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METHOD TO DIAGNOSE WINDOW FAILURES AND MEASURE U-FACTORS ON SITE

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Windows are an essential part of buildings due to the requirement for natural light, views, and fresh air. However, windows are thermally the weakest bridge in a building due to their high thermal conductivity. Therefore, window U-factor (thermal transmittance) information is indispensable in calculating the overall energy load of a building. U-factors of windows, however, are difficult to obtain on-site because the label mounted on a window exhibiting its U-factor is typically removed after its installation. Further, it is almost impossible to detect any of a variety of window failures, such as the loss of insulating gases, leaky or cracked windows, and localized air leakage, simply by visual inspection. In this study, a novel technique to measure window U-factor in the field by measuring four temperatures (interior and exterior air temperatures, and interior and exterior window surface temperatures) is presented. Experimental and field tests on various types of full-scale windows have been performed to obtain their field-measured U-factors. Experimental results show that the field-measured U-factors match within 8% of the rated U-factors of the windows. Several assemblies combining storm windows with single- or double-pane windows were tested and the combined U-factors of the assemblies were measured and the readings were compared with the U-factors estimated by ASHRAE. In another test, argon from a double-pane window was removed deliberately and results confirmed the leakage using the proposed method. In addition, field tests at five different buildings were performed and the comparison between measured and rated (or estimated) U-factors is presented.

Keywords: ***Window U-factor; Infrared thermometry; Window failure; Heat transfer***

INTRODUCTION

Windows are important in buildings; however, they are a source of substantial energy loss. In cold climate zones such as Northern states of the United States as well as several European and Asian countries, considerable energy is consumed in the form of heating in order to achieve thermal comfort in buildings. In China, a survey of energy consumption was performed in two major cities and the results show that 60% of the total heat loss occurred through doors and windows (Yang, Liu, and Zhao 2004). In Europe, like Germany where the concept of passive houses began in 1991, efforts are being made to build passive houses using similar standards (Rotar and Badescu 2011). In the United States, approximately 41% of the total energy (approximately 40,000 trillion Btu [11.7 trillion kWhr]) is consumed in residential and commercial buildings (U.S. energy information

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administration/Annual energy review 2010) and out of the energy consumed in residential and commercial building, approximately 50% is used for space heating. Typically, windows represent 10–30% or more of the area of the building envelope and, because of their high thermal conductivities, abundant heat is lost through them.

The overall heat transfer coefficient or thermal transmittance (U-factor) determines heat loss through a window. This is the reciprocal of the R-value ($U = 1/R$). Determining the U-factor of windows requires detailed knowledge of the thermal properties of their different components, because window U-factors are different for the center-of-glazing area, edge-of-glazing area, and frame. Thermal transmittance depends primarily on number of panes and type of framing material of windows. Double-pane windows are the most common type of windows in the United States. However, a recent survey indicates that 43% of the total windows installed in the residential buildings are single-pane windows (Klems 2003). In the United States, the National Fenestration Rating Council (NFRC), in conjunction with the American Society for Testing and Materials (ASTM), established a procedure to measure the U-factor of windows for labeling of energy performance of fenestration products (ASTM-1199 2000; NFRC-100 2004; NFRC-102 2004; ASTM-1363 2005).

Thermal transmittance through a window has been of great interest to researchers for over five decades. Arasteh, Mathis, and DuPont (1992) provided NFRC testing procedure, which has been modified a few times since then (NFRC-100 2004; NFRC-102 2004). Rubin (1982) presented a model to predict thermal transmittance through the glazed area of different types of windows and compared the results with experimental measurements. Drumheller, Kohler, and Minen (2007) investigated the thermal performance of single-pane windows with low-E storm windows and with clear glass storm windows. This research showed that the overall heating load reduced by 13% with clear glass storm windows and by 21% with low-E storm windows. Aydin (2000) showed that the heat loss through a double-pane window is a function of the thickness of the air layer between the panes, and optimizing the thickness of the air gap can minimize heat transfer through a double-pane window. A numerical study to calculate heat transfer through a double-pane window was performed by Korpela, Lee, and Drummond (1982), in which the description of convection flow was presented when the Rayleigh number and cavity aspect ratio are high. The heat transfer through a double-pane window with a screen and siphon was performed numerically by Medved and Novak (1998) using a commercially available CFD package, PHOENICS. Abodahab and Muneer (1998) performed Q4 experiments and modeling to analyze longitudinal temperature variation of double-pane windows and also presented a model to calculate temperatures along the height of the windows. More recently, Majali, Prasad, and Bhat (2008) developed software for transient periodic heat transfer analysis of non air-conditioned multizone buildings, which takes into account the effects of heat fluxes through various facades of buildings, that is, windows.

A few studies have been focused on the requirement of developing low-conductance window frames, because window frames typically represent an important portion of overall window area and because frames can be even more conductive than window glazing. The influence of air leakage on heat transfer in window frames with internal cavities was studied by Halle et al. (1998). Carpenter and McGowan (1989) used various frames in their study and showed the effect of frames on window U-factors. Gustavsen et al. (2008) presented an extensive review of literature on the methods of modeling heat transfer through window frames and concluded that for low-conductance frames, existing ISO standards are not sufficiently correct for precisely evaluating heat transfer. Sekhar and Toon (1998) studied the benefits derived from a double-pane "smart" window where one pane was made of a high-performance heat-reflective glass and the other had a low-E coating. A comparison of its impact on cooling load, energy consumption, and energy savings relative to other forms of glazing was presented.

Window U-factor information is instrumental in many aspects. In order to determine the total heat load in a commercial or residential building, windows' U-factors are required, which is difficult to obtain for two reasons. First, the labels mounted on windows showing their U-factors are typically removed after their installation, and second, U-factors vary with time as the result of a variety of failures, such as the loss of insulating gases, leaky or cracked windows, and localized air leakage which evolve with time, and these affect the U-factors significantly. In this paper, a novel method to measure window U-factor is presented. This method is rapid, inexpensive, and easy to use. The presented method can be used for measuring U-factors of new windows as well as old windows already installed in buildings.

