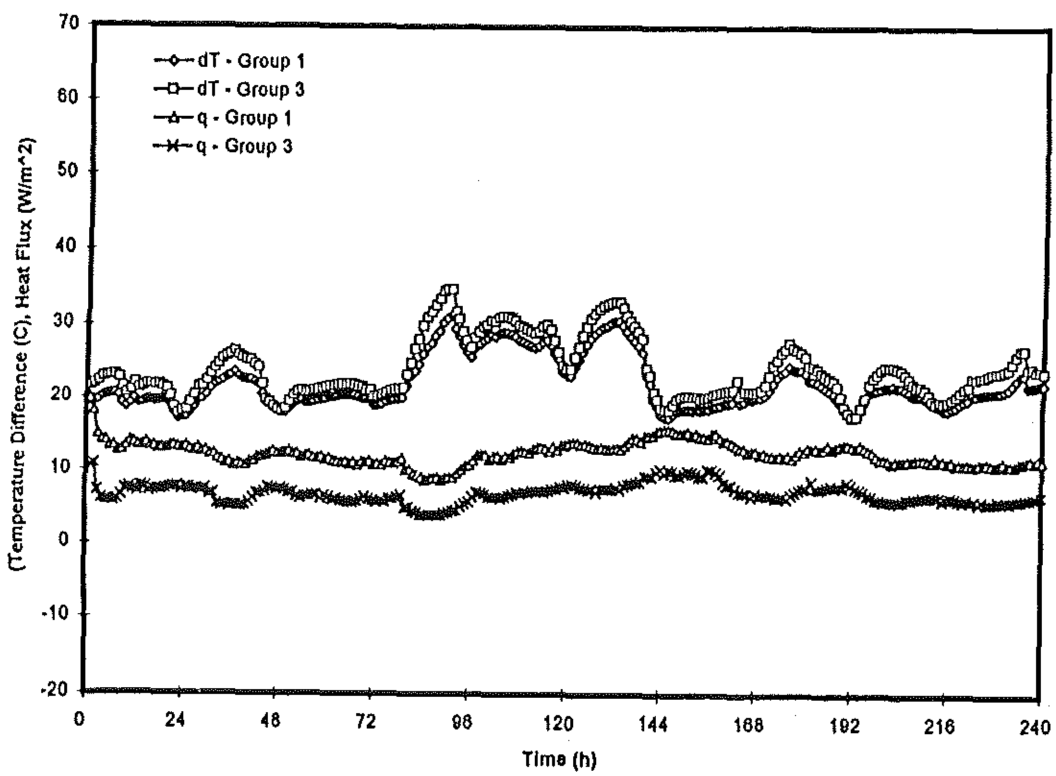

Figure 7 ΔT and q for the sensors on the masonry wall in the telephone service room of building P 10630 at Fort Drum, N.Y.

TABLE 6 Precision of R-Value Measurements for the Masonry Building at Fort Drum, N.Y.

Sensor Group	Construction	Sum of Least Squares 95% Confidence Interval	Summation Coefficient of Variation
1	Masonry	14%	7%
3	Masonry	5%	6%

TABLE 7 Summary of R-Value Measurements in $m^2 \cdot K/W$ ($ft^2 \cdot °F \cdot h/Btu$) on the Masonry Building at Fort Drum, N.Y.

Sensor Group	Construction	Sum of Least Squares R-Value (R_{SLS})	Summation R-Value (R_{SUM})	Ratio of R_{SLS} to R_{SUM}
1	Masonry	0.56 (3.2)	0.56 (3.2)	100%
3	Masonry	1.1 (6.2)	1.1 (6.2)	100%

TABLE 8 Time to Obtain a Calculation that Remains Within 10% of the Final R-Value for the Masonry Building at Fort Drum, N.Y.

