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ABSTRACT

Data from nighttime measurements of the net heat flow through several types of skylights is presented. A well-known thermal test facility was reconfigured to measure the net heat flow through the bottom of a skylight/light well combination. Use of this data to determine the U-factor of the skylight is considerably more complicated than the analogous problem of a vertical fenestration contained in a test mask. Correction of the data for heat flow through the skylight well surfaces and evidence for the nature of the heat transfer between the skylight and the bottom of the well is discussed. The resulting measured U-values are presented and compared with calculations using the WINDOW4 and THERM programs.

INTRODUCTION

As progress in specifying the U-factors of predominantly planar, vertical windows has been made by both ASHRAE and NFRC, and as increasing consensus has been reached on methods of modeling the nighttime thermal performance of these windows using computer programs, attention has turned to the thermal transmittance through projecting products. Of these, probably the most important market segment is skylights. An ASHRAE study of the U-values of some common commercial skylights has recently appeared (McGowan, Desjarlais et al. 1998) and an NFRC research project on residential skylight U-factor testing (Curkeet 1999) is expected to yield a future published report.

Both of these projects concentrate on measuring the value of the U-factor in the laboratory, using simulated interior and exterior conditions. This is oriented toward allowing comparison between different types of units and different products. But to estimate accurately the energy use of a fenestration requires knowledge of the interior and exterior heat transfer ("film") coefficients; these are both variable and, on average, different from the values used in the laboratory tests. Both of these points are well known, and a fair amount of information on actual versus test performance exists for conventional vertical windows. However, there is essentially no information on the actual performance of skylights.

It is quite difficult to estimate how actual skylight performance might differ from test lab performance, based on one's experience with vertical windows. On the exterior side, radiation exchange with the nighttime sky is important for vertical windows, and a skylight will have a larger view factor to the sky. The argument sometimes made for vertical windows, that the view of the sky will be occluded by vegetation or neighboring buildings, is less convincing for skylights, which are also less likely than vertical windows to experience wind shadowing (either self-shadowing by the building, or wind shadowing by adjacent objects). This would argue for

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higher average values for the exterior film coefficient for skylights than for vertical windows. A review of the literature on solar collectors should provide more specific information on this point. On the other hand, for projecting windows a reduced view factor to the warm interior space can result in a lower interior film coefficient (see, e.g., (Klems 1998) and (Griffith, Curcija et al. 1998)). For a skylight in wintertime the air near the skylight will have an adverse temperature gradient, a situation that can be either stable or unstable with respect to convection and the development of thermal plumes, depending on the magnitude of the temperature gradient. The actual performance of a skylight relative to a comparably sized window therefore depends on several effects of opposite signs and uncertain magnitudes.

This paper reports our measurements of the winter performance of several conventional skylights. It is part of an ongoing study of skylight performance under realistic outdoor and indoor conditions. We have previously reported results from summer tests of electrochromic skylights (Klems 1999).

MEASUREMENT PROCEDURE

We utilized an accurate, well-characterized and well-known outdoor test facility (Klems, Selkowitz et al. 1982; Klems 1992) for our measurements. Although normally used to study vertical fenestrations, this facility was also designed with ports in its nearly flat roof for the installation of skylights. Figure 1 shows the utilization of these ports to install skylights. General features of the conversion have been described previously (Klems 1999). Since the roof thickness of the facility is 0.7 m due to the air guard space, a vertical-sided well resulted when the ports were extended with a commercial skylight adapter, as shown in Figure 2.



Figure 1. Conversion of the test facility to skylight operation. (a) Overall view from the north, before installation of the skylight adaptors. Here Chamber A is on the right. (b) View from the southwest during installation of the light wells on the chamber skylight ports. Chamber A is on the left.

The skylight adapters and aluminum-clad wooden frames mounted on the two test chambers were identical units donated for the tests by a skylight manufacturer. The skylight tilt was nominally 20°; the actual angle of the adapter face was 18.5°. The test chambers themselves, denoted A and B, respectively, are distinguished by their location in the facility, as indicated in Figure 1. The chambers are mirror images of one another, rather than identical. A large number of tests on them made over the years have not revealed any significant performance differences in the chamber

construction. Construction of the light wells within the adapters and ports was also done in as nearly an identical manner as possible, given that construction was by hand on-site, and that there are normal construction tolerances to be dealt with.