METHODOLOGY

As stated earlier, in the United States, NFRC implements a national rating system for energy performance of fenestration products that employs both computer simulation and physical testing to determine U-factors. In these procedures, NFRC uses specific test conditions (i.e., interior air temperature is set at 70°F/21.1°C and the exterior air temperature is set at 0°F/–17.8°C). The proposed method can be employed to measure U-factors not only for new and old windows but at a wide range of exterior and interior air temperatures. The measured U-factor (U_M) of the window assembly is calculated using the following equation, by definition:

$$U_M = \frac{1}{\left(\frac{1}{h_h} + \frac{1}{h_c} + \frac{1}{U_L}\right)}, \tag{1}$$

where h_h and h_c are the interior and exterior heat film coefficients, respectively; h_h can be calculated using the following equation (as present in NFRC-102 2004):

$$\begin{aligned} h_h &= \left[0.30 \times \left(\frac{T_3 - T_1}{L}\right)^{0.25} + \sigma e \left(\frac{(T_3 + 459.67)^4 - (T_1 + 459.67)^4}{T_3 - T_1}\right)\right] \text{(I.P.) or} \\ h_h &= \left[1.46 \times \left(\frac{T_3 - T_1}{L}\right)^{0.25} + \sigma e \left(\frac{(T_3 + 273.16)^4 - (T_1 + 273.16)^4}{T_3 - T_1}\right)\right] \text{(S.I.).} \end{aligned} \tag{2}$$

Yazdanian and Klems (1994) presented equations which have been used in this study for calculating exterior heat film coefficient for smooth and rough surfaces.

For smooth surfaces, $h_c = 1.445 + 0.205\ V - 7.68 \times 10^{-4}\ V^2$ (I.P.),

for rough surfaces, $h_c = 2.04 + 0.355\ V$ (I.P.),

where V is air velocity in ft/sec.

Or (3)

for smooth surfaces, $h_c = 8.23 + 3.83\ V - 0.047 \times 10^{-4}\ V^2$ (S.I.),

for rough surfaces, $h_c = 11.58 + 6.806\ V$ (S.I.),

where V is air velocity in m/sec.

U_L, in Equation 1, is the heat transfer coefficient of the window assembly alone without air film coefficients. Assuming steady-state condition, homogeneous T_1, T_2, and T_3, and neglecting edge and radiation effects, U_L can be derived using the following set of equations:

$$\text{Heat lost through the window assembly} = U_L \times A \times (T_1 - T_2). \tag{4}$$

$$\text{Similarly, heat lost from the room to the indoor surface of the window} = h_h \times A \times (T_3 - T_1). \tag{5}$$

By conservation of energy, these two heat loss rates (Equations 4 and 5) must be equal:

$$U_L \times A \times (T_1 - T_2) = h_h \times A \times (T_3 - T_1).$$

Using Equation 2 for h_h,

$$U_L = \left[0.30 \times \left(\frac{T_3 - T_1}{L}\right)^{0.25} + \sigma e \left(\frac{(T_3 + 459.67)^4 - (T_1 + 459.67)^4}{T_3 - T_1}\right)\right] \times \frac{T_3 - T_1}{T_1 - T_2} \quad \text{(I.P.)},$$

or (6)

$$U_L = \left[1.46 \times \left(\frac{T_3 - T_1}{L}\right)^{0.25} + \sigma e \left(\frac{(T_3 + 273.16)^4 - (T_1 + 273.16)^4}{T_3 - T_1}\right)\right] \times \frac{T_3 - T_1}{T_1 - T_2} \quad \text{(S.I.)}.$$

Using the Equations 1–3 and 6, U_M can be expressed as

$$\left.\begin{array}{l}
U_M = \dfrac{1}{\dfrac{1}{h_c} + \dfrac{1}{0.30 \times \left(\dfrac{T_3 - T_1}{L}\right)^{0.25} + \sigma e \left(\dfrac{(T_3 + 459.67)^4 - (T_1 + 459.67)^4}{T_3 - T_1}\right)} \times \left(\dfrac{T_3 - T_2}{T_3 - T_1}\right)} \quad \text{(I.P.)} \\[4ex]
\text{or} \\[4ex]
U_M = \dfrac{1}{\dfrac{1}{h_c} + \dfrac{1}{1.46 \times \left(\dfrac{T_3 - T_1}{L}\right)^{0.25} + \sigma e \left(\dfrac{(T_3 + 273.16)^4 - (T_1 + 273.16)^4}{T_3 - T_1}\right)} \times \left(\dfrac{T_3 - T_2}{T_3 - T_1}\right)} \quad \text{(S.I.).}
\end{array}\right\} \tag{7}$$

It can be seen in Equation 7 that the temperatures and surface film coefficients affect the U_M.

EXPERIMENTAL SET-UP, INSTRUMENTATION, AND FIELD TESTING STRATEGY

A thermal box was fabricated for determining thermal transmittance (U-factor) of several types of windows, using the proposed method. A schematic of the thermal box is presented in Figure 1. The thermal box consists of a warm chamber and a cold chamber, a test window, a refrigerator unit in the cold chamber (evaporator section of split refrigeration system), and a heater in the warm chamber. The production of the thermal box was divided into four steps: (1) assembly, (2) front panel attachment, (3) door installation, and (4) installation of internal equipment. The outside walls of the chamber were insulated with rigid insulation panels (R-value = 17.5 hr·ft^2·°F/[Btu] or 3.08 m^2·K/W) to prevent substantial heat transfer through the walls of the thermal box. A split refrigeration unit (evaporator and condensing unit) was installed in the cold chamber, which was capable of maintaining the temperature in the cold chamber as low as –20°F (–28.88°C).

Accurate and reliable instantaneous temperature and velocity measurements with rapid response from the transducers are important (Varshney and Panigrahi 2005; Cramer et al. 2006; Varshney et al. 2011). In all lab experiments, air temperature in the cold chamber was measured by a T-type thermocouple situated 1 ft (0.3 m) away from the test window surface and 5 ft (1.52 m) above the floor. On the warm side of the test specimen, the same thermocouple arrangement was used to measure the air temperature. Air temperature in the warm chamber was set at 70°F (21.11°C). A datalogger (Campbell Scientific model CR1000), which has eight differential channels in conjunction with a 32 differential channel relay multiplexer (Campbell Scientific model AM 16/32B), was used to acquire instantaneous temperature signals at 1 Hz. In all lab experiments, window surface temperatures (T_1, T_2) were also measured by T-type surface-mounted thermocouples.

