Final Report

REVISION OF STANDARD SPECTRAL WEIGHTING FUNCTION FOR CALCULATION OF SOLAR OPTICAL PROPERTIES AND SOLAR HEAT GAIN

Submitted to:
NFRC Project Monitoring Task Group, and
NFRC Research Subcommittee

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Background

NFRC 200 and NFRC 300 use a standard spectrum for the purpose of weighting the spectral calculations of solar transmission performed by appropriate fenestration analysis software (e.g., WINDOW and OPTICS). Since the inception of these NFRC documents, the spectrum used for this task has always been the ASTM E 891 standard spectrum [Tables for Terrestrial Direct Normal Solar Spectral Irradiance Tables for Air Mass 1.5 (E891)], which was initially adopted 25 years ago (ASTM 1982), and later elevated to international status (ISO 1992). This is a direct irradiance spectrum at an air mass of 1.5. The use of a single standard spectrum is necessary for rating purposes, and therefore needs to be carefully chosen and validated.

ASTM E891 was withdrawn in 1999 and is now obsolete. It has been replaced by ASTM G173 [Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface (G173)] in 2003 (ASTM 2003). This new standard has marked differences; its overall direct irradiance is more intense, its spectral balance is blue-shifted compared to E891, and its resolution is an order of magnitude finer than that of E891. The adoption of this new standard was also backed by a careful validation process based on comparison to actual measurements and other state-of-the-art atmospheric computer models. It is anticipated that international standards organizations, such as CIE, ISO and the International Electrotechnical Commission (IEC), will follow suit and adopt G173 or similar spectra as the standard spectrum for their practices. In particular, IEC is currently in the final steps of adopting a revised version of its standard 60904-3 for photovoltaic applications. The revised IEC reference spectrum consists of a slightly modified version of the global spectrum of G173. Similarly, CIE has established a Technical Committee (TC 2.17) to prepare new spectral standards based on the same radiative model as specified in G173, but for purposes other than those of the ASTM Standard.

With the E891 standard now withdrawn, the NFRC procedures are currently without the proper standard-backing umbrella, and can therefore be considered outdated and obsolete. There is an opportunity to develop new standard spectra in either ASTM or CIE that are more appropriate for the window industry. These new standard spectra would include global irradiance on vertical surfaces, which for vertical fenestration, is closer to reality than direct irradiance. It is important that NFRC can be represented in the ASTM or CIE technical discussions so that the standard spectra they eventually adopt respect the specific needs of NFRC. For instance, a particularly sensitive case is the rating of skylights, which can be improved by relying on a specific spectrum corresponding to a tilted—rather than vertical—surface. ASTM and/or CIE should address the issue of non-vertical surfaces in their deliberations, using their own expertise to offer NFRC some educated choices. All these developments would offer NFRC the opportunity to participate in the replacement of the currently outdated weighting function with more accurate data, and to insure that tilted products, such as skylights, are represented too. It is anticipated that, through the use of more accurate solar spectral data, simulation software will generate Solar Heat Gain Coefficients (SHGC) that are in better agreement with actual solar calorimeter test results, thus removing a source of uncertainty in SHGC calculations.

In order to keep up with the latest and more accurate procedures, NFRC 200 and NFRC 300 need to update the standard spectrum used in those procedures. To accomplish this goal, NFRC needs
to decide if it should reference ASTM G173, or a potentially more appropriate spectrum from
ASTM or CIE. Knowledge about how this change will affect the current SHGC and Visible
Transmittance (VT) ratings is crucial in order to select a new solar spectral weighting function
(SWF) for NFRC’s use.

Furthermore, it is anticipated that the current standardization process at ASTM and CIE will
have a ripple effect in Europe, with the likely result of changes into ISO standards and European
rating procedures. Therefore, this project provides a timely opportunity of finally harmonizing
the North American and European rating methodologies, at least regarding the spectral issues.

**Objectives**

The intent of this research project is to provide a *recommended solar spectrum* to NFRC by
assessing the impact of a potential change in the reference spectrum that is used to weigh the
spectral transmission calculations through glazing. It is therefore proposed

(i) to evaluate the effect that adopting one of the new possible spectra would have on the
optical properties, SHGC and VT ratings of typical fenestration systems;

(ii) to follow closely the progress of the standardization work at ASTM and CIE with the
help of a liaison; and

(iii) to orient their work so that NFRC’s needs for a single spectrum (specifically applicable to
fenestration rating) are fully taken into consideration.