Tests were conducted during December, 1997 and February, 1998 as listed in Table 1.

Table 1. Skylight Test Configurations

Test Period	Chamber A	Chamber B
December, 1997	Flat Selective Double Glazed	Flat Clear Double Glazed
February, 1998	Flat Clear Double Glazed	Clear Double Bubble

Measurements were made on two flat double-glazed skylights and on one double-dome bubble type skylight. The flat units were obtained as sealed-insulating glass units sized to fit into the commercial wood frames, into which they were inserted. They consisted of an air-filled clear double glazed unit (“Clear Double”) and an argon-filled double-glazed unit with a selective low-emissivity coating on the number 2 surface (“Selective Double”); Both units had the same glass thicknesses (3.0mm). The bubble skylight had an exterior “bottlecap” frame of anodized aluminum, and this was sized to fit over the top of the adapter frame, over which it was mounted. The aluminum frame of the bubble skylight had no thermal break. There was a plastic flange covering the interior side of the visible part of the aluminum frame. The domes were of acrylic plastic, with an air space between them that varied from a maximum distance at the center to zero at the edges, where both domes fit into the frame without any spacer. The two test setups are shown in Figure 3.

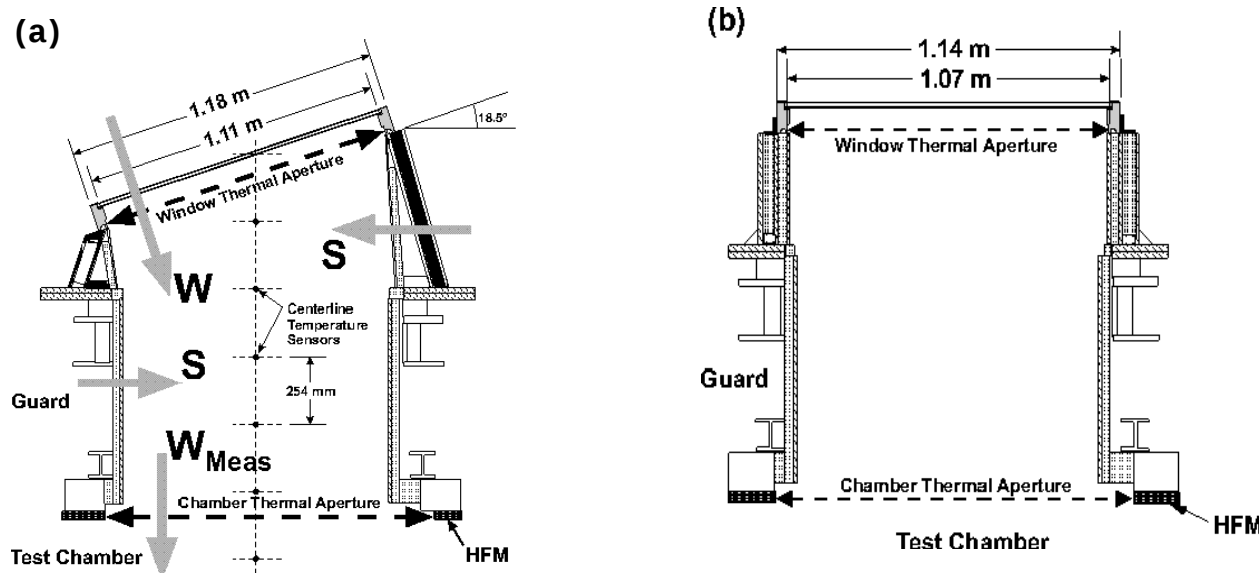


Figure 2. Light Well Cross Sections. Effective thermal aperture of the calorimeter chamber and the definition of the window thermal aperture are indicated by dashed arrows. (a) Plane of Skylight Tilt. Also shown are the locations of centerline air temperature sensors. Labeled grey arrows indicate definitions of heat flows. (b) Plane Perpendicular to Skylight Tilt, at centerline.