Sensor Group	Construction	Sum of Least Squares (Days)	Summation (Days)
1	Masonry	1	2
3	Masonry	1	2

TABLE 9 Precision of R-Value Measurements for the Attic of the Masonry Building at Fort Drum, N.Y.

Sensors	Construction	Sum of Least Squares 95% Confidence Interval	Summation Coefficient of Variation
4, 5, 6	Fiberglass batt 250 mm (10 in.)	12%	7%
3	Metal framing under batts	10%	3%

TABLE 10 Summary of R-Value Measurements in $m^2 \cdot K/W$ ($ft^2 \cdot °F \cdot h/Btu$) in the Attic of the Masonry Building at Fort Drum, N.Y.

Sensors	Construction	Sum of Least Squares R-Value (R_{SLS})	Summation R-Value (R_{SUM})	Ratio of R_{SLS} to R_{SUM}
4, 5, 6	Fiberglass Batt 250 mm (10 in.)	3.7 (21)	3.7 (21)	100%
3	Metal Framing under Batts	2.3 (13)	2.3 (13)	100%

DISCUSSION

R-Value Agreement

For metal panels, R-value agreement between the two techniques was within 3%. For the metal panel/block wall, R-value agreement between the two techniques was within 13%. For masonry walls, R-value agreement between the two techniques was within 1%. For the attic insulation, R-value agreement between the two techniques was also within 1%. The sum-of-least-squares method always rendered a lower value than did the summation technique.

Speed of Determination

In general, speed of determination was equal for the two techniques, except for the masonry building at Fort Drum, where massive construction and slightly lower ΔTs than at Riverdale may have delayed the determination of the R-value, as demonstrated by Table 8. Additional insulation in the attic did not prolong the determination beyond that required for insulated metal panels at ΔTs near 20°C to 30°C (36°F to 54°F).

Sensitivity to Temperature

The Riverdale building's R-value measurements occurred during the highest ΔT conditions, reaching as high as 60°C (108°F). During the first 120 hours, the ΔT was in the range of 20°C to 30°C (36°F to 54°F), similar to the prevailing conditions at Fort Drum. The greater ΔTs at Riverdale did not cause appreciably faster speeds of determination at Riverdale than the lesser ΔTs. The speed of determination may be expected to exponen-