**Scope**

This research project consists of four inter-related tasks, which were originally defined as:

**Task 1 – Selection of Glazing Systems**

**Task 2 – Calculate and Analyze Optical Properties and SHGC with Different Spectra**

**Task 3 – Monitor CIE Technical Committee 2.17**

**Task 4 – Reports on CIE Activities, Final Report, and Technical Paper.**

Details on how these tasks have been accomplished are reported as follows.
Task 1 – Selection of Glazing Systems

It is anticipated that a change in the spectral weighting function will affect some glazing systems more than others. For instance, negligible change in the SHGC of clear glass should occur because the latter’s transmittance is essentially flat over the most important part of the shortwave spectrum. Conversely, glazing systems characterized by strong spectral selectivity due to their use of coatings, films, etc., are more likely to be affected in one way or another. At this stage, it would not be productive or cost-effective to analyze all possible glazing systems that can be invented by combining various elements. Hundreds of thousand such combinations might exist.

To explore the effect of a change in the spectral weighting function, the Principal Investigators (PI) worked in close contact with the assigned Project Monitoring Task Group (PMTG) to develop an appropriate and manageable methodology. The PI proposed, and the PMTG approved, to analyze combinations of glazing and coatings that would be representative of a large range of optical properties and glazing system types. Because of the anticipated key role that would be played by spectral selectivity, the PI selected glazing systems of different types of glass and coatings, using one to three layers, as well as specific glazing systems used for skylights. The PI defined six categories:

1. Window Films on Glazing
2. Laminates and Laminated Glazing
3. Reference Glazing
4. Double Glazing—Low-E
5. Double Glazing—Electrochromic
6. Triple Glazing—Clear, Heat Mirror & Low-E.

These categories were populated with glazing systems that appeared to be either “typical” or “extreme” in various ways, and to respect a few important criteria, which are detailed below. The third category (“Reference Glazing”) was created to represent specific systems from the technical literature, known to the PI or members of the PMTG for their special characteristics or scientific value.

The following criteria and objectives were used to develop the specimen list in Table 1.

*LSG Ratio*: The intent was to select different glazing systems that would create a large scatter in a “$T_{vis}$ vs SHGC” plot (see Figure 1). Spectral selectivity can be characterized by the Light-to-Solar-Gain ratio, LSG, which is simply the ratio of the Visible Transmittance ($T_{vis}$) and SHGC. The importance of LSG in characterizing the performance of glazings vis-à-vis solar heat gains and energy conservation in buildings has been studied extensively in the literature (see, e.g., McCluney, 1993, 1996). Hopefully, this deliberate large scatter in LSG will ensure that the broadest range of both non-spectrally selective and spectrally selective glazing systems is chosen. The LSG of the selected specimens spans from 0.058 to 2.381 (Table 2), indicating glazing systems of very diverse properties and performance.

*Manufacturer Representation*: Although it was impossible to include all manufacturers listed in the Glazing Library, there was an effort to have each of the NFRC Members’ and major
United States manufacturers’ products represented. To that end, there was also an attempt to include the most common product types.

*Reference Glazing:* Some of the glazing systems were selected because they were used in previous research projects, such as those by McCluney (1993, 1996) and McCluney and Gueymard (1993). The results for these reference systems can be used for comparison and verification purposes, or future scientific research.

A list of the 37 glazing systems analyzed in this project is presented in Table 1. A plot of the visible transmittance vs. the Solar Heat Gain Coefficient (SHGC) for each glazing system is presented in Figure 1. Both Table 1 and Figures 1–3 are also included in a separate spreadsheet file. [In that file, moving the cursor over a symbol in the original Figure (in the “Figure 1” tab, reproduced here also as Figure 1) helps to identify that point.]