(a)



(b)



Figure 3. Test Sample Arrangements. (a) Setup for December Selective Double/Clear Double Tests. This photo was taken during tests of identical clear double skylights, but the differences in insulated glazing units would not be visible. In the December tests the Selective Double insulated glazing unit was installed in the far sample. (b) February Clear Double / Double Bubble Tests.

The Clear Double unit was utilized as a reference between the two tests. Note that it was mounted on a different test chamber in the two test runs.

Skylight frames normally have systems of weep holes connecting the interior and exterior, intended to channel condensation outside. These were sealed during the tests to prevent air infiltration from confusing the results. While infiltration through these openings could affect actual skylight performance, special test provisions would be necessary to study it, and the subject was reserved for possible later tests.

Measurements were carried out at our field test site in Reno, NV. Each test was run for several weeks or more, and during that time the normal facility data collection included measurement of temperatures, all calorimeter heat exchange flows, and solar intensities on a continuous basis: each ten minutes, the average of each measurement over the preceding ten minutes is recorded. For most quantities the standard deviation of the measurements over the ten-minute interval is also recorded. Sampling intervals during the ten minutes varied with the type of sensor being sampled. Figure 3 shows three of the solar measuring instruments, a horizontally mounted pyranometer and two similar instruments mounted in the skylight plane. Of these, one of the sample-plane instruments is relevant to nighttime measurements. The nearer of the two instruments (distinguished by its opaque dome, which appears dark in the photograph) is a far-infrared pyrgeometer that measures the effective radiant temperature of the hemisphere viewed by the skylights.

A set of equally-spaced, radiation-shielded air temperature sensors was mounted along the vertical centerline of each skylight well, as indicated in Figure 2a. In addition, very small-diameter thermistors were mounted at the center of the interior and exterior skylight surfaces, in order to obtain an accurate surface temperature measurement. While the standard facility procedure includes mounting two thermistors on each of these surfaces, the standard thermistors are too large to give a very accurate measurement of the surface temperature. The thermistors mounted on the exterior surface can be seen in Figure 3.

DATA SELECTION AND ANALYSIS

The outdoor air temperature was first examined over each test period and sections of the data selected for which there were cold nighttime periods without sharp changes in outdoor temperature. The motive for this selection was to have the magnitude of the nighttime heat flow as large as possible, in order to maximize measurement accuracy. Also, sudden air temperature changes may signal a weather front and precipitation, which would produce anomalous measurements. While it is true that this procedure somewhat biases our measurements toward extreme conditions (for Reno), the resulting conditions are still considerably milder than those used in laboratory tests.

Next, we examined the calorimeter temperatures, heat flows, and other relevant data, and excluded periods when the facility functioning was not stable and normal. During both tests there were problems with either noise or an intermittent poor connection on the chamber A temperature control sensor, which would cause sudden temperature excursions in the calorimeter air temperature. (Two of these can be seen in Figure 4, at 1800 on December 11 and just before 1800 on December

12.) We excluded nights where any of these occurred between the hours of 2000 and 0700.

The test period selected under these criteria for the Selective Double / Clear Double test was the period December 12-16, 1997, shown in Figure 4. This was a period when nighttime temperatures varied between 0° C and -5° C. Sky radiant temperatures were considerably below the air temperature (which is usual during clear weather in Reno). Nighttime wind speeds were quite low, (which is again usual) except for December 14. During the day on December 14 there was apparently a weather front moving through (indicated by the increased and variable wind speed and the increased sky temperature; the latter indicates cloudy conditions). By nighttime it appears to be again clear, with some residual windiness; there was no sign of precipitation.

Similar considerations were applied in selecting data from the second (February) test period.

