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Abstract

The need for information about fenestration net energy performance under realistic conditions is discussed and the method of measuring it in a "field test" on a complete building is reviewed. A detailed consideration of the energy flows entering the energy balance on a building space adjacent to a fenestration system and the effect of random measurement errors on the determination of fenestration performance is presented. Estimates of the error magnitudes are made for prototypical field tests utilizing a residential and a moderate-sized commercial building. In both cases, it is shown that these errors make it difficult to isolate the fenestration performance even for relatively low-performance windows (1-2 times the resistance of single glazing). It is concluded that whole-building measurements are not a viable means of measuring the performance of advanced fenestration systems (thermal resistance 2-10 times that of single glazing or shading coefficient less than 0.7).

Introduction

There is a wide range of questions relating to the development and utilization of energy-efficient window systems which cannot be answered without a quantitative knowledge of fenestration thermal performance under realistic conditions. Examples of these are as follows:

- (1) How should design specifications or building codes be written to optimize the energy-efficiency of fenestration systems without unnecessarily restricting architectural flexibility?
- (2) What are the most appropriate laboratory test methods to use in comparing the performance of alternative fenestration products?
- (3) Is it worthwhile to invest research effort in developing very highly insulating (for example, R-10) fenestration systems?
- (4) What are the payback period and life cycle cost for adding an exterior venetian blind to a single-glazed window?

The current method of answering questions such as these utilizes calculations of average net energy costs/benefits which are based on the U-value and shading coefficient of the fenestration. These calculations, which are often embedded in building simulation models such as DOE-2¹ or BLAST², require numerous subsidiary assumptions and approximations to specify the actual conditions to which the fenestration is subjected and the way in which these interact with the adjacent building space. The method by which fenestration U-values should be measured is somewhat controversial^{3,4,5}, and some systems, such as fenestrations with exterior venetian blinds, do not have a well-defined U-value. The validity of superposition of U-value

and shading coefficient has been experimentally verified only for simple fenestration systems^{6,7}. In short, to go from measured U-values and shading coefficients to average net energy cost/benefit requires a theory with substantial physical content. To test this theory requires the ability to measure average net energy performance of fenestration systems under conditions representative of actual use.

This immediately suggests a "field test" approach, in which the fenestration system to be studied is installed in an existing or specially-constructed building and the energy inputs, relevant weather variables, and internal temperatures are measured. Such an approach has been used to study, for example, the accuracy of computer predictions of interior temperatures and space loads.⁸⁻¹⁰ Isolating the performance of fenestration, however, involves new issues of separating the results from the building characteristics and of distinguishing the fenestration performance from thermal "noise" originating in other building subsystems.

For complete separability of the fenestration performance from the building characteristics, it is necessary to extract the instantaneous net heat flow through the fenestration from the measurements made on the building. Because of the complexity of instantaneous heat flows, it is sometimes useful to use the average net heat flow through the fenestration as a figure of merit. It represents the potential energy benefit or cost of a particular fenestration system for a given orientation, climate, and time period. By comparing this to the impact of the fenestration on the average and peak space loads and on the average building energy consumption, one can determine how well the fenestration is matched to the building space and to what extent the potential is realized.

The need for measurement accuracy follows from the way in which fenestration systems may be optimized. In general, the optimal fenestration system will have (if possible) an average net heat flow which satisfies the average heat demand of the building (e.g., energy-gaining fenestrations for a building with a heating demand). When this optimization is carried out to its fullest extent, (i.e., favorable energy flows maximized and unfavorable ones minimized) the result is a passive solar building. However, the optimization must be achieved within the constraints of local thermal and visual comfort, user demands on the building space, cost and (possibly) utilization of daylight. The result of these often conflicting requirements is frequently that average net heat flows are kept small, either because all peak heat flows are made small, or because cancellation between daytime thermal gains and nighttime losses is achieved through thermal storage. From a measurement standpoint, this requires either measuring a small signal or averaging the difference between two large signals, which immediately raises the question of accuracy and sources of error.

