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ABSTRACT

Thermal conductances (U-values) and thermal resistances (R-values) are discussed throughout the literature as the appropriate parameters for characterizing heat transfer through walls. Because the quoted numbers are usually determined from handbook values of material properties, they have several drawbacks: (1) they do not take into account degradation effects, (2) they ignore construction irregularities, and (3) they do not take into account multi-dimensional heat flow. This paper examines the use of *field measurements* of heat flow and surface temperatures to determine the U-values of walls. The effects of thermal mass on measurements of wall U-values are described in detail, using two data interpretation techniques to estimate the U-values of insulated and uninsulated cavity walls, with and without brick facing. The errors in U-value estimation are determined by comparison with an analytical model of wall thermal performance. For each wall, the error in the U-value determination is plotted as a function of test length for several typical weather conditions. For walls with low thermal mass, such as an fiberglass-insulated cavity wall, it appears that, under *favorable test conditions*, a 6-hour measurement is adequate to measure the U-value within about 10% uncertainty. For masonry walls, the measurement time required is considerably longer than 6 hours. It is shown that for masonry walls, and in general, the optimal measurement time is a multiple of 24 hours due to the effects of diurnal weather fluctuations.

KEY WORDS

Wall conductance, heat flow meter, periodic heat flow, data interpretation

LIST OF SYMBOLS

d	thickness [m];
i	imaginary unit ($i = \sqrt{-1}$);
k	conductivity [W/m-K].
Q	heat flux [W/m^2],
Q_{in}	indoor surface flux [W/m^2],
Q_{out}	outdoor surface flux [W/m^2],
t	time [s],
T	temperature [K],
T_{in}	inside temperature [K],
T_{out}	outside temperature [K],
ΔT	indoor-outdoor temperature difference [K],
ΔT	indoor-outdoor temperature difference [K],
ΔT_{in}	amplitude of periodic fluctuation of indoor temperature [K],
ΔT_{out}	amplitude of periodic fluctuation of outdoor temperature [K],
x	distance into the wall [m],
U_0	actual U-value [W/m^{2}K],
U	U-value estimated with equation 1 [W/m^{2}K],
U^*	U-value estimated with equation 2 [W/m^{2}K],
$Y_{in}(\omega)$	inside surface admittance [W/m^{2}K],
$Y_{out}(\omega)$	outside surface admittance [W/m^{2}K],
$Y_a(\omega)$	across-the-wall admittance [W/m^{2}K],
$\mid Y_{in}(\omega_{in}) \mid$	modulus of $Y_{in}(\omega_{in})$,
$\mid Y_a(\omega_{out}) \mid$	modulus of $Y_a(\omega_{out})$,
α	thermal diffusivity [m^2/s],
γ_{in}	phase angle of $Y_{in}(\omega_{in})$,
γ_a	phase angle of $Y_a(\omega_{out})$,
ω	angular frequency [rad/sec].

INTRODUCTION

The thermal conductances of building envelopes are often the basis for comparison of buildings throughout the country, the quoted numbers usually determined from the individual U-values of the components of the building envelope. The U-values of walls, which represent a significant fraction of the total thermal conductance of a building, are usually determined from handbook values of material properties. Because U-values determined from material properties do not take into account degradation effects and ignore construction irregularities, field tests are sometimes used to verify the computed values.

As with determining U-values from handbook material properties, there are several drawbacks to using field tests to determine the U-value of a wall. These drawbacks are associated both with the required measurements of heat flux through the wall and temperature difference across the wall, as well as with the interpretation of these measurements.[1,2]

In addition to the accuracy limitations of the sensors themselves, field measurements introduce uncertainties due to interference between the sensors and the heat fluxes being measured. Because the sensor represents an additional thermal resistance in series with the wall thermal resistance, the heat flux through the wall section under the sensor will be reduced, implying that the surface temperature must be measured directly under the sensor. Even if the thermal resistance of a heat flow sensor is small relative to the total transverse resistance of the wall being measured, the sensor can change the surface resistance, causing lateral heat transfer at the surface. Changes in surface resistance are caused by mismatches of either convective heat transfer coefficients, or infra-red or solar emissivities. Because a given sensor can not conform to the radiative properties of all surfaces (especially in the solar spectrum where color is important) and because the effects of a sensor on convective air flow are often difficult to define, using a general-purpose heat flux meter can cause additional measurement uncertainties. A related problem with heat flux measurements is that of making good thermal contact between the sensor and the surface being measured. Ideally, the meter substrate material should be supple, so as to conform to surface irregularities, but should maintain its thermal resistance characteristics under the required deformations. In practice, such a material is hard to find; most materials represent some compromise between the two requirements.

Another problem with heat flux measurements is that of measuring a flux that is representative of the entire wall rather than a local perturbation of the heat flow. In practice, heat flow through walls is not uniform, especially in walls with thermal bridges (such as stud walls, or sections of walls near windows or doors). This implies that sensor placement can be important, and that depending upon the size of the heat flow sensor, it may be difficult to determine the thermal resistance of some wall systems.

These problems associated with making heat flux measurements have been discussed extensively in the literature.[3,4] The purpose of this paper is to explore the errors associated with interpreting heat flux and temperature measurements, rather than the problems associated with the measurements themselves. The focus is on the interaction of the thermal mass in walls with the normal fluctuations in heat fluxes and temperatures that occur during field tests. Two data interpretation techniques are examined, and the measurement time required to make accurate determinations of the U-values of several walls are computed.

U-VALUE DETERMINATION

Using heat flux and temperature measurements to determine the U-value of a wall is often considered to be analogous to using electric current and voltage measurements to determine the electric conductance of a circuit element. Using such an analogy, the relationship between the measured flux, temperature difference, and wall conductance is:

$$U = \frac{Q}{\Delta T} \tag{1}$$

Equation 1 ignores all transient effects in a wall, implying that the wall must be at steady-state conditions when the measurement is made. However, because all walls contain some thermal mass, and because surface temperatures and fluxes are always fluctuating, true steady-state conditions are virtually impossible to attain in the field.

An alternative technique for determining the U-value of a wall from heat flux and temperature measurements would be to integrate the heat flux and the temperature difference for an extended period. Because most of the transient effects in a wall are periodic (e.g. furnace cycling and diurnal weather variations), integrations for sufficiently long time periods will have the effect of filtering these transient effects from the data (the integral of a periodic function over an integral or infinite number of cycles is equal to zero). If the integrated (i.e. filtered) temperature differences and heat fluxes are substituted for the instantaneous values in equation 1, the U-value estimation becomes:

$$U^*(t) = \frac{\int_0^t Q(t')\,dt'}{\int_0^t \Delta T(t')\,dt'} \tag{2}$$

Theory

As a means of quantifying the effects of the thermal mass in walls, and the effects of the dynamic temperature changes inherent in any field measurements, we shall return to the basic physics of heat transfer in walls.