![Fig. 1 Visible transmittance ($T_{vis}$) vs SHGC for the 37 specimens](image)

Figure 1 also indicates some properties of glass, such as the limits of the “Color Zone”, “Forbidden Zone”, and “Neutral Zone”, as defined by Mike Rubin and explained in McCluney and Gueymard (1993).
<table>
<thead>
<tr>
<th>Glazing</th>
<th>GRCBC 1.1 Layers</th>
<th>Glass ID</th>
<th>Name</th>
<th>Product Name</th>
<th>Manufacturer</th>
<th>Source</th>
<th>Model</th>
<th>Thick.</th>
<th>Short</th>
<th>Max</th>
<th>Span</th>
<th>Max</th>
<th>Comments</th>
</tr>
</thead>
</table>
| 1       | ROCKWOOL 1.1   | 75      | RIM   | Granite MT3 1.1 | GRCBC        | 1.1     | 2.0   | 112  | 217  | 25  | 250  | 25  | Low Level/ 
|         |                 |         |      |              |             |         |       |       |       |     |      |     | Low Transmittance |
| 11      | GEM 1.1        | 79      | GEM   | Sedona Gray 1.1 | GRCBC        | 1.1     | 2.0   | 112  | 217  | 25  | 250  | 25  | Low Transmittance |
| 44      | LEER 2.1       | 109     | LEER  | Cerro 2.1    | GRCBC        | 1.1     | 2.0   | 112  | 217  | 25  | 250  | 25  | 3.014 | 0.284 | 0.142 0.195 | Low Transmittance |
| 28      | CLEAR 3.2      | 108     | CLEAR | Clear 3.2    | GRCBC        | 1.1     | 2.0   | 112  | 217  | 25  | 250  | 25  | 3.014 | 0.284 | 0.142 0.195 | Low Transmittance |
|         |                 |         |      |              |             |         |       |       |       |     |      |     | Low Transmittance |
| 16      | 3M 3173         | 134     | 3M    | 3173         | GRCBC        | 1.1     | 2.0   | 112  | 217  | 25  | 250  | 25  | 3.014 | 0.284 | 0.142 0.195 | Low Transmittance |
| 17      | 3M 3173         | 134     | 3M    | 3173         | GRCBC        | 1.1     | 2.0   | 112  | 217  | 25  | 250  | 25  | 3.014 | 0.284 | 0.142 0.195 | Low Transmittance |
| 26      | ROCKWOOL 1.1   | 134     | ROCKW | ROCKWOOL 1.1 | GRCBC        | 1.1     | 2.0   | 112  | 217  | 25  | 250  | 25  | 3.014 | 0.284 | 0.142 0.195 | Low Transmittance |
| 44      | ROCKWOOL 1.1   | 134     | ROCKW | ROCKWOOL 1.1 | GRCBC        | 1.1     | 2.0   | 112  | 217  | 25  | 250  | 25  | 3.014 | 0.284 | 0.142 0.195 | Low Transmittance |
|         | 119             | 134     |       |              |             |         |       |       |       |     |      |     | 3.014 | 0.284 | 0.142 0.195 | Low Transmittance |

Table 1 Summary statistics for the optical properties of the 37-specimen dataset.
Figure 2 presents the distribution of LSG for all of the glazing systems, in increasing order of LSG. The frequency distribution of LSG (in number of cases per bin of 0.2 LSG) appears in Figure 3. These figures demonstrate the large range of spectral selectivity of all the specimens. For the whole dataset, the range in LSG, U-factor, Tvis and SHGC is quite large (Table 2).

![Figure 2](image1.png)

**Fig. 2** Distribution of LSG (=Tvis/SHGC) among the 37 specimens, in increasing order of LSG

![Figure 3](image2.png)

**Fig. 3** Frequency distribution of LSG, i.e., number of specimens per bin of 0.2 LSG

<table>
<thead>
<tr>
<th>Variable</th>
<th>U-Factor</th>
<th>SHGC</th>
<th>Tvis</th>
<th>LSG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>W/(m² • K)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Minimum</td>
<td>1.204</td>
<td>0.102</td>
<td>0.035</td>
<td>0.229</td>
</tr>
<tr>
<td>Mean</td>
<td>3.529</td>
<td>0.477</td>
<td>0.555</td>
<td>1.202</td>
</tr>
<tr>
<td>Maximum</td>
<td>5.912</td>
<td>0.897</td>
<td>0.921</td>
<td>2.381</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>1.868</td>
<td>0.236</td>
<td>0.273</td>
<td>0.550</td>
</tr>
</tbody>
</table>

**Table 2** Summary statistics for the optical properties of the 37-specimen dataset.
Some details need to be stressed for a proper interpretation of Table 1.