Fenestration Energy Flows in Sunlit Spaces

Consider a fenestration system F forming part of the envelope of a closed building space, and let an imaginary surface E be located, as shown in Fig. 1, an infinitesimal distance beneath the interior surface of the envelope of the building space (a glossary of symbols used is given in Appendix A). By assumption, E completely encloses the building space with the exception of the area of F . (This discussion applies to vertical, horizontal, or tilted fenestration systems.) We assume that E has small holes through which air may pass (leaks) or through which climate control systems may move energy, and that these are sufficiently small or geometrically

shielded so that we may neglect radiant or conducted energy transfer through them. Let W be the total energy flow rate through the fenestration, H be the total heat flow rate across the surface E , I be the rate of heat flow by (uncontrolled) air movement through the holes in E , and L_C be the rate at which heat is removed from the building space by the climate control system. (Internal loads such as lights are included in L_C .) All other energy flows are defined as positive flowing into the building space. Then if T is the mean temperature of all the mass contained inside E , C is the weighted average of the product of density and specific heat for that mass, and V is the volume of the building space, it follows from conservation of energy that

$$W(t) = CV\frac{dT}{dt} - H(t) - I(t) + L_C(t) . \quad (1)$$

It is instructive to consider some of the terms in this equation. The fenestration energy flow, W , consists of two parts, $W = Q_W + S_W$, where Q_W is the net heat flow from the innermost surface of the fenestration by conduction, convection and radiation, and S_W is the net transmitted solar energy, i.e., the transmitted visible and short-wave infrared radiation (direct and diffuse) less the transmitted outgoing radiation (from back-reflection inside the building space). For fenestrations with an inner surface which is appreciably transparent to thermal infrared radiation, the net transmitted flow is taken to be contained in Q_W . We can further subdivide Q_W into Q_C , the part which is convectively (and conductively) transferred to or from the interior air, and Q_R , the part which is radiatively transferred to or from the interior surfaces of the building space. These heat flows are indicated schematically in Fig. 1.

The envelope heat flow, H , is a purely conductive flow since the surface E was taken to lie inside the solid comprising the envelope. If we consider the heat balance on the (infinitesimal) envelope layer inside E , we find that

$$H(t) = H_C(t) - Q_R(t) - S_W(t), \quad (2)$$

where H_C is the heat flow to the air by conduction and convection. Note that because this equation has been integrated over the surface E , terms involving interreflections or radiative exchanges between different parts of the envelope do not appear.

The heat-balance equation for the air and other mass inside the building space, while similar in form to Eq. (1), is quite different in content:

$$CV \frac{dT}{dt} = H_C(t) + Q_C(t) + I(t) - L_C(t) . \quad (3)$$

It contains only Q_C , the conductive/convective part of the fenestration energy flow; the radiative and solar gain parts, Q_R and S_W , enter only partially and indirectly through H_C as determined by Eq. (2).

This discussion allows us to state clearly the dilemma of fenestration performance measurement: Fenestration energy flows are not well-localized, but are distributed by a complex radiative and convective equilibrium process over the entire adjacent building space. To localize and simplify the energy flow processes (as is done in laboratory-scale measurement) one must replace this equilibrium with a different one, and one is unable to calculate reliably the effects of this replacement because of the complexity of

the radiative-convective problem. In order to determine the energy costs or benefits for a fenestration system in a particular building, one needs to determine the effect on $L_C(t)$ averaged over time. However, if one directly measures this quantity the result is characteristic as much of the particular building space as of the fenestration, because of the indirect and partial manner in which the radiative and solar heat flows enter Eq.(3). In order to extract the fenestration performance under realistic conditions from a particular test situation one must determine all three components of the fenestration energy flow; yet each of the above equations contains at least one quantity which is very difficult to measure (H in Eqns. (1) and (2), H_C in Eq.(3)) in addition to the fenestration energy flows.