The differential equation for one-dimensional heat transfer in a homogeneous isotropic solid whose thermal conductivity is independent of temperature is:[5]

$$\frac{\delta^2 T}{\delta x^2} = \frac{1}{\alpha}\,\frac{\delta T}{\delta t} \tag{3}$$

We shall use the solution to this equation for a solid bounded by two parallel planes under steady periodic conditions. As we are only interested in the fluxes and temperatures at the two surfaces, the solution can be written in matrix form:[6,7]

$$\begin{pmatrix} T_{in} \\ Q_{in} \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \times \begin{pmatrix} T_{out} \\ Q_{out} \end{pmatrix} \tag{4}$$

where

$$A = \cosh\left(d \sqrt{i\,\omega / \alpha} \right) \tag{5.1}$$

$$B = \frac{\sinh\left(d \sqrt{i\,\omega / \alpha} \right)}{k \sqrt{i\,\omega / \alpha}} \tag{5.2}$$

$$C = k \sqrt{i\,\omega / \alpha}\, \sinh\left(d \sqrt{i\,\omega / \alpha} \right) \tag{5.3}$$

$$D = \cosh\left(d \sqrt{i\,\omega / \alpha} \right) \tag{5.4}$$

The temperatures and fluxes in equation 4 should all be in the form of periodic functions, including pure sinusoids, as well as more complex functions expressed in the form of fourier series. The solution for steady-state temperatures and fluxes is obtained by substituting zero for ω in equation 5, and using l'Hopital's rule for equation 5.2.

The expressions for A-D in equation 5 can be used in equation 4 to determine the indoor temperatures and fluxes from the outdoor temperatures and fluxes for a single layer wall. This solution can be extended to a multi-layer wall by matrix multiplication of all the component layer matrices:[8]

$$\begin{pmatrix} T_{in} \\ Q_{in} \end{pmatrix} = \begin{pmatrix} A_n & B_n \\ C_n & D_n \end{pmatrix} \times \begin{pmatrix} A_{n+1} & B_{n+1} \\ C_{n+1} & D_{n+1} \end{pmatrix} \times \cdots\cdots \times \begin{pmatrix} T_{out} \\ Q_{out} \end{pmatrix} \tag{6}$$

Because matrix multiplication is not commutative, the component layers must be put into equation 6 in exactly the order that they are in the wall. A *purely resistive layer* can also be added into equation 6; its matrix elements are independent of frequency:

$$A = 1 \tag{7.1}$$

$$B = d/k = R \ (\textit{thermal resistance}) \tag{7.2}$$

$$C = 0 \tag{7.3}$$

$$D = 1 \tag{7.4}$$

For the purposes of this report we would like to specify the indoor and outdoor surface temperature fluctuations and determine the flux response on the wall surfaces. To accomplish this, equation 4 can be rearranged to give the indoor and outdoor fluxes as a function of the indoor and outdoor temperatures:

$$Q_{in} = \frac{D(\omega)}{B(\omega)} T_{in} - \frac{1}{B(\omega)} T_{out} = \tag{8.1}$$

$$= Y_{in}(\omega)\, T_{in} - Y_{s}(\omega)\, T_{out} \tag{8.2}$$

$$Q_{out} = \frac{1}{B(\omega)} T_{in} - \frac{A(\omega)}{B(\omega)} T_{out} = \tag{8.3}$$

$$= Y_{s}(\omega)\, T_{in} - Y_{out}(\omega)\, T_{out} \tag{8.4}$$

The admittances (Y's) in equation 8 depend on the thermal properties of the component layers of the wall, and on the frequency of the periodic boundary conditions. They are complex numbers, and can thus be represented as a magnitude and phase at each frequency.

Application to U-value determination

Equation 8 can be used to estimate the expected error in the U-values determined with equations 1 and 2. By computing the admittances of a sample wall from handbook thermal properties, the flux response of that wall to a specified surface temperature distribution can be determined with equation 8. These surface temperatures and fluxes can then be inserted into equations 1 and 2, and the resulting U-values compared with the known U-value of the sample wall.

Because of the wide variation in weather conditions and wall characteristics to be expected when performing field measurements, it is not possible to determine a single number or general expression for the expected error when using equations 1 or 2. However, we can show the general trend in the expected errors by simulating several walls under representative test conditions. The conditions we chose for our simulations are:

1) A steady outdoor temperature sine-wave with frequency ω_{out} (e.g., a 24 hour cycle) and amplitude ΔT_{out} (simulating diurnal temperature cycle);

2) A steady indoor temperature sine-wave with frequency ω_{in} (e.g., a one hour cycle) and amplitude ΔT_{in} (simulating furnace cycling); and

3) An *average* indoor-outdoor temperature difference of ΔT.

Under these assumptions, and further assuming that the indoor and outdoor sine waves are in phase, the temperatures can be expressed as a function of time:

$$T_{in}(t) = T_{in} + \Delta T_{in} \sin(\omega_{in} t) \tag{9.1}$$

$$T_{out}(t) = T_{out} + \Delta T_{out} \sin(\omega_{out} t) \tag{9.2}$$

Substituting equation 9 into equation 8.2, we can express the inside heat flux as:

$$\begin{aligned} Q_{in}(t) = {} & Y_{in}(0) T_{in} + |\, Y_{in}(\omega_{in}) \,|\, \Delta T_{in} \sin(\omega_{in} t + \gamma_{in}) \\ & - Y_a(0) T_{out} - |\, Y_a(\omega_{out}) \,|\, \Delta T_{out} \sin(\omega_{out} t + \gamma_a) \end{aligned} \tag{10}$$

Taking the limits of the admittances as the frequency goes to zero, using l'Hopital's rule it can be shown that:

$$Y_{in}(0) = Y_a(0) = U_0 \tag{11}$$

Thus, we can re-express equation (10) as:

$$Q_{in}(t) = U_0 \Delta T + |Y_{in}(\omega_{in})| \Delta T_{in} \sin(\omega_{in} t + \gamma_{in}) - |Y_a(\omega_{out})| \Delta T_{out} \sin(\omega_{out} t + \gamma_a) \tag{12}$$

Substituting the instantaneous surface temperatures and inside heat flux into equation 1, the estimated U-value of the wall can then be expressed as a function of time:

$$U(t) = U_0 \frac{1 + \dfrac{|Y_{in}(\omega_{in})|}{U_0} \dfrac{\Delta T_{in}}{\Delta T} \sin(\omega_{in} t + \gamma_{in}) - \dfrac{|Y_a(\omega_{out})|}{U_0} \dfrac{\Delta T_{out}}{\Delta T} \sin(\omega_{out} t + \gamma_a)}{1 + \dfrac{\Delta T_{in}}{\Delta T} \sin(\omega_{in} t) - \dfrac{\Delta T_{out}}{\Delta T} \sin(\omega_{out} t)} \tag{13}$$

Substituting the instantaneous surface temperatures and inside heat flux into equation 2 and performing the integrations, the estimated U-value of the wall can also be expressed as a function of time:

$$U^*(t) = U_0 \frac{1 - N}{1 - D} \tag{14}$$

where

$$N = \frac{|Y_{in}(\omega_{in})|}{U_0} \frac{\Delta T_{in}}{\Delta T} \frac{[\cos(\omega_{in} t + \gamma_{in}) - \cos\gamma_{in}]}{\omega_{in} t} - \frac{|Y_a(\omega_{out})|}{U_0} \frac{\Delta T_{out}}{\Delta T} \frac{[\cos(\omega_{out} t + \gamma_a) - \cos\gamma_a]}{\omega_{out} t} \tag{14.2}$$

$$D = \frac{\Delta T_{in}}{\Delta T} \frac{[\cos(\omega_{in} t) - 1]}{\omega_{in} t} - \frac{\Delta T_{out}}{\Delta T} \frac{[\cos(\omega_{out} t) - 1]}{\omega_{out} t} \tag{14.3}$$

RESULTS

Equations 13 and 14 have been be used to quantify the difference between the estimated U-values computed with equations 1 and 2, and the known U-values of four typical residential walls. The U-values based on equation 1 are determined from the instantaneous values of indoor surface temperature, outdoor surface temperature, and indoor heat flux, whereas U-values computed with equation 2 are determined from integrated values of the three simulated measurements. All four walls are 4 cm by 8 cm cavity walls: 1) with plywood facing, 2) with R-11 insulation and plywood facing, 3) with 20 cm brick facing, and 4) with R-11 insulation and 20 cm brick facing. The heat flow through each wall was simulated by ignoring the effects of wooden studs, ostensibly corresponding to measurements made on the cavity sections centered between the studs. The U-values and admittances of each wall are presented in Table 1.