The basic measurement made by the calorimeters is the total rate of heat flow W_{Meas} through the calorimeter thermal aperture, indicated in Figure 2a. As also indicated in the figure, this quantity differs from the heat

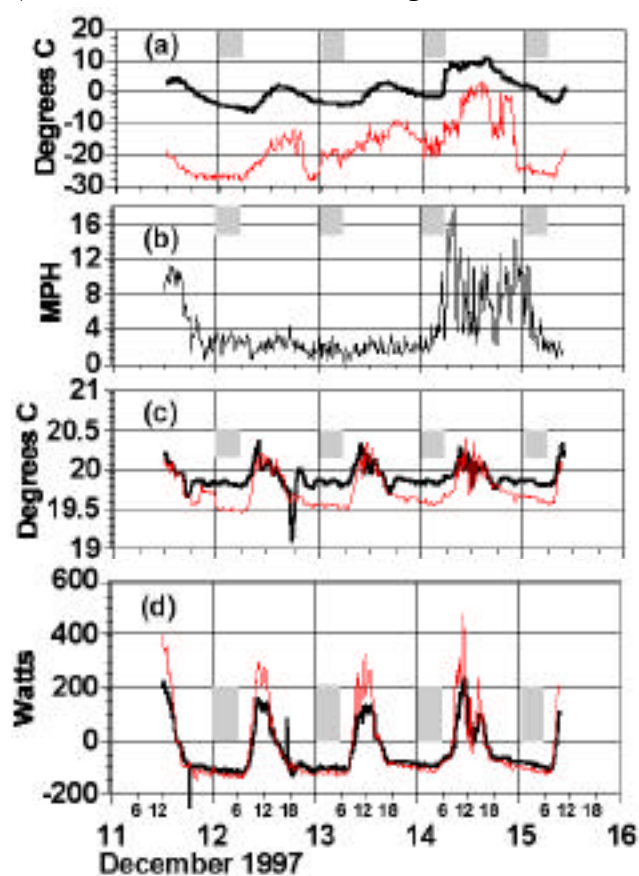


Figure 4. Conditions During Selective/Clear Double Nighttime Heat Flow Measurement. (a) Outdoor Temperatures: Heavy curve: air temperature; Light curve: sky radiant temperature. (b) Wind Speed. (c) Calorimeter Air Temperatures: Heavy curve: chamber A; Light curve: chamber B. (d) Corrected Heat Flow (W): Heavy curve: chamber A; Light curve: chamber B. Shaded areas in each plot indicate the time periods from which data was used for U-factor measurements.

flow, W , through the skylight by the heat flow, S , through the skylight well. We have previously discussed our method of determining S and correcting the measurement (Klems 1999). In these tests the well heat flow is always quite small and does not greatly affect the measured value of the U-factor; however, the uncertainty in this correction is the chief contributor to the uncertainty estimate for the measurement.

Once the heat flow through the skylight, W , has been determined by subtracting the well heat flow from the measured net heat flow, the U-factor is calculated by the usual formula:

$$U = \frac{W}{A_{Therm} \cdot (T_{out} - T_{in})} \quad (1)$$

This calculation was carried out for each ten-minute-average set of heat flows and temperatures, and the results averaged over all the nights in the test period. The standard deviation of these measurements gives an estimate of the measurement error arising from random (or other) fluctuations in heat flows and temperatures. However, as mentioned above this error estimate was smaller than the estimated systematic uncertainty in the well heat flow correction, and the latter was used in determining the uncertainty of the measurement.

There are a number of definitional issues hidden in formula (1). We have taken the effective thermal aperture of the skylight to be the quadrilateral formed by the lower (i.e., innermost) edge of the skylight frame. The outdoor air temperature was taken to be T_{out} , and the calorimeter air temperature was taken as T_{in} (since U-factor calculations typically use the average room temperature). Other possible choices of T_{in} are discussed below.

RESULTS

The values obtained for U in the two tests are given in Table 2. The average conditions corresponding to the measurement periods are listed in Table 3.