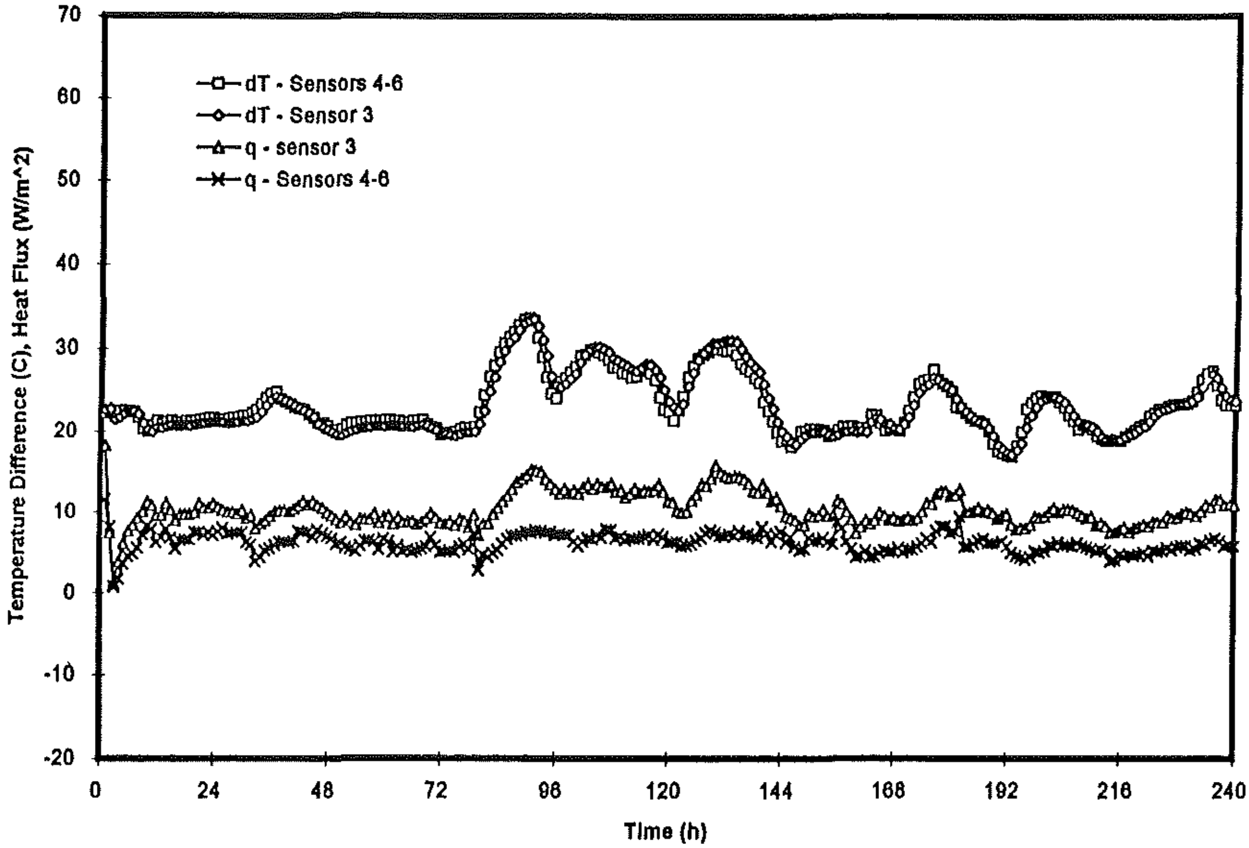

Figure 8 ΔT *and q for the sensors on the telephone service room ceiling below the attic of building P 10630 at Fort Drum, N.Y.*

tially approach a maximum value fairly rapidly as a function of ΔT for the construction tested.

The period of greater ΔT at Riverdale corresponds to lower R-values, according to both techniques. The 34% drop in R-value for the metal panel/masonry case compares with a 17% drop for the metal panel on the north side and a 4% drop for the metal panel on the south side. A drop of R-value with an increase of ΔT is atypical of insulation. Often it is an indicator of convective heat transfer. The metal panel construction offered no obvious paths for convection.

The northerly vs. southerly orientation of sensors on the Riverdale building provided the best opportunity to demonstrate the effect of variations in ΔT (Figure 7) on R-value determination. The average ΔTs tracked each other well, but sun exposure often depressed ΔTs substantially on the south side. This had no significant effect on confidence intervals or coefficients of variation. A possible effect shows up for R-value determination and speed of determination (Table 3), where R-values differ consistently between the two sides during the times of higher variation in ΔT.

CONCLUSIONS

Experience vs. Theory

The measurements during periods when ΔTs were 20°C (36°F) and greater demonstrated that mass and moderate levels of insulation were not a dominant factor in achieving a determination of R-value within a day or two. This is consistent with what theory would suggest.

The R-value comparisons suggest that one of the techniques may be slightly biased because the sum-of-least-squares technique always reported a slightly lower value than the summation technique. Ample theoretical justification exists for the summation technique, recognizing an inevitable random error.

Choice of Techniques

During the temperature conditions encountered in this study for the construction that was instrumented, there would be no reason to choose one technique over the other. Each has its intrinsic advantages. The summation technique is simpler to use in a data logger or spreadsheet. The sum-of-least-squares technique gives more information about sensitivity of R-value to temperature and better statistical reporting. The software used for the sum-of-least-squares technique is difficult for an inexperienced user to use and interpret reliably.

This study demonstrates that both techniques are suitable for use in the proposed revision of ASTM C 1155-90 during the temperature regimes encountered and for construction consistent with the range of mass and insulation levels studied.

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