TABLE 1: Admittances of Simulated Walls

Wall	U-value [W/m^2K]	$Y_{in}(\omega_{in})$ [W/m^2K]	$Y_a(\omega_{out})$ [W/m^2K]	$\gamma_{in}(\omega_{in})$ [rad]	$\gamma_a(\omega_{out})$ [rad]
Cavity	1.5	6.0	1.5	0.34	-.24
Insulated Cavity	0.42	6.3	0.41	0.35	-.35
Brick-face Cavity	1.5	5.9	0.60	0.34	-1.9
Brick-face Insulated Cavity	0.41	6.3	0.12	0.35	-2.1

Simulated Instantaneous Measurements

Figures 1 through 4 contain plots of the fractional error in U-value that occurs when equation 1 is used to determine U-values under two sets of simulated conditions. The errors corresponding to simulated instantaneous measurements are plotted for a 24 hour period; the error cycle repeats itself every 24 hours. Figures 1 and 2 are error plots for outdoor temperature fluctuations of 5.56 K, indoor temperature fluctuations of 1.11 K, and an average temperature difference of 22.2 K,* Figure 1 for insulated and uninsulated cavity walls, and Figure 2 for insulated and uninsulated brick-faced walls.

The errors in Figures 1 and 2 show several important effects: 1) the influence of the diurnal temperature swing and that of the indoor temperature variations (the short, superimposed oscillations) are easily distinguished, 2) the short-term temperature swings are significantly more important for insulated walls, and 3) the diurnal temperature swing is relatively unimportant for the walls without brick facing (i.e. without significant thermal mass). For the uninsulated cavity wall in Figure 1, the estimated U-value differs up to 25% from the true U-value, whereas for the insulated wall the errors in estimated U-value are as high as 100%↓. Figure 2 shows that the diurnal temperature swing has a more significant effect on the instantaneous U-value for brick walls. The increased error due to the low-frequency outdoor temperature fluctuation is a result of the thermal mass of the brick wall. As for the cavity wall, the effects of the indoor temperature fluctuation is accentuated by the addition of insulation to the brick wall.

Because of the large amplitudes of the U-value errors associated with fluctuations in indoor temperature, simulations that assume smaller fluctuations in indoor temperature were performed. These tests correspond with efforts to control the indoor climate more carefully (e.g. a thermostat with a smaller deadband). In figures 3 and 4, the errors in the estimated U-values are plotted for the same walls for an indoor temperature fluctuation of only $\pm$ 0.28K. The errors in the estimated U-value show considerably smaller maxima and minima, but display a pattern similar to that shown in Figures 1 and 2. These results suggest that better control of indoor temperatures can significantly reduce the uncertainty in the estimated U-value for all of the walls.

* The experiments were performed in ^{o}F, therefore quoted temperatures in K are not exact. The actual temperature differences are 10 ^{o}F, 2 ^{o}F, 40 ^{o}F.

↓ Unlike the simulations, in an actual test the indoor and outdoor temperatures will not be pure sine-waves and the apparent U-value will not quite display such a regular pattern.

A close examination of Equation 13 provides some trends in the errors that occur when determining the U-value of a wall from instantaneous measurements. We find that the estimated U-value at any time is likely to be furthest from the true U-value for:

a) well insulated walls;

b) large indoor and outdoor temperature fluctuations;

c) small average indoor-outdoor temperature differences;

d) thermally massive walls.

The first three trends are directly apparent in Equation 13, whereas the fourth trend (thermal mass) appears indirectly in the admittances. As the thermal mass of a cavity wall is increased (see the brick-faced walls in Table 1), the phase angle ($\gamma_a(\omega_{out})$) at the diurnal frequency is increased, thereby increasing the error.

To use these trends to improve instantaneous measurement results, we must realize that the only variable over which we have control is the indoor temperature. The smaller fluctuations in estimated U-value in Figures 3 and 4 correspond to the reduced amplitude of the indoor temperature fluctuations. This simulation of better indoor temperature control essentially corresponds to a reduction in the deadband of the thermostat. Although the U-value accuracy improves dramatically, the accuracy remains unacceptable, especially for the more massive walls in Figure 4. The errors are as high as 30% for the cavity walls, and as high as 60% for the insulated brick wall.

Simulated Long-Term Average Measurements

Possible accuracy improvement by using longer-term measurements is examined by plotting the estimation errors that result when computing the U-value with Equation 14. The fractional deviations, $(U^*(t) - U_0)/U_0$, for three of the walls considered previously are plotted in Figure 5. For the same assumptions of $\pm$ 1.11K indoor fluctuation, $\pm$ 5.56K outdoor fluctuations, and ΔT = 22.2K, we see that the influence of indoor temperature fluctuations on the $U\text{-}value$ is lost after a relatively short time, especially for the uninsulated walls. However, the effect of outdoor temperature fluctuations lingers for a long time, especially for the high thermal mass walls. The averaging performed in equation 14 serves as a form of low-pass filter, slowly filtering out the fluctuations, and passing only the average value after a significantly long time. Figure 6 includes the same information as Figure 5, except that the results are extended to tests as long as 48 hours. Focusing on the brick wall, we see that the 24 hour error oscillations decay with time, although much more slowly than the 1 hour oscillations. From figures 5 and 6 we can conclude that by using equation 14 under the assumed weather conditions, the U-value of the insulated wood frame wall can be approximated within 10% in about 6 hours. It also appears that the U-value of the brick wall can be approximated with the same accuracy within about 16 hours.

Further analysis of Figures 5 and 6 yields some additional observations. We find error peaks in Figure 6 at t = 8 hours and t = 32 hours. Furthermore, we find that the average error in measured average U-value is positive for all walls for the conditions considered in figure 6. In fact, both the time of occurrence and size of the error peak, as well as the sign of the average error are not generalizable to all walls. They are determined simply by the choice of starting time relative to the outdoor sine-wave. In practice, this means that U-values computed with equation 14 may be biased. They will be more accurate for longer measurement times, but the error does decay uniformly as the test length increases. Figures 7 and 8 are plots of the fractional errors in the U-value computed Equation 14 for two different starting times relative to the outdoor sine wave. In Figure 7 the data acquisition was started 90^{o} after the beginning of the sine wave and the data acquisition in Figure 8 starts 180^{o} after the beginning. We see that the error starts off positive and then becomes negative in Figure 7, and that the error due to the outdoor sine wave is always negative in Figure 8. In all cases we see that the error tends towards zero at 24 hours into the test,or after one complete outdoor weather cycle. The rules that can be derived so far are:

1) There are diurnal error peaks;

2) The magnitudes of the error peaks decrease rapidly with the length of the measurement period;

3) For heavier walls the average U-value measured over any time less than 24 hours is likely to be biased.