Table 2. Measured Values of U-Factor

Test Period	Sample	Test Chamber	Measured U (W/m ² K)
Dec 12-15, 1997	Selective Double	A	3.77 ± 0.16
Dec 12-15, 1997	Clear Double	B	4.60 ± 0.26
Feb 26-27, 1998	Clear Double	A	4.47 ± 0.16
Feb 26-27, 1998	Double Bubble	B	4.79 ± 0.23

Table 3. Average Conditions During the Measurement of Table 2

Test Period	Outdoor T (°C)	Sky Radiant T (°C)	Wind Speed (m/s)	Chamber A		Chamber B	
				Interior Air T (°C)	Heat Flow (Watts)	Interior Air T (°C)	Heat Flow (Watts)
Dec. 97	-2.04	-22.35	1.41	19.85	-96.97	19.57	-116.5
Feb. 98	0.34	-10.84	1.38	19.98	-103.8	19.96	-111.0

Air temperatures within the light wells were relatively uniform vertically. Figure 5 shows the vertical temperature distributions at the centerline. These distributions indicate that in all cases the air in the well appears to be well mixed. The small temperature difference between the well air and the test chamber (spatial) mean indicates that thermal contact between the well air and the test chambers is good, but not perfect.

Calculations of U do not typically include the effects of a skylight well, and we have analyzed the data to exclude well effects as completely as possible. The difference in air temperature between the well and the chamber indicates that for purposes of comparison to calculations, it might be more appropriate to use in formula (1) the well air temperature rather than the chamber air temperature. In Table 4 we compare the U-factors obtained under that assumption with those in

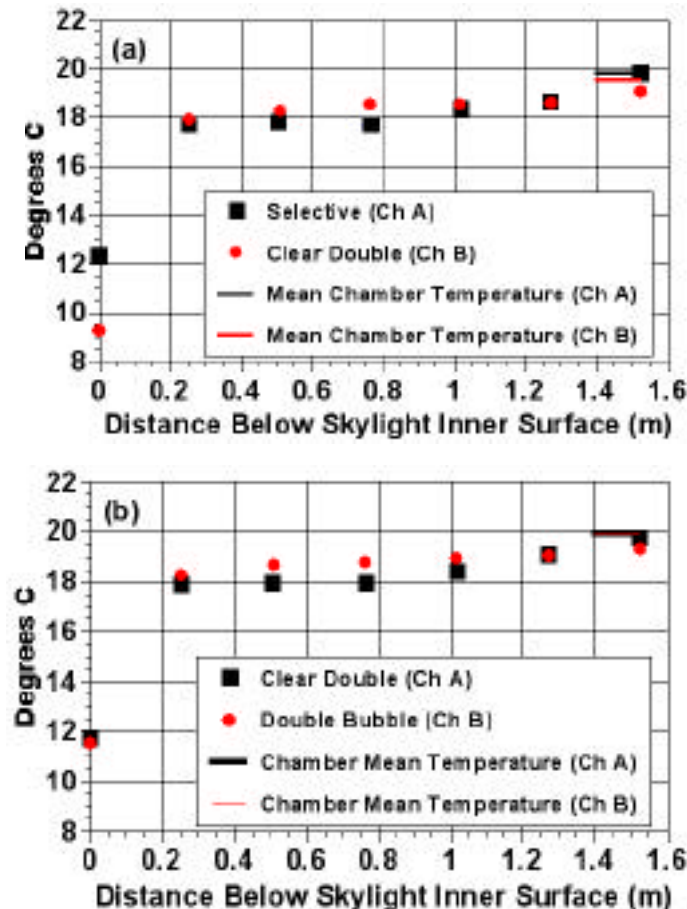


Figure 5. Vertical Centerline Temperature Distribution in the Skylight Well. Points compare the mean temperatures in the two skylight wells as a function of the distance from the skylight number 4 surface. The points at zero distance are surface temperature measurements. The right-most point (1.52m) in each chamber is below the bottom of the skylight well. Lines compare these points with the chamber spatial mean air temperature. (a) December tests of Selective Double/Clear Double (b) February tests of Clear Double / Double Bubble.

Table 2. We have taken the temperature at 254 mm (10 in.) below the skylight as representing the well temperature “near” the skylight. We note, however, that this ignores the effect of radiative coupling between the skylight and the light well surfaces. The light well surfaces in the upper part of the well are significantly below the air temperature, while those of the lower well are close to the temperature of the adjacent air. A portion of the skylight view solid angle also includes some of the calorimeter chamber surfaces, which are at a temperature close to the mean chamber temperature.