In field testing, a highly accurate infrared (IR) thermometer (Fluke, model 568) was used, which could measure the temperature of a nonreflective surface from –40°F to 1472°F (–40°C to 800°C). The accuracy of the IR thermometer was ±1% and the resolution was 0.1°F (0.1°C). The IR thermometer was tested thoroughly before it was used in the field for temperature measurements. It should be noted that an IR thermometer does not actually measure the temperature of the exact spot where the single-point laser beam

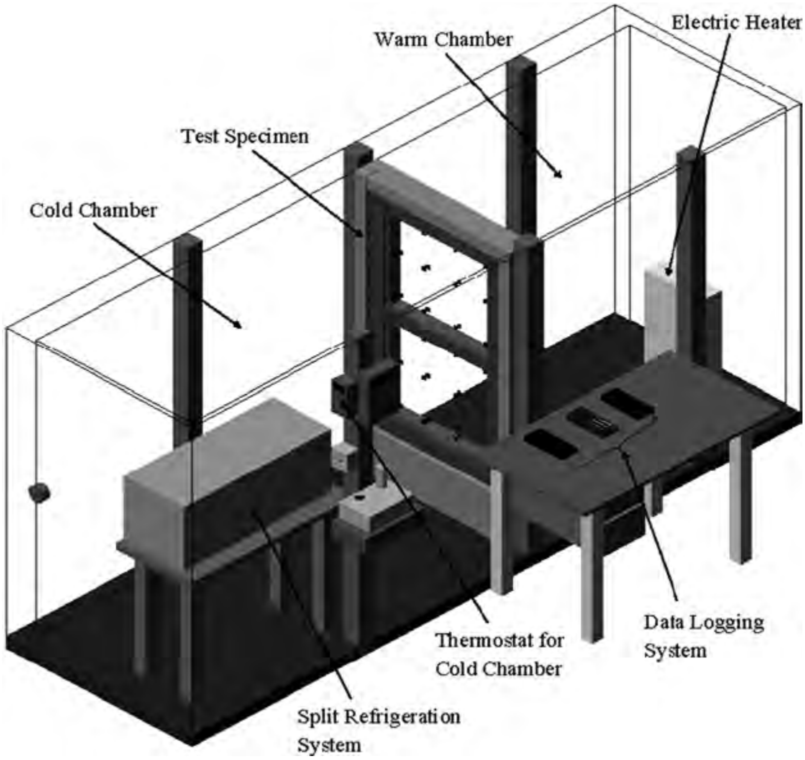

Figure 1 Schematic representation of the test facility for indirectly measuring. the U-factor of a window.

visually “hits” the surface; instead it gives an average temperature of the area surrounding the beam, which is determined by distance to measurement spot size ratio. The farther away from the object being measured, the larger the area averaged. To verify IR thermometer readings at various temperatures, the temperature in the cold chamber was varied from 0°F (–17.78°C) to 65°F (18.33°C), while the temperature in the warm chamber was maintained at 70°F (21.11°C). In order to eliminate reflective effects, self-adhesive black electric tape of 1 inch $\times$ 1 inch (2.54 cm $\times$ 2.54 cm) size, was used on the window surfaces and then the IR thermometer was used to measure the surface temperatures in the middle of the tape. IR thermometer readings at various temperatures in the cold chamber were recorded and compared with the readings obtained using a surface-mounted T-type thermocouple. The temperatures obtained during the test by both the contact T-type thermocouple and the noncontact IR thermometer matched closely. This shows that noncontact IR thermometry is valid for measuring window surface temperature in both hot and cold environments. Temperature readings using IR thermometers were taken on different color papers to assess the influence of the color on the readings. It was observed that the temperature readings measured by the IR thermometer did not change with the color of the paper (0.2°F [0.1°C]). In addition, the distance between the IR thermometer and the window surface was also varied from 0.5 ft (0.15 m) to 3 ft (0.9 m) in increments of 0.5 ft (0.15 m), to find the optimum distance for accurate measurements. Temperature readings taken from IR thermometers from various distances were close to each other within this range. In order to standardize on a distance, 1 ft (0.3 m) was selected, because the IR thermometer measures an area that gets larger as the thermometer is farther from the surface and, at the same time, if the readings are taken too close to the surface, the heat radiating from the hand holding the thermometer can affect the results.

U-factors at various locations on the windows were measured using Equation 7. Results showed that the U-factors measured near the bottom corners of the glass were higher than the rated U-factor (U_R), whereas the U-factors measured near the center of the glass were lower than the U_R of the window. Several surface-mounted thermocouples were used to measure local U-factors between the corner and the center of the glass at various locations. It was found that the U-factor measured at $X = 1.25$ inch (0.032 m) and $Y = 1.25$ inch (0.032 m) from a bottom corner and toward the center of the glass was very close to the $\mathrm{U_R}$ of the windows (Figure 2). X and Y are the horizontal and the vertical distances from the bottom corner and toward the center of the glass, respectively. This point was used to measure interior (T_1) and exterior (T_2) window surface temperatures for all the windows used for both lab and field testing. Hereafter, this point will be referred as a *point of measurement*.

In field testing, to eliminate reflective effects, custom-built 2.5 inch (0.064 m) square, nonreflective, self-adhesive stickers with a 0.25 inch (0.64 cm) diameter black target in the middle were mounted on the bottom corner of the window surfaces. Once they came to steady state (approximately 2 minutes), the IR thermometer was used to measure window surface temperatures (Figure 2). A nonreflective custom flag (2.5 inch [0.064 m] square), which had a 0.25-inch (0.64 cm) diameter black target in the middle was attached to one end of a 1-ft-long (0.3 m) light-weight plastic stick which had a suction cup on the other end (Figure 2). Two such flags were mounted on the interior and exterior window glass surfaces with the use of suction cups, at a height of 5 ft (1.52 m) from the floor. The IR thermometer was then used to measure interior and exterior air temperatures by targeting the center points of the flags. Window-thermometer spacing was kept at 1 ft (0.3 m) from the surface of glass. Other equipment required at the time of field testing is shown in Figure 2.

UNCERTAINTY ANALYSIS

Uncertainty analysis is required to indicate the accuracy of the experiments. An uncertainty analysis was performed using the method described by Coleman and Steele (1995) which states

$$e_Y^2 = \left(\frac{\partial Y}{\partial Y_1}\right)^2 e_{X_1}^2 + \left(\frac{\partial Y}{\partial Y_2}\right)^2 e_{X_2}^2 + \dots\dots\dots + \left(\frac{\partial Y}{\partial Y_J}\right)^2 e_{X_I}^2, \tag{8}$$

where e_Y represents the overall uncertainty, Y_J are the calculated results, $Y = Y(X_1, X_2, \ldots X_I)$, and represent the individual uncertainties in the variables $x_{1\ldots I}$. The instrumentation ranges and their uncertainties are presented in Table 2. In the present study, temperature was measured using T-type thermocouples and the IR thermometer, and air velocity was measured with a velocity transducer described earlier. U-factors of the different window assemblies were measured using Equation 7.