An additional consideration concerning the field measurement of U-value is the size of the average indoor-outdoor temperature difference. As noted for Equation 13, Equation 14 also indicates that the accuracy should improve with larger indoor-outdoor temperature differences. Figure 9 is a plot of U-value errors obtained when using Equation 14 for conditions identical to those in Figure 5, except the average indoor-outdoor temperature difference has been reduced from 22.2K to 11.1K. We see that it takes twice as long (12 hr) for the error in the U-value determination for the insulated cavity wall to drop below 10%. We also see that the error peak at t = 8 hours for the brick wall reaches 80% under this small indoor-outdoor temperature difference, compared with 30% for the larger indoor-outdoor temperature difference in Figure 5. This indicates that the average indoor-outdoor temperature difference has a significant effect on the minimum test length required to provide a given level of accuracy.

We should also note that this analysis does not take into account the possibility of long-term trends in the weather during an actual test. For example, if the average daily outdoor temperature is changing during the course of a test, the wall will either store or release energy, thereby causing an error in the average heat flow in equation 14. This effect can become important for thermally massive walls, especially when the average indoor-outdoor temperature difference is small. The errors will be periodic as for the 24 hr cycle, but on a longer time scale and with a smaller amplitude. The amplitude is smaller because the weather fluctuations are normally less severe and the wall has more time to adapt to lower frequency fluctuations.

CONCLUSIONS

One of the goals of this paper was to give some insight into the minimum time necessary to measure the U-value of a wall in the field. As a partial answer to this question, our analysis has shown that instantaneous field measurements of surface temperatures and heat flux cannot provide accurate estimates of the U-value of a wall. Our analysis has also shown that the accuracy of wall U-value estimations can be significantly improved if time-integrated temperatures and fluxes are used. As an example, it appears that a 6-hour measurement of temperatures and fluxes is adequate to measure the U-value of an insulated cavity wall within about 10% error, ***provided that:***

1) The indoor-outdoor temperature difference is at least 20K;
2) The daily outdoor temperature swing (high to low) is not larger than half the average indoor-outdoor temperature difference;
3) The average indoor and average outdoor temperatures do not vary significantly over the course of the test; and

More generally, we have shown that the required test length for a given level of accuracy is extremely sensitive to the size of the average indoor-outdoor temperature difference, and that by using the long-term average flux and temperatures, the effects of short-term fluctuations in indoor or outdoor temperature become unimportant. We found that for masonry walls the required measurement time is considerably longer under the same test conditions listed above. In general, the error in U-value estimation is minimized by using an integral number of 24-hour cycles as the test period, thereby averaging the diurnal weather fluctuations over a full cycle.

It is important to recognize that these accuracy limitations are independent of the particular instruments used to determine the heat flux and temperatures. The point is to emphasize the as yet unresolved questions about what one does with the heat flux and temperature data once they are collected, and to provide some guidelines for field measurements.

The most important conclusion to be drawn from the analysis presented in this paper is that accurate determination of the U-value of a wall from field measurements requires more care and understanding than is readily apparent. We have focused on quantifying the errors associated with data interpretation. The analysis that we have used to describe the heat transfer through a wall can help quantify the errors introduced by the normal temperature fluctuations that occur during field tests and could be further utilized to quantify the effects of long-term outdoor temperature swings.

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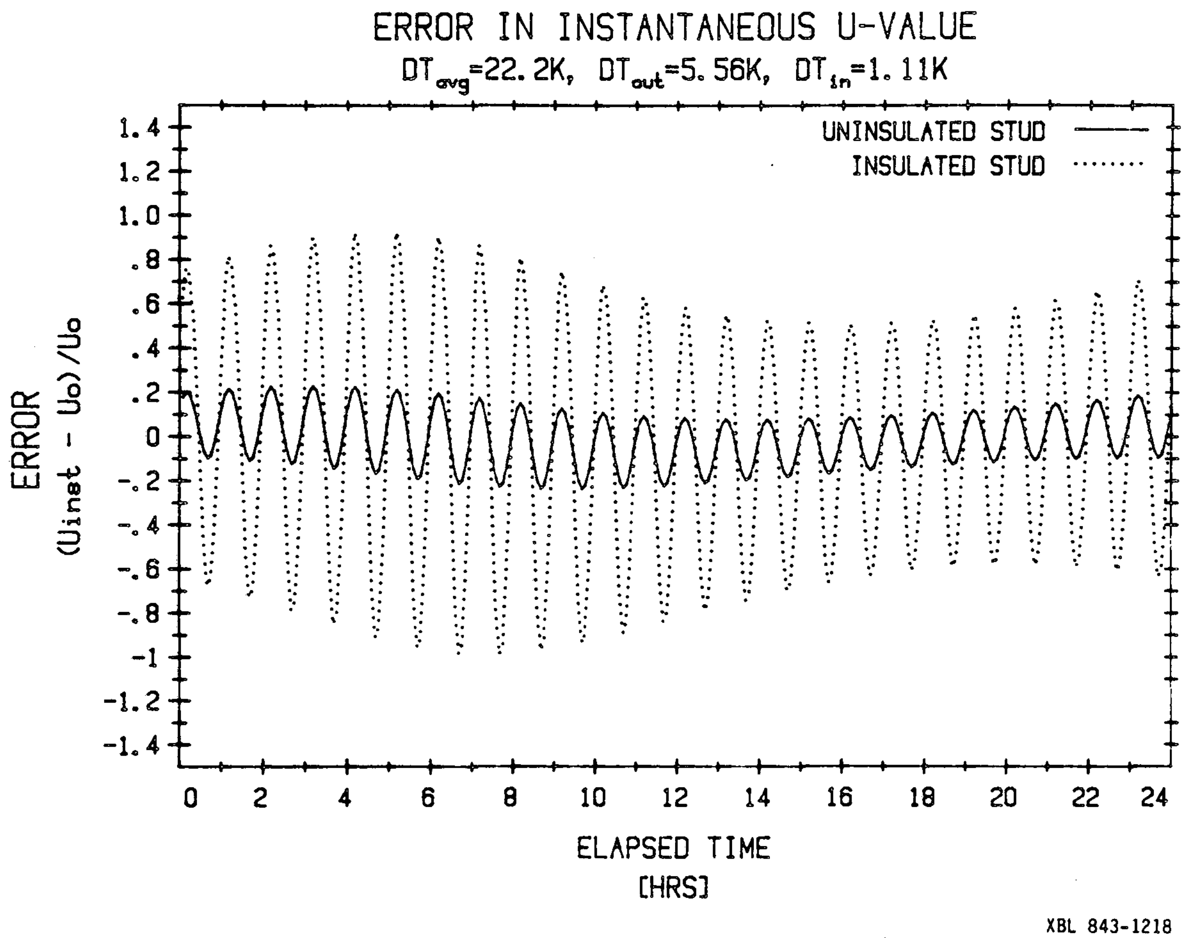

Figure 1. Fractional error in instantaneous U-value for insulated and uninsulated stud walls ($\Delta T_{in} = 1.11$K, $\Delta T_{out} = 5.56$K, $\Delta T = 22.2$K).