Error Analysis

Let us consider the effect of finite accuracy in measuring the terms on the right-hand side of Eq.(1). Assuming that the errors are random and uncorrelated, the fractional error in the fenestration energy flow is given by

$$\frac{\delta W}{W} = \left\{ \left[\frac{\delta(CV \frac{dT}{dt})}{W} \right]^2 + \left[\frac{H}{W} \left(\frac{\delta H}{H} \right) \right]^2 + \left[\frac{I}{W} \left(\frac{\delta I}{I} \right) \right]^2 + \left[\frac{L_C}{W} \left(\frac{\delta L_C}{L_C} \right) \right]^2 \right\}^{1/2}, \quad (4)$$

where δW denotes the error in W , and similarly for the other quantities in the equation. The terms on the right-hand side of this equation arise respectively from the heat capacity of the air (etc.) inside the building space, envelope heat conduction, infiltration, and the climate-control

system.

In order to estimate the magnitudes of the various terms in Eq.(4), we consider a simple model of the building space. We first parameterize the fenestration heat flows using (for nighttime heat loss) U_0 , the U-value for single glazing, a dimensionless thermal resistance, R , (defined as U_0/U for a fenestration of thermal transmittance U) the fenestration area, F , and the inside-outside air temperature difference, ΔT :

$$W = -\frac{F}{R}U_0\Delta T . \quad (5a)$$

Similarly, for the daytime heat flow we use the shading coefficient, B , the heat flux through single glazing (solar heat gain factor), J_0 , and the fenestration area receiving direct sunlight, F' :

$$W = BJ_0F' . \quad (5b)$$

For simplicity, we neglect the comparatively small $U\Delta T$ term when the fenestration is in the solar gain mode. Nighttime envelope heat flows are analogously defined, neglecting the effects of thermal lags:

$$H = -E\frac{U_0}{R_E}\Delta T , \quad (6a)$$

where E is the total envelope area excluding the fenestration and R_E is the dimensionless envelope resistance. We assume that in the daytime the envelope heat flow is dominated by the fenestration heat gain, a fraction, α , of which flows into the envelope rather than into the air of the

building space:

$$H = -\alpha B J_0 F' . \quad (6b)$$

Infiltration is parameterized using the air exchange rate per unit time, a :

$$I = -CVa\Delta T . \quad (7)$$

Finally, the heat transferred by the climate control system is taken at nighttime to be

$$L_C = \xi(W+H) + I + z_I G , \quad (8a)$$

where the parameter ξ is included to account for thermal lags, z_I is the internal load per unit floor area (from lights, etc.), and G is the gross floor area. The daytime space load is taken to be

$$L_C = (1-\alpha)BJ_0F' + \xi\Delta T_S \left(\frac{U_0}{R_E}\right)E + z_I G . \quad (8b)$$

Here ΔT_S is the temperature difference based on the sol-air temperature and ξ is the fraction of the envelope illuminated by sunlight.

Because the mean temperature of the air (and other thermal mass) inside the building space varies with time and is sampled only at finite intervals, there is an uncertainty associated with its heat content given by

$$\delta(CV\frac{dT}{dt}) = \frac{\sqrt{2CV}\delta T_A}{\tau} , \quad (9)$$

where τ is the sampling period and δT_A is the RMS error for an individual measurement of T.

With these equations it is possible to calculate the individual terms in Eq. (4), which are shown in Table 1. These are then added in quadrature to obtain $\delta W/W$. It can be seen that the errors contain ratios of building volume to fenestration area and envelope area to fenestration area. The relative magnitudes of errors from the different sources will therefore change with differing building size.

Error Estimates for Sample Buildings

Using the formulas in Table 1, we make numeric estimates for two prototypical buildings, a small one and a large one. For the small building we consider a 1500 square foot one-story residence with a glazing area equal to 20% of the floor area and half of it on the south side. For the large building we consider a seven-story office building with the dimensions of the Norris-Cotton Building,¹¹ but with a glazing area equal to 30% of the exterior wall area. These two examples are chosen to represent the range of buildings in which one might do field tests of fenestration performance.