The total uncertainties of the measurements are estimated to be ±1°F (±0.5°C) for the temperatures measured using T-type thermocouple and ±2°F (±1°C) for the temperatures measured using the IR thermometer, and ±1% for the air velocity sensor.

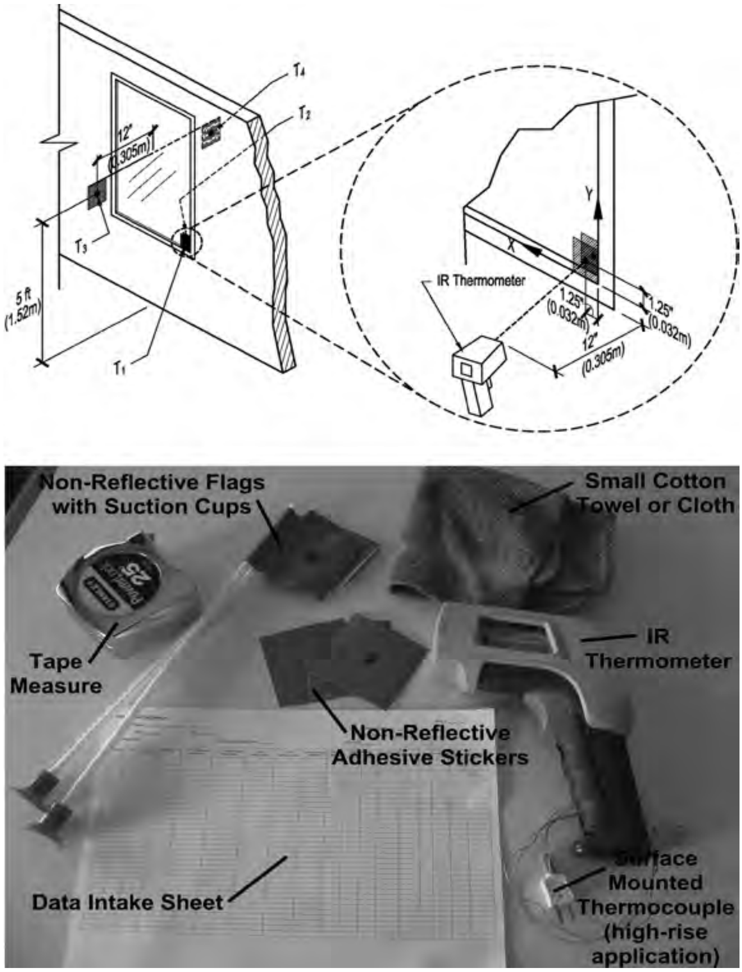

Figure 2 Field testing equipment and procedure to measure window U-factor.

The uncertainty of the U-factors for all the windows tested was calculated on the basis of measured uncertainties of all the temperatures, and air velocity (Table 1).

$$U_F = f(T_1,T_2,T_3,T_4,V). \tag{9}$$

Table 1 Instrumentation Range and Uncertainty Q11

Instrument	Range	Uncertainty
1. T-type thermocouple	−328°F to 662°F (−200°C and 350°C)	± 1°F (±0.5°C)
2. K-type thermocouple	−328°F to 2462°F (−200°C and 1350°C)	±1°F (±0.5 °C)
3. IR thermometer	−40°F to 1472°F (−40°C to 800°C)	±1% or ±2°F (±1°C), whichever is greater
4. Velocity sensor	10 to 90%	±2.50%

RESULTS AND DISCUSSION

Window U-Factor Measurements in the Test Chamber

In this study, several windows with different rated U-factors (U_R) were investigated. Table 2 shows the specifications and the NFRC-rated U-factors of the window samples used in this study. A total of 10 different windows were tested and of these windows, four of the windows were also tested with a clear glass storm window. A comparison between U_R and U_F at 0°F (–17.78°C) exterior air temperature and 70°F (21.11°C) interior air temperatures of various windows tested under controlled test conditions is presented in Figure 3. It can be noted in this figure that the rated U-factor of the windows (U_R) are within 8% of the measured U-factor. Uncertainties in measurement resulting from instrument accuracy are presented by vertical error bars.

It was also found that the measured U-factor was a function of outside ambient temperature (T_4). The measured U-factor was the greatest at 0°F (–17.78°C) and decreased with increasing exterior ambient temperature. An empirical second-order polynomial, based on the tests on several windows, was derived to correct the U-factor at a given outdoor ambient air temperature.

The corrected U-factor is

$$U_F = U_M\,(1 + 0.00019T_4 + 0.0001T_2^4)\ \text{(I.P.)}$$

$$\text{and} \qquad (10)$$

$$[U_F\ \text{(S.I.)} = 5.678U_F\ \text{(I.P.)}],$$

where U_M is the U-factor of a window measured at a given outdoor temperature using Equation 7, and U_F is the corrected U_M at a given T_4, which is equal to U_M at 0°F (–17.78°C). In Figure 4, U_F and U_M are plotted together for several windows tested in

Table 2 Window Samples and Their Rated NFRC U-Factors

No.	Frame	Glazing	Rated U-factor		Storm	Argon	Low-E	Type	Size (W × H)	
			Btu/(hr·ft^2·°F)	W/(m^2·°K)					ft × ft	m × m
1	Vinyl	T.P.	0.25	1.42	No	Yes	Yes	D.H.	3 × 5	0.9 × 1.52
2	Vinyl	D.P.	0.31	1.76	No	Yes	Yes	D.H.	3 × 5	0.9 × 1.52
3	Vinyl	D.P.	N.A.	N.A.	Yes	Yes	Yes	D.H.	3 × 5	0.9 × 1.52
4	Wood	D.P.	0.33	1.87	No	Yes	Yes	D.H.	3 × 5	0.9 × 1.52
5	Wood	D.P.	N.A.	N.A.	Yes	No	No	D.H.	3 × 5	0.9 × 1.52
6	Vinyl	D.P.	0.34	1.93	No	No	Yes	D.H.	3 × 5	0.9 × 1.52
7	Vinyl	D.P.	N.A.	N.A.	Yes	No	Yes	D.H.	3 × 5	0.9 × 1.52
8	Vinyl	D.P.	0.47	2.67	No	No	No	D.H.	3 × 5	0.9 × 1.52
9	Vinyl	D.P.	N.A.	N.A.	Yes	No	No	D.H.	3 × 5	0.9 × 1.52
10	Vinyl	D.P.	0.27	1.53	No	Yes	Yes	C	3 × 5	0.9 × 1.52
11	Vinyl	D.P.	0.30	1.70	No	No	Yes	C	3 × 5	0.9 × 1.52
12	Wood	D.P.	0.32	1.82	No	Yes	Yes	C	3 × 5	0.9 × 1.52
13	Vinyl	D.P.	0.40	2.27	No	No	No	C	3 × 5	0.9 × 1.52
14	Wood	D.P.	0.48	2.73	No	No	No	C	3 × 5	0.9 × 1.52

T.P. = Triple pane; D.P. = Double pane; D.H. = Double hung; C = Casement.