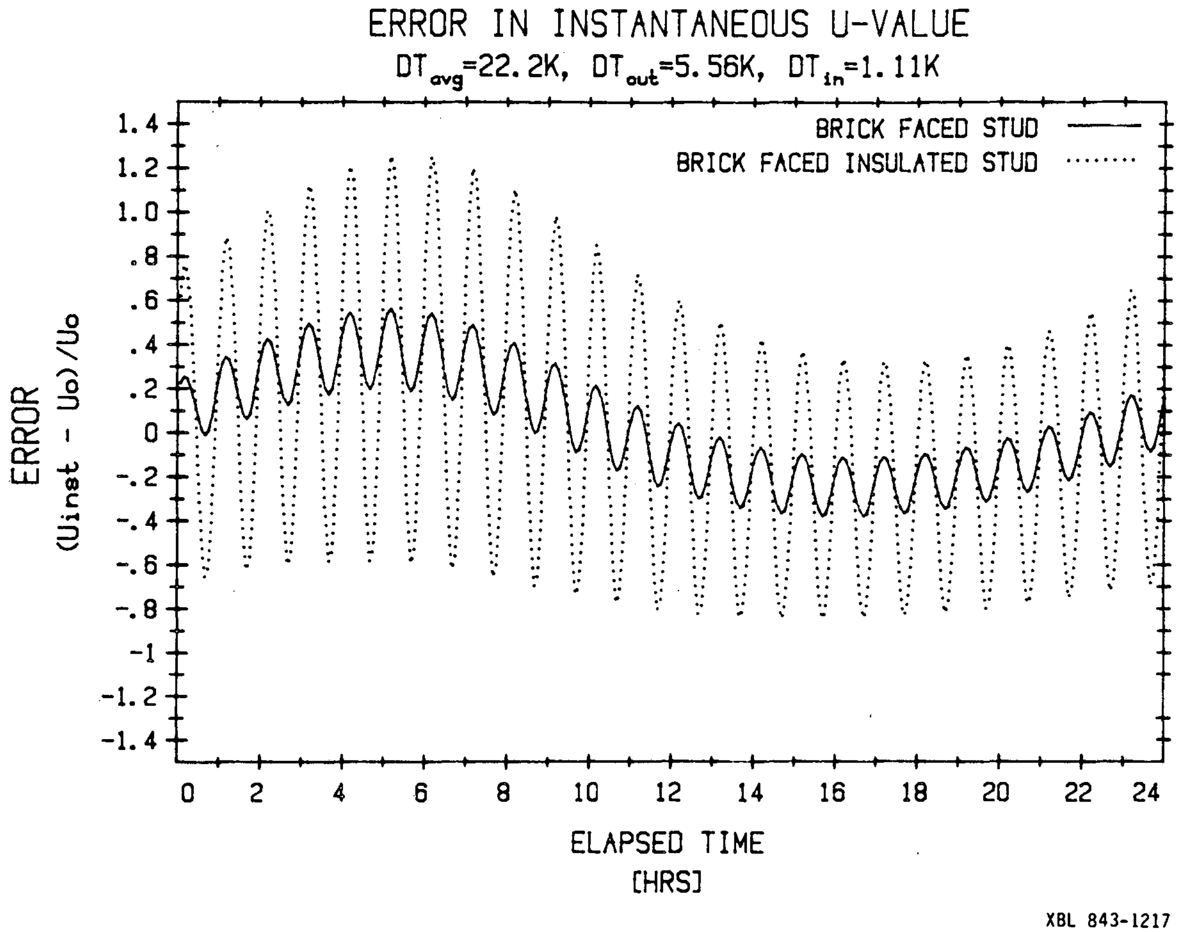

Figure 2. Fractional error in instantaneous U-value for insulated and uninsulated brick walls (ΔT_{in} = 1.11K, ΔT_{out} = 5.56K, ΔT = 22.2K).

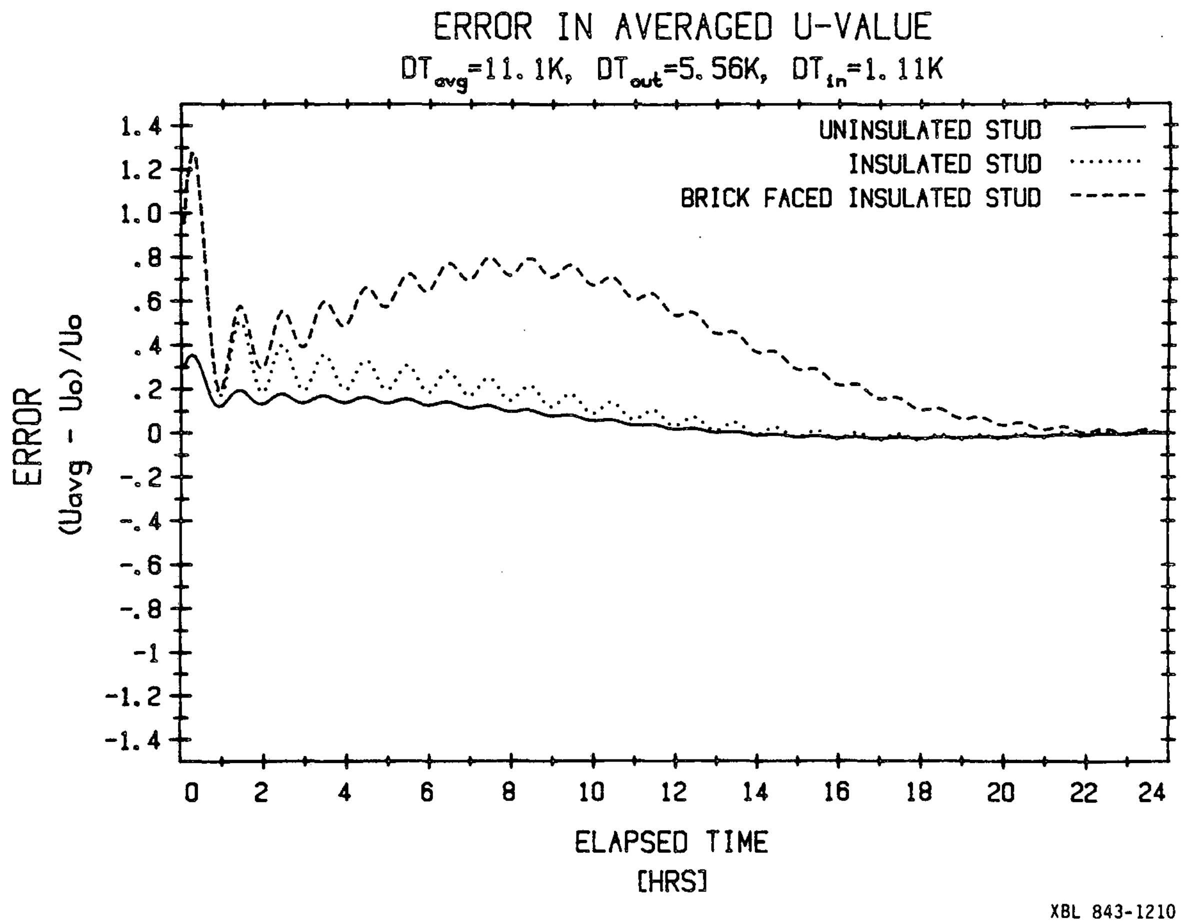

Figure 3. Fractional error in instantaneous U-value for insulated and uninsulated stud walls (ΔT_{in} = 0.28K, ΔT_{out} = 5.56K, ΔT = 22.2K).