Each building is assumed to face due south, and daytime estimates are made for a clear winter day at noontime. Numerical values of $U_0 = 5.7\text{W/m}^2\text{K}$ and $J_0 = 800\text{W/m}^2$ are assumed. The latter corresponds to the solar heat gain for a south-facing window at noon on Jan. 21 at 40° N latitude. The inside-outside temperature difference is assumed to be 20° C, and the solar air temperature is assumed to be 30° C above the outside air temperature. Both buildings are assumed to have a ventilation/infiltration rate of 0.75 air changes/hour. Other assumptions are $R_E = 20$, $V/F = 12.2\text{m}$, and

$E/F = 18.5$ for the small building; $R_E = 17$, $V/F = 33m$, $E/F = 5$, $G/F = 58.3$ and $F'/F = 0.25$ for the large building. Internal heat sources are assumed to be zero for the small building and $z_I = 8.0W/m^2$ ($0.75 W/ft^2$) for the large one. Indoor air temperature measurements are assumed to be recorded hourly with an RMS error of $2^\circ C / \sqrt{2}$. It is also assumed that $\alpha = 0.4$.

The resulting error estimates are shown in Table 2. An example of how these estimates are used to derive measurement accuracy requirements in the following sections is given in Appendix B.

Limitations of Field Measurements

Examination of Table 2 yields some interesting insights into the usefulness of field measurements for determining fenestration performance. If we consider first the large building in the nighttime heating mode, Table 2 indicates that the HVAC system performance, air infiltration, internal temperature, and envelope heat flow may all be important sources of error. If we assume that we require an accuracy of at least 10% for the window heat flow, Table 2 implies (by the calculation outlined in Appendix B) that to measure the nighttime heat loss through single glazing one would need to measure the HVAC system performance (L_c) to 3%, the infiltration rate to 3%, the envelope heat flow to 33% and the mean internal temperature to $0.4^\circ C$. For daytime measurements one would need to measure L_c to 2%, infiltration to 6%, envelope heat flow to 13% and mean internal temperature to $0.6^\circ C$. Attaining these accuracies in a large building with a complex HVAC system would be exceedingly difficult, to say the least.

Attaining the required accuracy on internal temperature would be particularly difficult, since it is the effective mean temperature of all the

material inside E which must be determined. This requires accurate knowledge of both the temperature and thermal capacity of everything inside the surface that we have denoted E. For a large building considered as a single zone, this includes interior partitions, furnishings, etc. In Table 2, the space is assumed to contain only air; when these other masses are included, the internal heat content can easily become the dominant error source. If one restricts attention to a sub-zone to make this problem more tractable, then new uncertainties are introduced by heat and mass exchanges between zones, which were neglected in this analysis.

In short, measurement of heat transfer through unshaded single glazing turns out to be a difficult undertaking in a large building. It would clearly be a poor place to attempt measurements for systems with R or 1/B in the range 2 - 10.

In the case of the one-story residence, use of electric heating makes it possible to attain a very small value for $(\delta L_C/L_C)$, so that errors from this source may be neglected. (This may not be the case for cooling, however.) Table 2 then indicates that the dominant error source is envelope heat conduction, followed closely by air infiltration. To measure the heat loss through single glazing requires that the envelope heat flow be known to 5% and the air infiltration be known to 9%. The latter requirement is certainly attainable, although it would require continuous monitoring of the air infiltration rate. Attaining the former is more difficult, since the accuracy requirement is on the heat flow integrated over the entire exterior envelope (excluding the fenestration) rather than on the localized heat flux. This is a formidable measurement problem, since it must take account of inhomogeneities in construction and variations in material

properties. Uncertainties from these sources are notoriously difficult to eliminate in an existing building.

Two additional considerations not included in this analysis add to the difficulty of using field testing as a method of determining fenestration performance. First, in reality one must know dynamic envelope properties rather than the static ones used in the simplified analysis. Second, measurements in a building will mix the contributions of fenestrations in different orientations performing in different modes, for example, south-facing in a direct gain mode and north-facing in a diffuse gain/thermal loss mode. Attempting to separate these by zoning re-introduces the problems of interzone energy transfers.