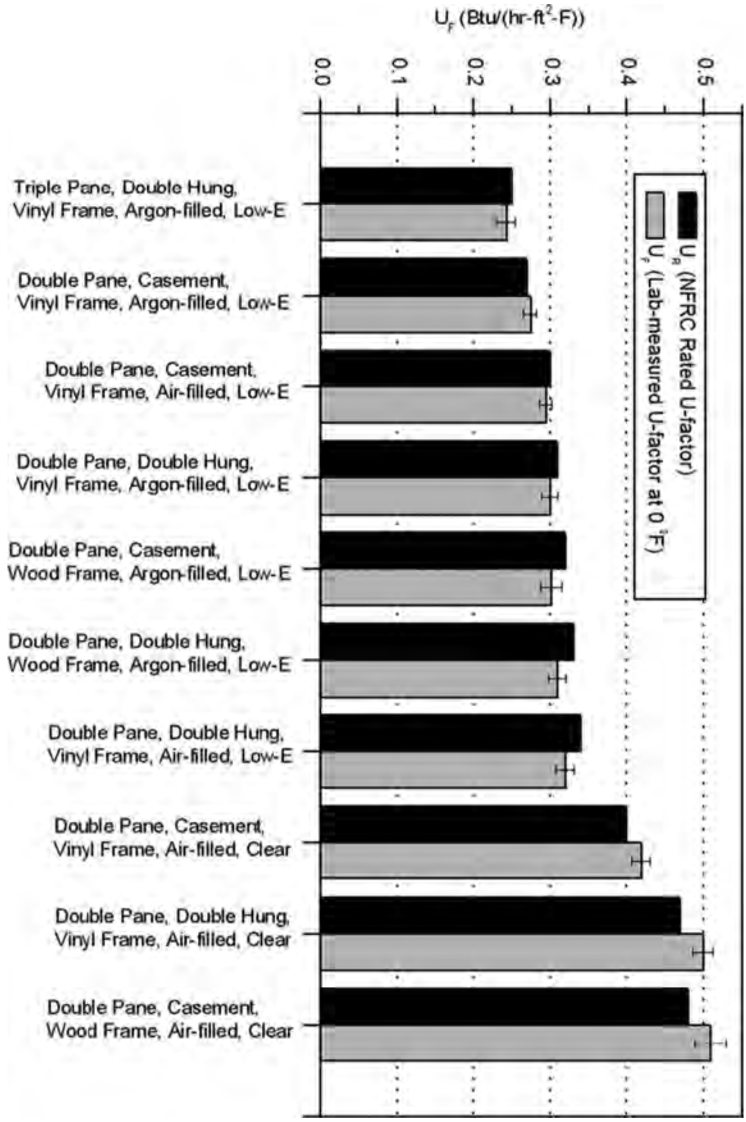

Figure 3 Comparison between U_R and U_F at 0°F (–17.78°C) exterior and 70°F (21.1°C) interior air temperatures. Uncertainties due to instruments accuracies in the measurements are presented by vertical error bars.

this study at different exterior air temperatures. It can be noted that after applying the correction factor using Equation 10, for a given window U_F was approximately constant for all outdoor air temperatures. Equation 10 becomes important in the cases when the outdoor air temperature is not 0°F (–17.78°C) and in such field conditions, Equation 10 can be used to determine U_F, which corresponds to U_R of the windows.

Several double-pane windows (configurations 2 through 9, described in Table 2) were also tested with a storm window mounted on the exterior (cold) side. It was found that the U-factor of a prime/storm window combination improved significantly relative to a