Table 4. Effect of Alternative Choice of Indoor Temperature

Test Period	Sample	Well Air Temperature (°C)	U Based on Well Air Temperature (W/m ² K)	U Based on Chamber Air Temperature (from Table 2) (W/m ² K)
Dec 12-15, 1997	Selective Double	17.64	4.20 ± 0.18	3.77 ± 0.16
Dec 12-15, 1997	Clear Double	17.87	5.00 ± 0.28	4.60 ± 0.26
Feb 26-27, 1998	Clear Double	17.84	5.02 ± 0.18	4.47 ± 0.16
Feb 26-27, 1998	Double Bubble	18.25	5.24 ± 0.25	4.79 ± 0.23

DISCUSSION

Consideration of Systematic Errors

The striking feature of Table 2 is the relatively small (18 %) reduction in U-factor in going from a clear double, air-filled glazing to a selective low-emissivity, argon-filled one. Based on the characteristics of the glazings alone, one would expect this difference to be on the order of 50%. This immediately raised the question of whether there may be biases in the measurement of one or both test chambers.

The normal method for insuring the absence of measurement errors in the overall heat balance method is to perform a “closed-box” test on each of the chambers. This was done prior to converting to skylight measurements, and rules out measurement errors greater than 8 W. In the context of Table 2, that would correspond to a U uncertainty of 0.3 W/m² K. However, once the conversion to skylight testing was done, a “closed-box” test is no longer possible, so we needed to seek other evidence that nothing had gone wrong since the beginning of skylight testing (May, 1997).

After the measurements reported here, we recalibrated the instruments used in measuring the net heat flow, and found that the calibration had remained stable during the entire period. Just prior to the winter measurements tests were conducted with identical clear double flat insulating glazings in both skylight frames and the measured heat flows in the two chambers were found to agree to within 2 W. In addition, as shown in Table 2, the same clear double glazing was measured in both chambers (with the measurement in chamber a occurring after the selective double measurement)

and the resulting measured U-factors are consistent within the uncertainty resulting from the well heat flow correction.

We conclude, then, that no relative error between the two chambers can have developed since the last “closed-box” calibration (which is an absolute measurement).

A large “common mode” error (i.e., one that affects both measurements in the same way) could produce the observed effect. However, there are no measurement elements common to both chambers in determining the net heat flow. It is difficult to conceive of two separate instrumental problems that produce a large error that is the same in both chambers, but which does not show up in the instrument recalibrations.

A physical mechanism that could produce a significant common error in both measurements is a high rate of air infiltration. Between the measurements made with the same glazing in both chambers and the December and February tests the only physical change in the experimental set-up was changing the insulating glazing units. If in the process of changing the insulated glazing units leaks were introduced, then an unexpected heat loss due to air infiltration could occur. Moreover, this is the only plausible physical mechanism that could produce a common measurement error.

Several lines of reasoning exclude air infiltration as a possibility. The facility has a tracer-gas infiltration measurement system that monitors both calorimeter chambers. While this system was unfortunately not operating throughout both tests, it operated at the beginning of the December tests, after installation of the insulated glazing units, and showed no unusual level of infiltration in either chamber.

Furthermore, we have a large amount of measurement experience with infiltration in the chamber prior to the conversion to skylight operation. From this we know that the primary air flow path (other than those contained in a test sample) for each chamber is a very small leak to the instrument control room, which is approximately at room temperature, through a cable duct in the facility floor. In addition, only the introduction of air at a different temperature than that of the chamber has an effect on the net heat flow measurement. Exfiltration of chamber air has no effect, unless the corresponding infiltrating air is at a different temperature.

Any leaks introduced in the conversion to skylight operation would have been high in the chamber, in the skylight or the light well. In winter the expectable mode for infiltration is infiltration at the floor level (through the leak in the cable duct) and exfiltration through the skylight/light well leaks. This would cause a net heat flow only proportional to the small temperature difference between the control room and the calorimeter chamber air. But for this to produce a significant heat flow error would require a very large leak, and such a large leak is excluded by the air infiltration measurements (which occurred both before the December data and after the February data).