Conclusions

We conclude that isolation of the thermal energy flows through fenestration in an existing building, built with standard construction techniques, is difficult even for unshaded single glazing and rapidly becomes unfeasible as R increases or B decreases. The analysis presented here indicates that one would be doing well to measure even unshaded single glazing performance to an accuracy of 10% in a large building. For a small residence the practical limit is probably somewhere between 1 and 2 for R and between 1 and 0.7 for shading coefficient.

This indicates that field tests are best adapted to the demonstration of successful use of fenestrations of known performance or to the discovery of qualitative indications of problem areas (e.g., condensation, discomfort, glare), rather than to the quantitative study of fenestration performance. In another publication, we show that extension of the "passive test cell"

approach results in a measurement facility that is expected to produce accurate and realistic performance measurements.¹²

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Appendix A: Glossary of Symbols

Term	Definition
B	Shading coefficient of the fenestration.
C	Volume-weighted average of ρC_p for all thermal mass contained in E.
C_p	Specific heat at constant pressure.
E	Denotes an imaginary surface lying just below the physical inner surface of the exterior envelope of V; also, the area of that surface.
f	Fluid flow rate (volumetric).
F	Area of fenestration.
F'	Fenestration area illuminated by sunlight
G	Gross floor area of the building in question.
H	Envelope heat flow across surface E.
H_C	Heat flow by conduction/convection between the exterior envelope and the air inside E.
I	Heat transfer by infiltration into V.
J_o	A reference solar intensity (W/m^2) incident on the structure and transmitted through single glazing.
L_C	Rate of removal of energy from building space by climate-control system (space load). Negative L_C is heating load.

Term	Definition
Q_C	Conductive/convective part of Q_w .
Q_R	Radiative part of Q_w .
Q_W	Heat leaving the innermost surface of the fenestration by conduction, convection, and (long-wave) radiation.
R	Dimensionless thermal resistance of fenestration, defined as the ratio of thermal resistance to that of single glazing.
R_E	Dimensionless thermal resistance of envelope, defined as the ratio of the envelope thermal resistance to that of single glazing.
S_W	Energy leaving the innermost surface of the fenestration as radiation in the visible and solar infrared bands.
T	Temperature.
T_A	Weighted mean temperature of all material inside E.
T_i	Inlet fluid temperature.
T_e	Exit fluid temperature
t	Time.
U	Thermal transmittance.
U_0	Thermal transmittance of single glazing.
V	Volume enclosed by surface E.
W	Energy flow rate through the fenestration.

Term	Definition
z_i	Internal load per unit floor area.
α	Fraction of solar energy incident on interior building envelope surface that flows across E.
δ	Operator denoting "measurement uncertainty in"; e.g., δW denotes measurement uncertainty in W.
ΔT	Difference between interior and exterior air temperatures.
ΔT_G	Difference between interior and guard air temperatures.
ΔT_S	Difference between interior air temperature and exterior sol-air temperature.
ϵ	Symbol used to denote an infinitesimal difference.
ρ	Density.
ζ	Parameter accounting for thermal lags between fenestration/envelope heat flows and space load.
ξ	Fraction of exterior envelope illuminated by sunlight.
t	Data sampling time period.