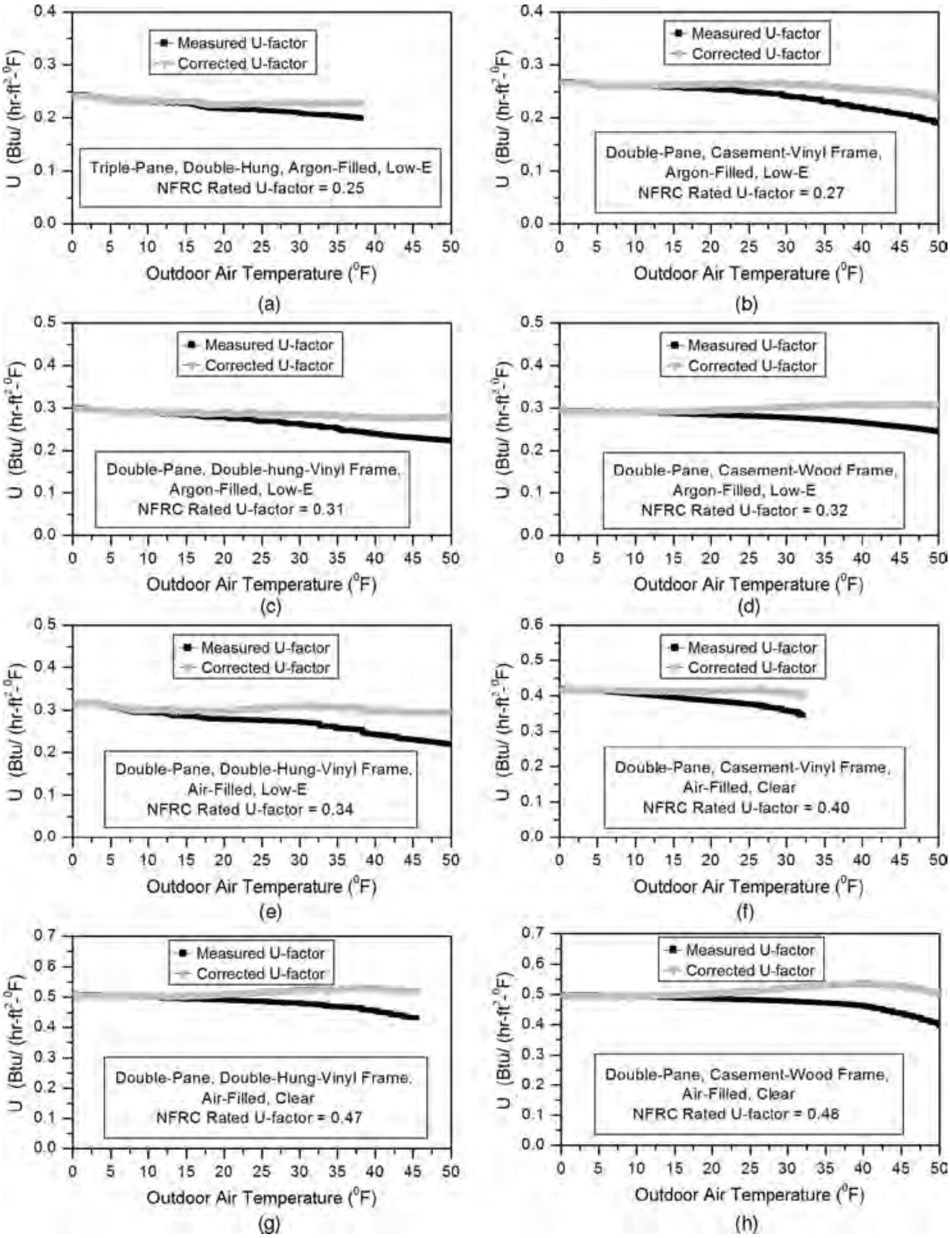

Figure 4 Window U-factor variations with outdoor air temperature for various windows tested. Corrected U-factors of the window are also plotted using the proposed correction equation.

window without a storm and was very similar to a U-factor of a sealed-insulating-glass (SIG) unit with an air fill. Typically the air gap between the storm and a prime window was larger than that of a window with an SIG unit. A gas fill, of course, is not an option for a storm window. Theoretically, therefore, one cannot equal the performance of a new gas-filled window by adding a storm window to a single-glazed or a double-glazed window, but 245

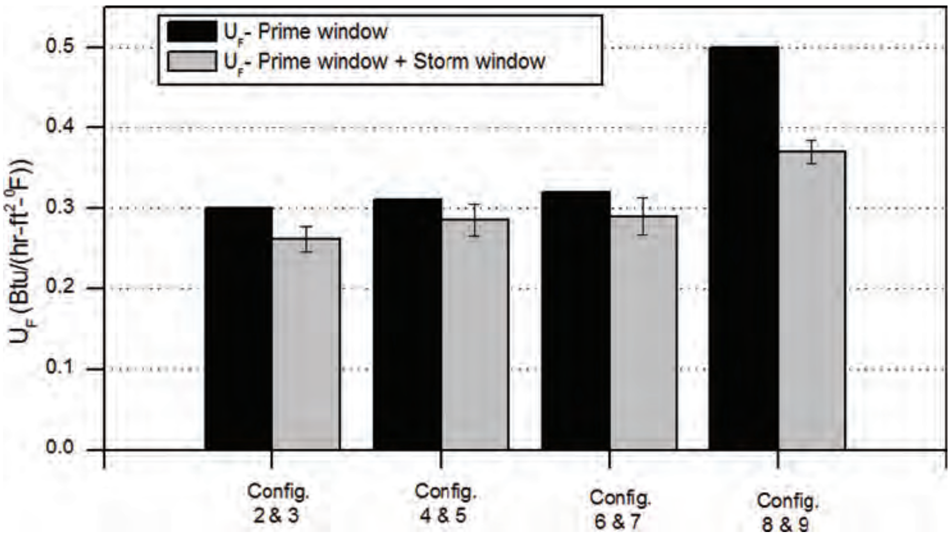

Figure 5 Comparison between the measured U-factors of various windows with and without a storm window unit. Configuration numbers of the windows shown at *x*-axis are taken from Table 3. Uncertainty resulting from instruments' accuracies in the measurements is presented by vertical error bars.

one can obtain a sizable improvement. Figure 5 shows a comparison between the measured U-factors of various windows with and without a storm window. It can be seen in Figure 5 that the measured U-factors of the prime/storm window combination is measurably less than that of a prime window alone.

In another test, an argon-filled, double-pane, double-hung, low-E-coated window was tested and the argon was deliberately removed from the window (configuration 2 in Table 2) to verify whether the method could detect the argon leakage. The rated U-factor of the argon-filled window was 0.31 Btu/(hr·ft^2·°F) (1.76 W/[m^2·K]). Figure 6 shows the measured U-factors of the window before and after argon leakage at 0°F (–17.78°C) exterior and 70°F (21.11°C) interior air temperatures. After removing the argon between the panes, the U_F of the window is expected to be comparable to an air-filled, double-pane, double-hung, low-E-coated window (configuration 6 in Table 2). It can be noted in Figure 6 that after the leakage, measured U-factors of argon-leaked window is close to a new "configuration 6" window.

Window U-Factor Measurements in the Field

Field measurements were performed at various residential and commercial buildings. Various types of windows such as single-pane, double-pane, and triple-pane, with different types of frames (aluminum, vinyl, and wood) were tested at five different building locations. In addition, an R-5 hr·ft^2·°F/ (Btu) (R-0.88 m^2·K/W) window was also tested which was installed in 2010 at a commercial building. Details of the windows tested and their rated or published U-factors (23) are presented in Table 3. These windows were installed in single-family houses, multistory residential building complexes, and a commercial two-story building.