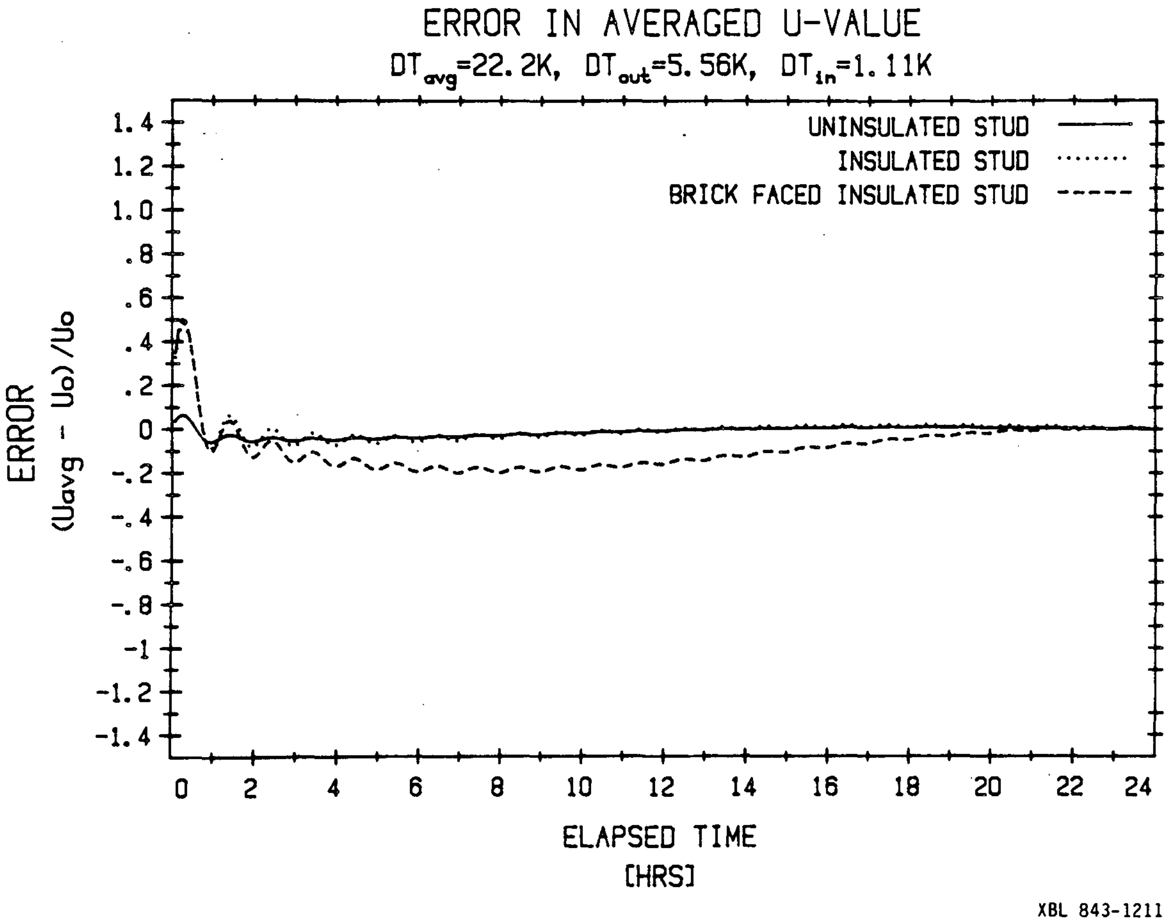

Figure 4. Fractional error in instantaneous U-value for insulated and uninsulated brick walls ($\Delta T_{in} = 0.28$K, $\Delta T_{out} = 5.56$K, $\Delta T = 22.2$K).

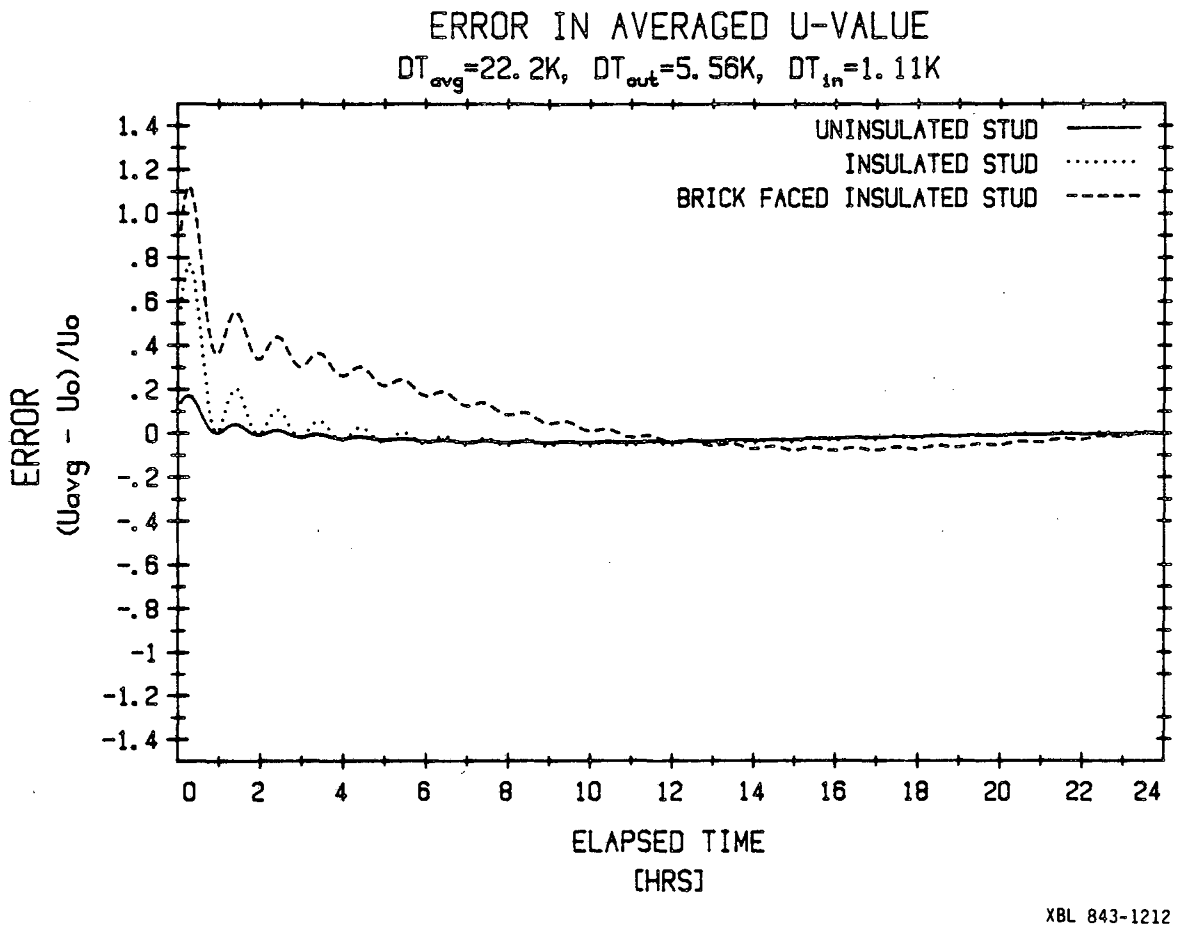

Figure 5. Fractional error in averaged U-value for insulated and uninsulated stud walls and insulated brick wall ($\Delta T_{in} = 1.11$K, $\Delta T_{out} = 5.56$K, $\Delta T = 22.2$K).