Appendix B. Derivation of Measurement Accuracy Requirements From the Tables

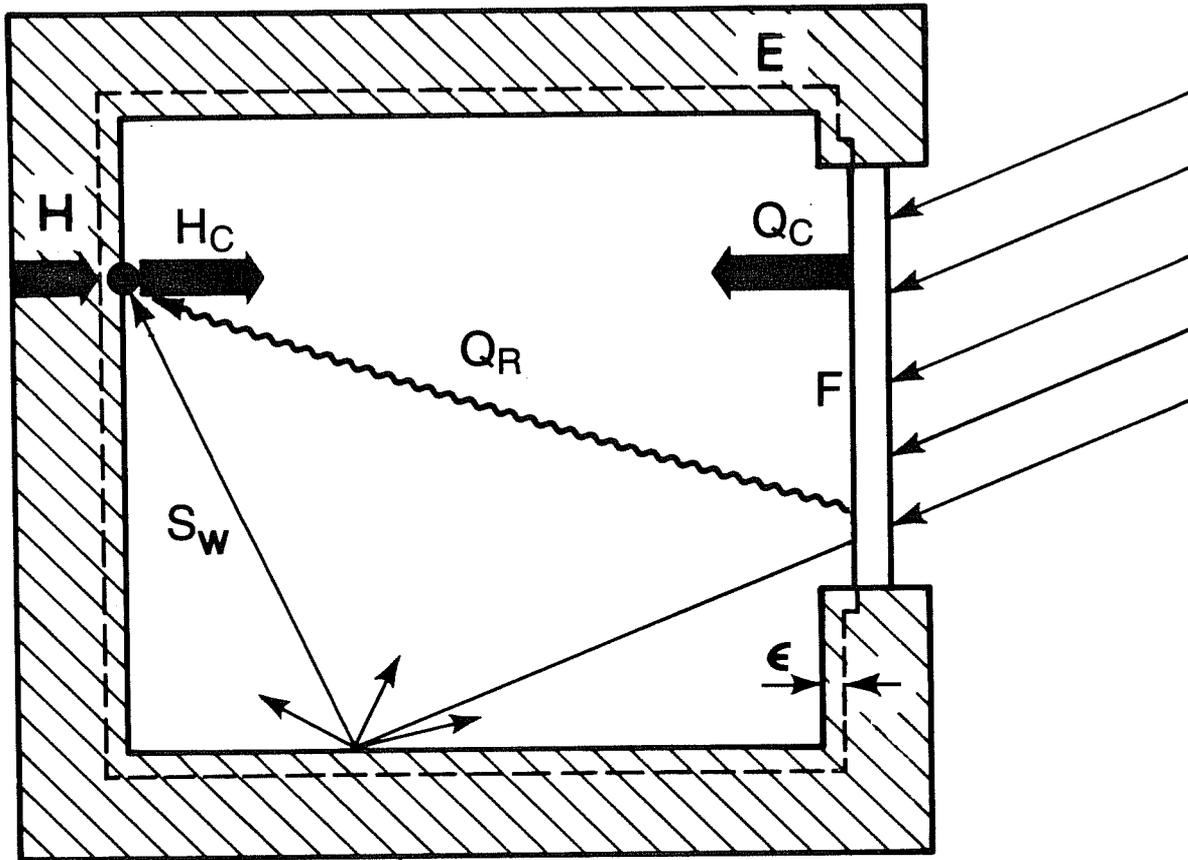
We discuss here the details of deriving accuracy requirements from the tables. As an example, we consider the derivation of our statements about the seven-story office building in the heating mode. Substitution into Table 1 of the values given in the text for V/F , C , δT_A , U_o , τ , ΔT , E/F , a, ζ , G/F and z_I yields the entries in the nighttime column of Table 2. For single glazing $R = 1$, and addition of the column entries in quadrature yields $\delta W/W$:

$$\begin{aligned} \left(\frac{\delta W}{W}\right)^2 &= (0.14)^2 (\delta T_A)^2 + (0.15)^2 \left(\frac{\delta H}{H}\right)^2 \\ &+ (1.5)^2 \left(\frac{\delta a}{a}\right)^2 + (-1.8)^2 \left(\frac{\delta L_C}{L_C}\right)^2 \end{aligned}$$

If we require that the overall accuracy be $\delta W/W \leq 10\%$ and allow an equal contribution to the uncertainty from each of the four independent sources of error, then, for example:

$$(2.0) \left(\frac{\delta L_C}{L_C}\right) \leq \frac{0.1}{2},$$

yielding $(\delta L_C/L_C) \leq 3\%$. The same requirement applied to each of the other terms in the sum yields $(\delta a/a) \leq 3\%$, $(\delta H/H) \leq 33\%$ and $\delta T_A \leq 0.4^\circ\text{C}$, as given in the text. Of course, if the measured accuracy on one of the variables (H , L_C , etc.) is much better than the requirement, then that term may be dropped from the sum and the uncertainty shared equally between the remaining terms. The limit of this process is obviously the case where a single error dominates all the others.