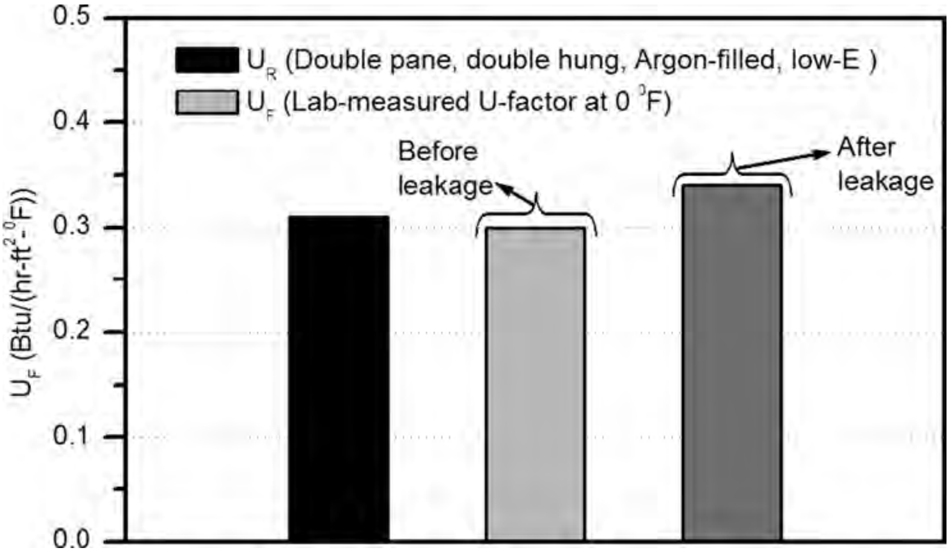

Figure 6 Measured U-factors of a window before and after removing argon from an argon-filled window (configuration 2 in Table 2). Rated U-factor of the window is also presented for comparison.

Table 3 Window Samples Tested in the Field and Their Rated/Published U-Factors

No.	Frame	Number of windows tested	Glazing	Rated or published U-factor		Storm	Argon	Low-E	Type	Size (W × H)	
				Btu/(hr·ft^2·°F)	W/(m^2·°K)					ft × ft	m × m
1	Metal	2	S.P.	1.27	7.21	No	N.A.	No	Slider	3 × 5	0.9 × 1.52
2	Metal	2	S.P.	0.60	3.41	Yes	N.A.	No	Slider	3 × 5	0.9 × 1.52
3	Metal	2	D.P.	0.60	4.03	No	No	No	D.H.	3 × 4	0.9 × 1.22
4	Metal	2	D.P.	0.49	2.78	Yes	No	No	D.H.	3 × 4	0.9 × 1.22
5	Wood	2	S.P.	0.89	5.05	No	N.A.	No	D.H.	3 × 4.5	0.9 × 1.37
6	Vinyl	11	D.P.	0.31	1.76	No	Yes	Yes	D.H.	Vary	Vary
7	Vinyl	1	T.P.	0.20	1.14	No	Yes	Yes	D.H.	3 × 4.1	0.9 × 1.25

T.P. = Triple pane; D.P. = Double pane; S.P. = Single pane; D.H. = Double hung; C = Casement.

Of the five sites, one single-family house was recently constructed (2010), one residential building complex was constructed in 2005, and the rest of the buildings were constructed more than 10 years ago. Besides cleaning the glazing of the windows, all measurements were performed in their existing conditions.

All temperatures were measured primarily with the Fluke 568 IR thermometer. However, in multistory buildings, exterior window surface temperatures (T_2) from the second floor onwards were measured by a K-type surface-mounted thermocouple because it was not possible to use the IR thermometer. One K-type thermocouple can be connected to the Fluke 568 IR thermometer, which eliminated any requirement of a separate instrument to measure the exterior window surface temperature. It was mounted on the exterior window surface at the point of measurement and the thermocouple wire was run through the open window. The window was closed and locked, and the thermocouple was connected to the IR thermometer and used to measure T_2 once it reached steady state. Measured U_F of all the widows enumerated in Table 3 are presented and compared with the rated/published U-factors in Figure 7. It can be seen in Figure 7 that the measured U_F are within ~10% of the published U-factors of the windows. Uncertainties in the measurements resulting from instrument accuracy are presented by vertical error bars. It should be noted that single- and double-pane windows with storm windows have been compared with published U-factors presented in ASHRAE handbook (2005) for the double-pane and triple windows, respectively, which had a 0.5-inch (1.27 cm) air gap between the panes. However, during field testing, for configurations 2 and 5 in Table 3, the air gap between the prime windows and the storm windows were 3 inch (7.62 cm) and 4.5 inch (11.43 cm), respectively. The measured U_F for these configurations are comparable to their published U-factors.

It should also be noted that the U-factor of single-pane windows is ~1 Btu/(hr·ft^2·°F) (5.68 W/[m^2·K]; Figure 7) but the U-factor of these windows without considering air film coefficients (h_h and h_c) is >>1 Btu/(hr·ft^2·°F) (5.68 W/[m^2·K]), which implies that the overall U_F of single-pane windows is mainly dependent on their air film coefficients.

An R-5 window was tested, which was installed recently in a commercial building. Measured and rated U-factors are presented in Figure 8(a). It can be noted in Figure 8(a) that the measured U-factor was approximately 10% higher than its NFRC-rated U-factor. In addition, 11 different windows that were installed in a residential building complex about 5 years ago were also tested. All 11 windows were double-pane, double-hung, argon-filled, and vinyl frame, and their U_R was 0.31 Btu/(hr·ft^2·°F) (1.76 W/[m^2·K]). Average measured and rated U-factors are presented in Figure 8(b). The measured U_F ranged from 0.30 to 0.37 Btu/(hr·ft^2·°F) (1.7–2.1 × 5.68 W/[m^2·K]). Of the 11 windows at this site,