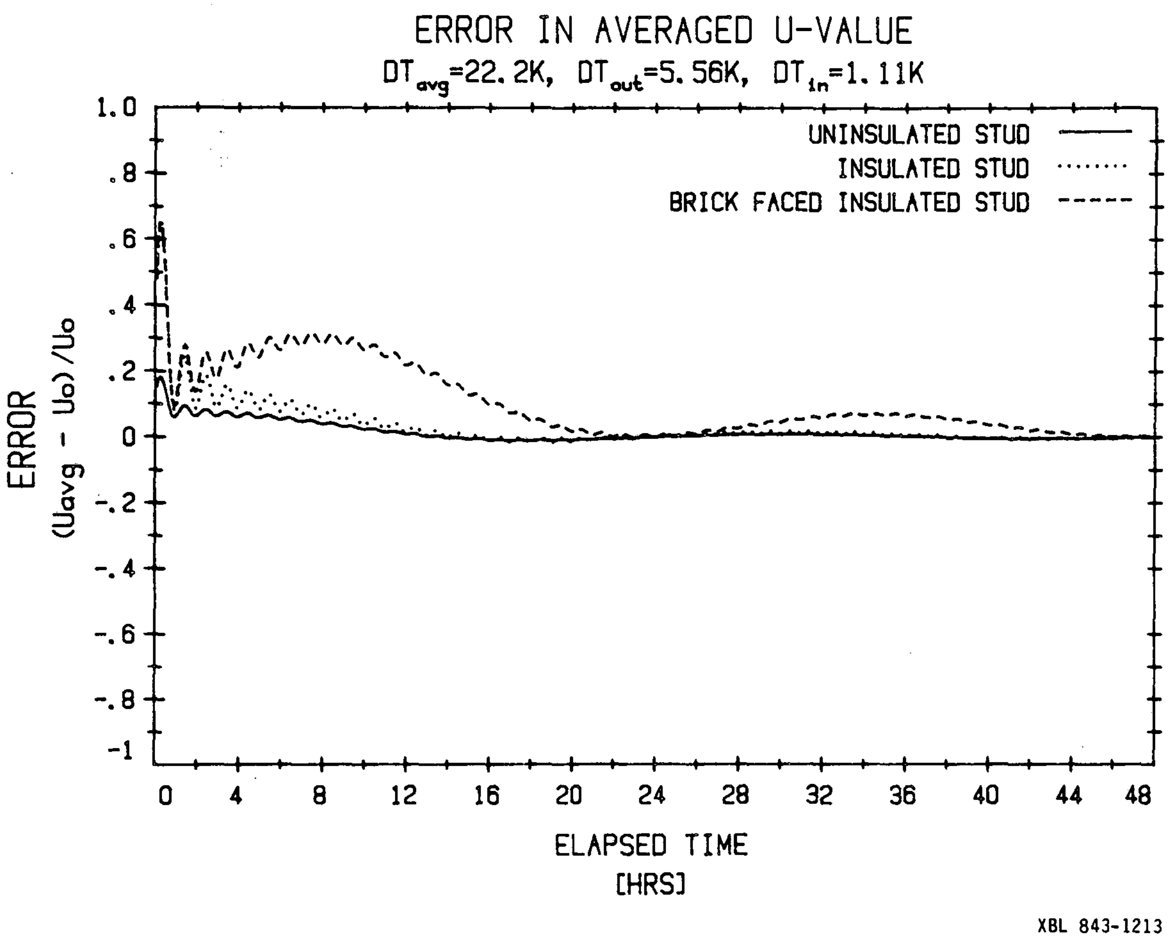

Figure 6. Fractional error in averaged U-value for insulated and uninsulated stud walls and insulated brick wall for 48 hour test (ΔT_{in} = 1.11K, ΔT_{out} = 5.56K, ΔT = 22.2K).

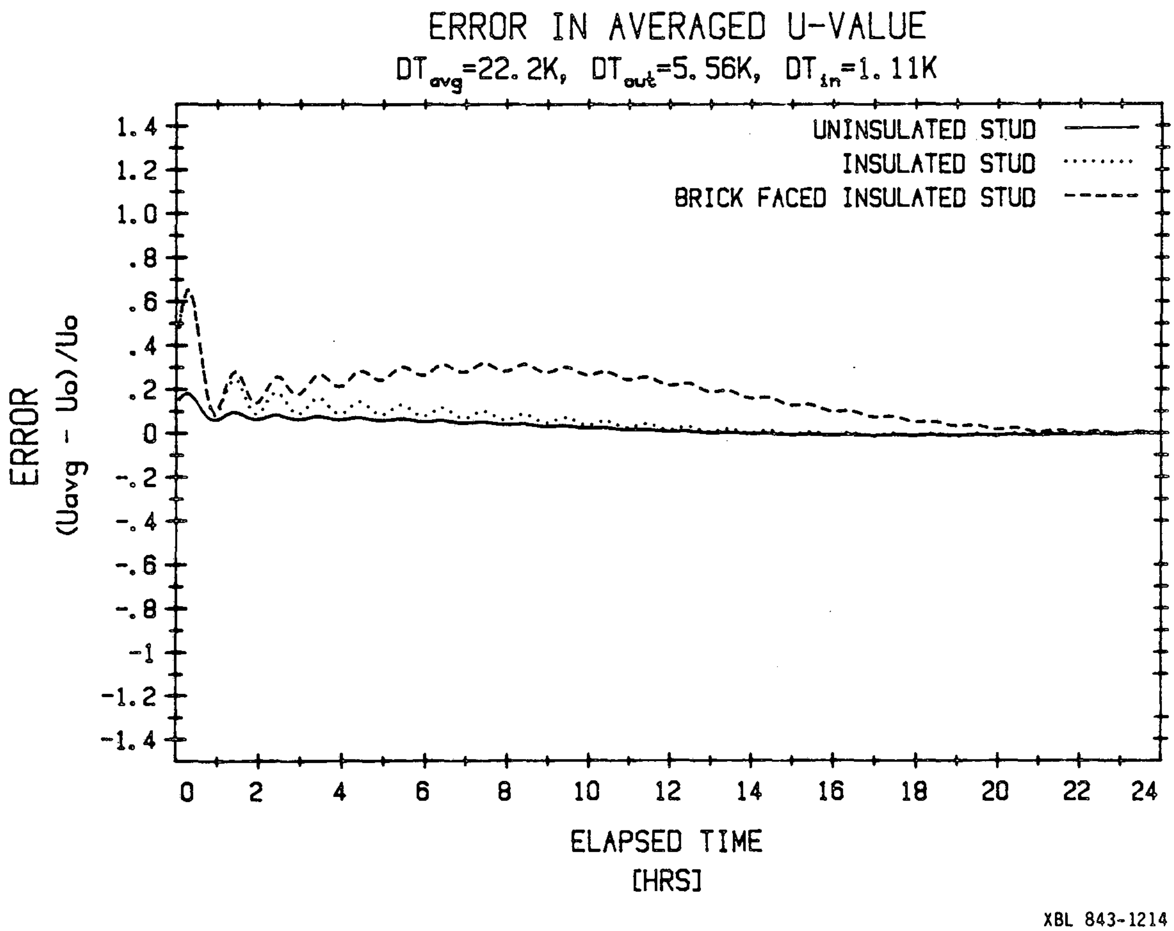

Figure 7. Fractional error in averaged U-value for insulated and uninsulated stud walls and insulated brick wall with test starting 90 $^{\circ}$ after beginning of outdoor sine wave (ΔT_{in} $=$ 1.11K, ΔT_{out} $=$ 5.56K, ΔT $=$ 22.2K).