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Figure 1. Components of Fenestration Energy Flow. Boundary E of control volume is located an infinitesimal distance ϵ inside wall surface and completely encloses volume except for fenestration F. Long-wave thermal radiation is indicated by wavy arrow, conductive/convective heat transmission by heavy arrows and solar-optical radiation by light arrows. The absorbed solar radiation S_w is shown as first having undergone diffuse reflection from an interior surface. All heat flows are area-integrated.

Table 1. Error Sources in Fenestration Heat Flow Measurement.

Contribution to $\delta W/W$	
Source	(a) Nighttime
Space Heat Content	$R \left(\frac{V}{F}\right) \frac{\sqrt{2} c \delta T_A}{U_0 \tau \Delta T}$
Envelope Conduction	$\frac{R}{R_E} \left(\frac{E}{F}\right) \left(\frac{\delta H}{H}\right)$
Infiltration	$R \left(\frac{V}{F}\right) \frac{Ca}{U_0} \left(\frac{\delta a}{a}\right)$
Space Load	$\left\{ \xi \left[1 + \frac{H}{W} \right] + \frac{I}{W} - R \left(\frac{G}{F}\right) \frac{z_I}{U_0 \Delta T} \right\} \left(\frac{\delta L_C}{L_C}\right)$
Source	(b) Daytime
Space Heat Content	$\left(\frac{1}{B}\right) \left(\frac{V}{F}\right) \frac{\sqrt{2} c v \delta T_A}{J_0 \tau}$
Envelope Conduction	$\alpha \left(\frac{\delta H}{H}\right)$
Infiltration	$\left(\frac{1}{B}\right) \left(\frac{V}{F}\right) \frac{Ca \Delta T}{J_0} \left(\frac{\delta a}{a}\right)$
Space Load	$\left\{ (1-\alpha) + \frac{I}{W} + \left(\frac{1}{B}\right) \xi \left(\frac{E}{F}\right) \frac{\Delta T_S U_0}{R_E J_0} + \left(\frac{1}{B}\right) \left(\frac{G}{F}\right) \frac{z_I}{J_0} \right\} \left(\frac{\delta L_C}{L_C}\right)$

Table 2. Error Source Contributions to $\delta W/W$ in Two Sample Buildings

(a) Single-Story Residence		
Source	Nighttime	Daytime
Heat Content	$0.051 R \delta T_A$	$0.014 \left(\frac{1}{B}\right) \delta T_A$
Envelope	$0.92 R \left(\frac{\delta H}{H}\right)$	$0.4 \left(\frac{\delta H}{H}\right)$
Infiltration	$0.54 R \left(\frac{\delta a}{a}\right)$	$0.15 \left(\frac{1}{B}\right) \left(\frac{\delta a}{a}\right)$
Climate-control System	$(1 + 1.5 R) \left(\frac{\delta L_C}{L_C}\right)$	$[0.6 - 0.12 \left(\frac{1}{B}\right)] \left(\frac{\delta L_C}{L_C}\right)$
(b) Seven-Story Office Building		
Source	Nighttime	Daytime
Heat Content	$0.14 R \delta T_A$	$0.078 \left(\frac{1}{B}\right) \delta T_A$
Envelope	$0.29 R \left(\frac{\delta H}{H}\right)$	$0.4 \left(\frac{\delta H}{H}\right)$
Infiltration	$1.5 R \left(\frac{\delta a}{a}\right)$	$0.83 \left(\frac{1}{B}\right) \left(\frac{\delta a}{a}\right)$
Climate-control System	$[0.5 - 2.5 R] \left(\frac{\delta L_C}{L_C}\right)$	$[0.6 + 1.5 \left(\frac{1}{B}\right)] \left(\frac{\delta L_C}{L_C}\right)$