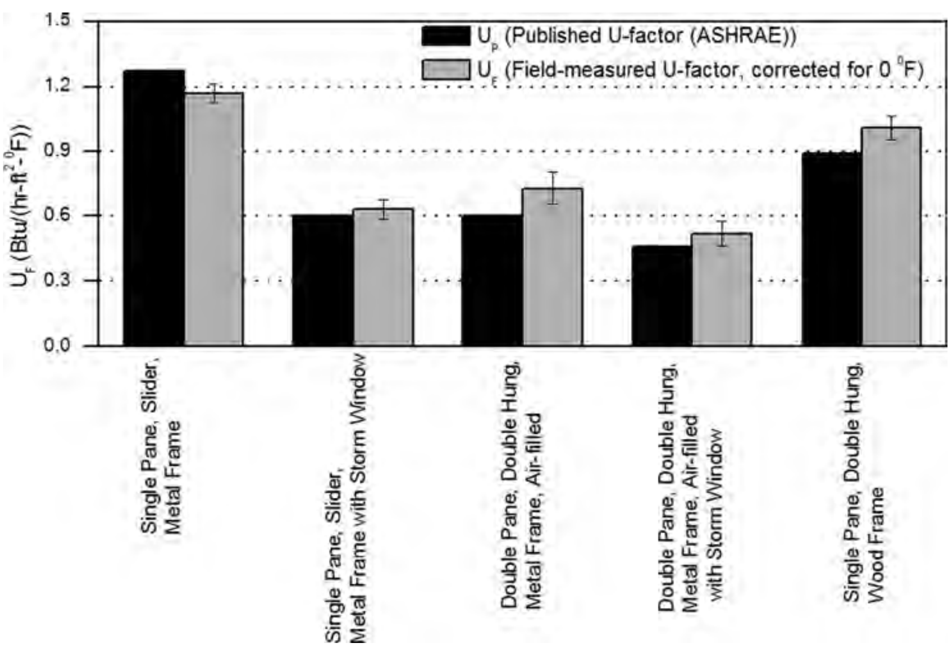

Figure 7 Comparison between U_P and U_F (corrected for 0°F using Equation 10). Uncertainties resulting from instruments accuracies in the measurements are shown by vertical error bars.

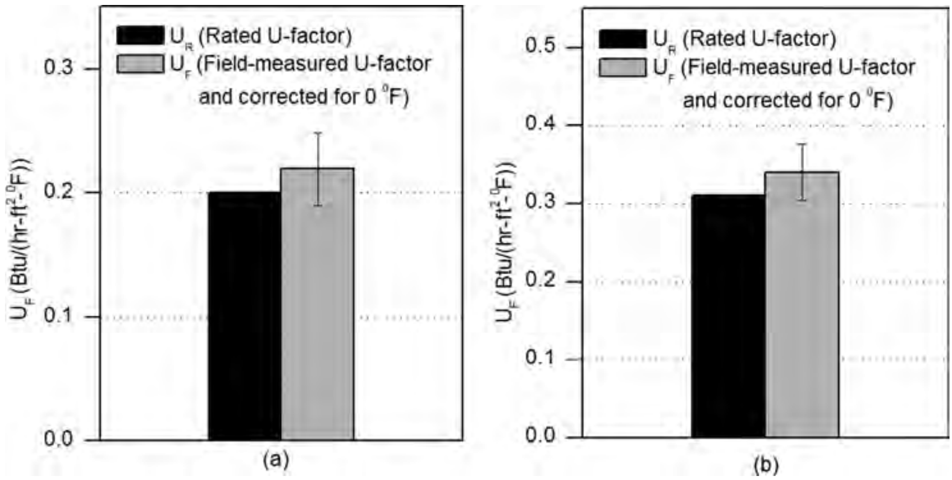

Figure 8 (a) Comparison between U_R and U_F of R-5 window; (b) Comparison between U_R and the average U_F (corrected for 0°F using Equation 10) of 11 different windows installed in a residential building complex. All 11 windows were double-pane, double-hung, argon-filled, and vinyl frame. Uncertainties due to instruments accuracies in the measurements are presented by vertical error bars.

U_F of two windows were 0.37 Btu/(hr·ft^2·°F) (2.1 × 5.68 W/[m^2·K]), which implied that some of the argon between the panes might have leaked. Q5

Based on lab and field results, the proposed method could be instrumental in making better decisions about replacing windows in buildings. Similarly, field measurements might allow installation problems of windows to be diagnosed and corrected early. As mentioned earlier, U-factor is also a function of exterior air temperature. By using Equations 7 and 10, an average U-factor of a window over a full year based on heating degree days (HDD) can be calculated. This might be helpful to estimate annual window heat loss accurately.

LIMITATIONS OF THE PROPOSED METHOD

There are a few limitations of this method which are listed below:

- Measurements should be avoided when windows are in direct sunlight.
- The method cannot be used for fixed/nonoperable windows in upper stories because in such cases, outdoor window surface temperatures cannot be easily measured.
- Measurements should be avoided if a baseboard/radiator or register is located underneath the window and is hot. The heat source such as a baseboard or register will change the interior window surface temperature and consequently the results.

CONCLUSION

The current results clearly show that noncontact IR thermometry is valid for measuring window surface temperature in both hot and cold environments. Temperature readings measured by the IR thermometer were in good agreement with T-type surface-mounted thermocouple readings for a wide range of temperatures. Several double- and triple-pane windows were tested in the thermal test chamber and their U-factors were measured using the proposed method. The measured U-factors are within 8% of those rated by NFRC. It was found that the U-factors of the windows varied with exterior air temperatures. An empirical correction factor, based on lab testing, was presented by which U-factors of windows at 0°F (–17.8°C) exterior air temperature could be calculated and the readings could be compared with the U_R of the windows. Storm windows together with a few double-pane windows were also tested, and the combined U-factors of these units were measured. Results show that the measured U-factors are within 10% of those published by ASHRAE. By using the proposed method, leakage of inert gases from the panes can also be determined. Argon from a double-pane window was removed deliberately and results confirmed the leakage using the proposed method. Finally, field testing on various types of windows such as single-pane, double-pane, triple-pane, with range of frame conductance (aluminum, vinyl, and wood), at five different buildings were performed. The measured U-factors matched closely with the rated and published U-factors of the windows.

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NOMENCLATURE

T_1	Temperature of the inner surface of the window, °F (°C)
T_2	Temperature of the outer surface of the window, °F (°C)
T_3	Interior air temperature, °F (°C)
T_4	Exterior air temperature, °F (°C)
U_R	NFRC-rated U-factor of a window, Btu/(hr·ft^2·°F) (W/[m^2·K])
U_P	ASHRAE (or other) published U-factor of a window, Btu/(hr·ft^2·°F) (W/[m^2·K])
U_L	U-factor of a window without air-film coefficients, Btu (in)/(hr·ft^2·°F) (W/[m^2·K])
U_M	Measured U-factor of a window, Btu/(hr·ft^2·°F) (W/[m^2·K])
U_F	Field (corrected) U-factor of a window, Btu/(hr·ft^2·°F) (W/[m^2·K])
L	Height of a window, ft (m)
A	Area of a window, ft^2 (m^2)
h_h	Interior air-film coefficient, Btu/(hr·ft^2·°F) (W/[m^2·K])
h_c	Exterior air-film coefficient, Btu/(hr·ft^2·°F) (W/[m^2·K])
σ	Stefan–Boltzmann constant, 0.1714×10^{-8} Btu/(hr·ft^2·R^4) (5.67×10^{-8} W/[m^2·K^4])
e	Emissivity
V	Wind speed, ft/sec (m/sec)

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