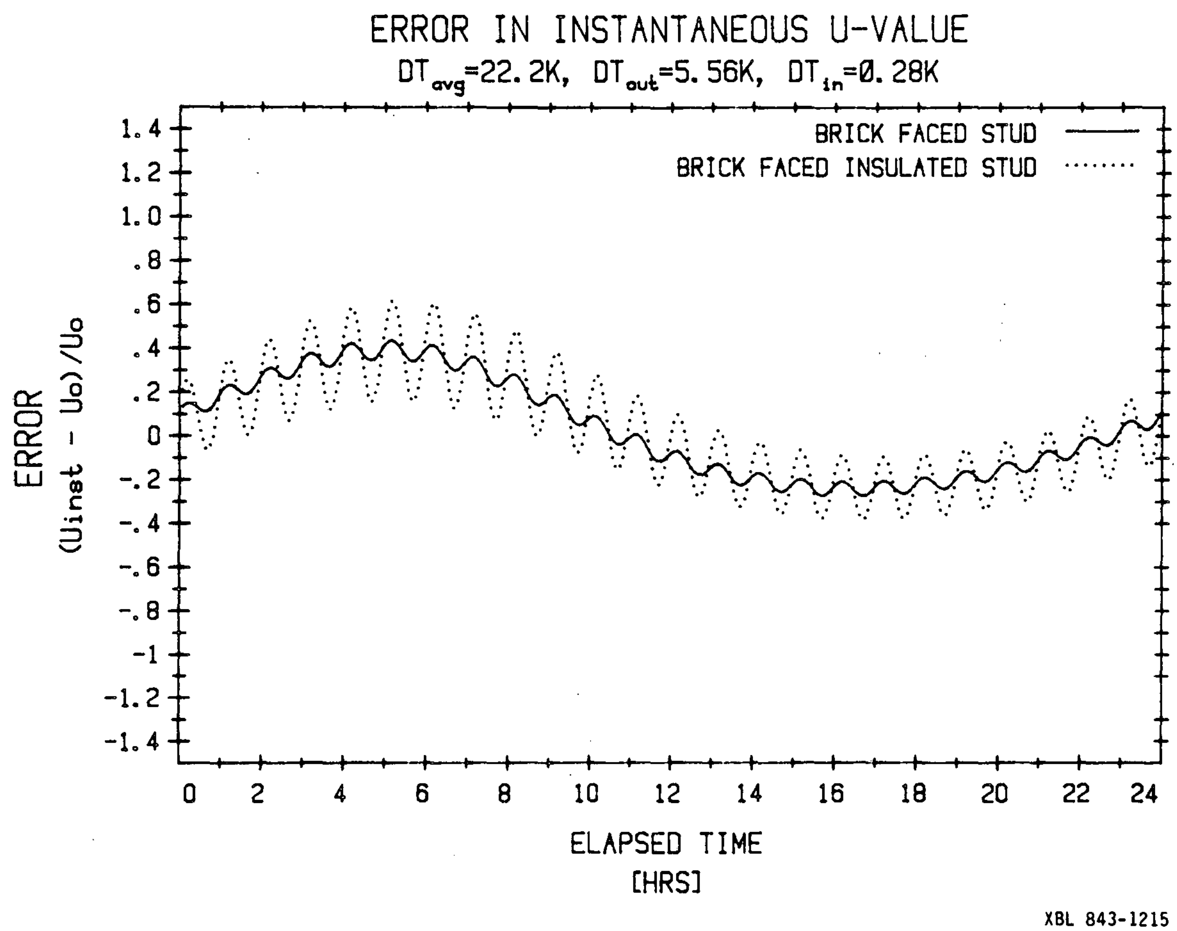

Figure 8. Fractional error in averaged U-value for insulated and uninsulated stud walls and insulated brick wall with test starting 180 $^{\circ}$ after beginning of outdoor sine wave (ΔT_{in} $=$ 1.11K, ΔT_{out} $=$ 5.56K, ΔT $=$ 22.2K).

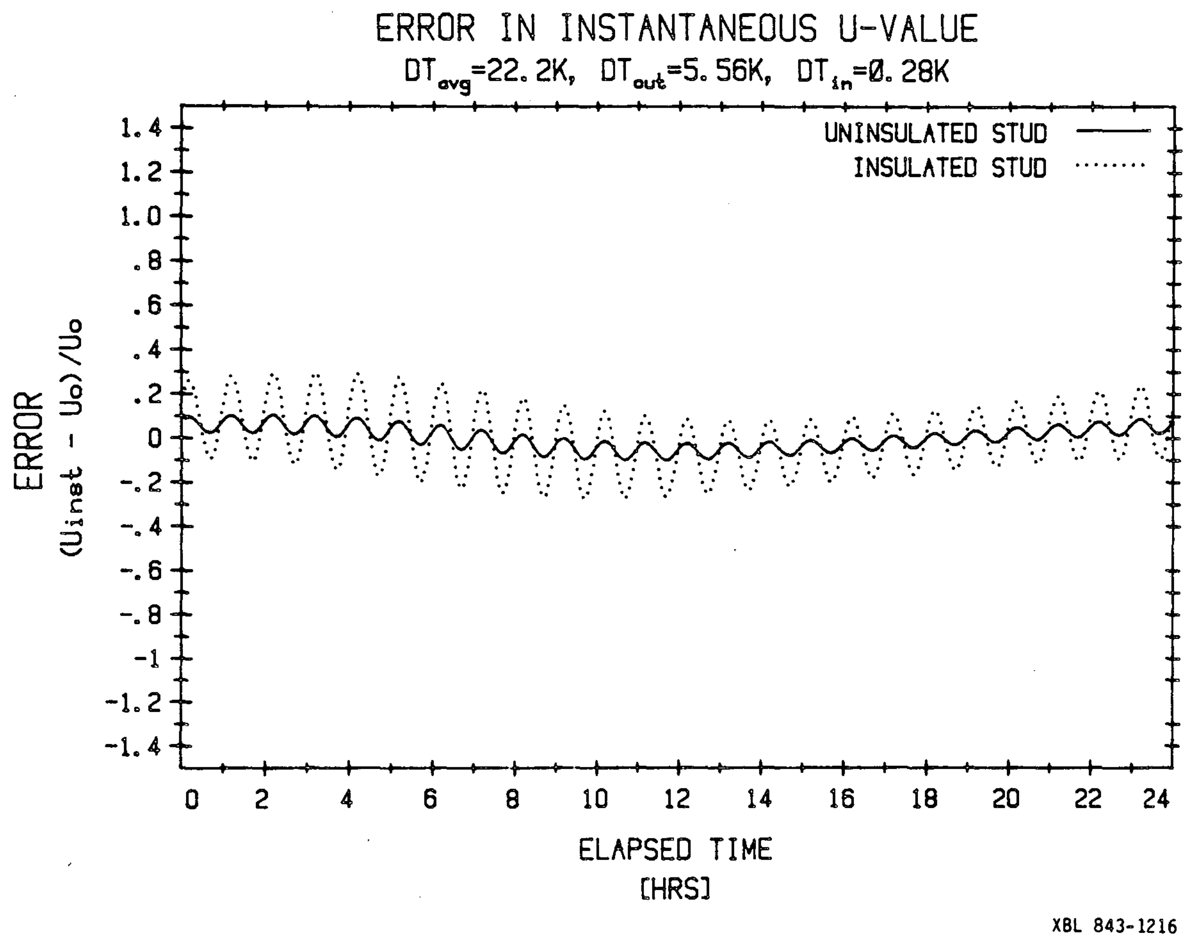

Figure 9. Fractional error in averaged U-value for insulated and uninsulated stud walls and insulated brick wall ($\Delta T_{in} = 1.11$K, $\Delta T_{out} = 5.56$K, $\Delta T = 22.2$K).

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