To cause a large net heat flow, it would be necessary to have the chambers infiltrating in the skylight/light well (and, presumably, exfiltrating at the floor). This could not happen by the stack effect, and would require that the chamber (and the control room) be at a negative pressure relative to the outdoors. But we can rule this out, because each chamber has a differential pressure sensor mounted to monitor the pressure difference across the sample normally placed in the window measurement position. Although this sample opening was insulated and covered with heat flow sensors, the pressure measurement was still made, and showed that at the window midline (approximately 1.5m from the floor) the pressure difference between the test chambers and the

outdoors was always positive. Hence we can exclude infiltration as a significant source of heat flow.

We conclude, then, that the values in Table 2 are not significantly affected by instrumental errors or extraneous physical mechanisms.

Comparison With Calculations

In Table 5 we compare our measured values for the flat skylights with the values that appear in the ASHRAE Handbook (ASHRAE 1997). Since the skylight frames used were wood with aluminum exterior flashing, we have included both the table values for wood frames and for clad wood frames. Fortuitously, the measured values do not fall too far from what one might naively expect for wood-framed skylights; however, comparison of the Handbook values for the same glazing in the two different frames points up the importance of having an accurate model of the frame. In fact, since the Handbook values correspond to different sizes, different frame details, and different interior and exterior conditions from the measurements, the apparent agreement is primarily accidental, as further investigation showed.

Table 5 ASHRAE Fundamentals Values Compared With Measured Values

Test Period	Sample	ASHRAE Fundamentals		U Based on Chamber Air Temperature (from Table 2) (W/m ² K)
		Aluminum-Clad Wood Frame (W/m ² K)	Wood/Vinyl Frame (W/m ² K)	
Dec 12-15, 1997	Selective Double	5.19	4.04	3.77 ± 0.16
Dec 12-15, 1997	Clear Double	5.90	4.74	4.60 ± 0.26

To better understand the effect of the frame and the environmental conditions, we used the WINDOW 4 (Arasteh, Finlayson et al. 1994) and THERM (Finlayson, Mitchell et al. 1998) programs to estimate expected U-factor values for the clear double and selective double skylights. In these calculations wind speeds and temperatures approximating the experimental values were used, but accurate modeling of the experimental interior and exterior heat transfer coefficients was not attempted. The values we obtained from these calculations did not agree with the measurements; in general, the measured U-factors were higher than the calculated ones, and while the absolute difference between the clear double and selective skylights approximately agreed with the measurement, both the overall magnitude and the fractional difference disagreed. In general, the disagreement between measurements and calculations was worse if the well air temperature (rather than the chamber air temperature) was used to calculate the measured U-factor. All of this pointed up the importance of having an accurate model of the frame and the environmental conditions. Research is continuing to develop such a model.

Bubble Skylights

The geometry of the skylight does not appear to have a strong effect on the U-factor. The measured U for the clear double bubble skylight is only slightly higher than that of the flat clear double skylight, and in fact the two measurements are consistent within the measurement uncertainty. Since no models are currently available to break down the heat flow into its components, and since the frame detail is also different for this unit, little more can be said.

CONCLUSIONS

Measurements have been made of skylight U-factors under winter field conditions for clear and high-performance (i.e., selective low-emissivity, argon filled) double-glazed flat skylights, and for a clear double-bubble acrylic plastic skylight.

Although the measured U-factors agree approximately with values in the ASHRAE Handbook, this agreement is accidental; when estimates of the U-factors were made including the measurement conditions, the estimates disagreed with the measurements.

The performance difference between the two flat skylights is surprisingly small, compared with the estimates, and both flat skylights have measured U-factors considerably higher than the estimated ones.

We have not presented the estimated values because of the unsatisfactory state of our models of the frame and boundary heat transfer coefficients. More work is needed on modeling the flat skylights, before it will be possible to produce a number deserving to be termed a calculation, rather than an estimate. There is presently no calculation program capable of modeling the bubble skylight.

The flat and bubble skylights had similar U-factors.

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