**Center-of-Glass:** All of the thermal and optical properties are listed for the center-of-glass region as calculated by WINDOW 5.2.17a. Although edge and spacer effects may affect the U-factor, they do not affect the visible transmittance or solar heat gain of the glazing system, and therefore were omitted from the scope of this analysis.

**Glazing Thickness:** Most of the glazing samples have a nominal thickness of 6 mm. (The exact thickness varies between 5.613 and 6.760 mm.) Two monolithic substrates (e.g., polycarbonate and bronze glass) of vastly different thicknesses (e.g., 3 and 12 mm) are included in the “Reference Glazing” category to show the combined effects of the spectral weighing function and glazing thickness on SHGC. All the clear glass layers in double and triple glazing systems are 3-mm thick. Finally, the thickness of the Heat Mirror suspended films (#61–65), of one laminate (#19), and of the electrochromic systems (#58 and 59) is less than 6 mm.

**Gas Fill and Cavity Thicknesses:** The gas-fill thicknesses are always 19.5 mm in the double-glazing systems, and 12.7 mm in triple-glazing specimens. The clear-glass layer in double- and triple-glazing systems is always the same 3-mm Generic Clear Glass. Air is used as the gas fill in all of the specimens as none of the gasses used to fill cavities in typical glazing systems are spectrally selective at these thicknesses.

**U-Factor:** The values listed in Tables 1 and 2 correspond to a vertical glazing system. This study considers that the same systems could also be mounted on a roof, whose standard tilt is 20° (NFRC 100). Under such conditions, the U-factor is larger (sometimes significantly) than in the vertical case. This effect has been considered in all of the simulations performed at a 20° tilt.

**Orientation of Films/Coatings:** The single glazed systems always have applied films facing indoors except for the SunClean on Clear (#25), which has the film facing outside. All of the double- and triple- glazed systems have the low-e coating or film applied to the inner surface of the outer pane (Surface 2), which is inside of the glazing cavity. The heat mirror films are all oriented in the same direction, with the lower-emittance surface facing toward the outside (Surface 3).

**Software and Naming Convention:** All of the thermal and optical properties in Table 1 were generated using WINDOW 5.2.17a and OPTICS 5.1. The Glass ID, Name, Product Name and other information in Table 1 was directly copied from the Glazing Library (15.5) in the WINDOW 5 program.

**Task 1 Deliverables:** The original Work Statement required that a list 20 specimens be provided to the PMTG, of which 16 would be selected for analysis.

In actuality, the PI analyzed 37 specimens after the list was approved by the PMTG.
Task 2 – Evaluation of Rated Optical Properties Using Various Spectral Weighting Functions

Using WINDOW and OPTICS (the current NFRC 200 and NFRC 300 approved computer modeling software) the SHGC and VT ratings of the glazing systems identified in Task 1 were determined, successively for various spectral weighting functions not currently available in these computer programs.

The PMTG approved the following seven spectra to be used to analyze the 37 test specimens chosen in Task 1. The first three spectra have already been standardized by ASTM. The last four are in the process (see Task 3), and have been given a temporary ASTM Work Item Number, WK 17196.

1. ASTM E891 Spectrum (used by default in WINDOW 5.2), as prescribed by NFRC 200 & NFRC 300. This is the “base case” scenario, to which all other results will be compared. The calculations in Table 1 use this default spectrum.
4. Proposed ASTM Direct Irradiance Spectrum for a 20º Tilt
5. Proposed ASTM Global Irradiance Spectrum for a 20º Tilt
6. Proposed ASTM Direct Irradiance Spectrum for a Vertical Surface

Discussion on Diffuse Radiation

It is important to stress that NFRC 200 and NFRC 300 specify a direct spectrum, whereas Europeans specify a global spectrum. In general terms, a global spectrum is a combination of a direct and a diffuse spectrum. The diffuse spectrum is always richer in blue wavelengths than a direct spectrum, but overall has a far lower intensity than the direct spectrum. This is illustrated in Figure 4, which refers to the proposed ASTM spectra mentioned above.

Another difference between a direct and diffuse spectrum is that the former is associated with a quasi-point source (the sun’s disc), whereas the latter originates from the whole sky vault and/or the ground (by reflection). Moreover, the spatial distribution of diffuse radiation is not homogeneous over the sky. This considerably complicates the analysis of diffuse solar heat gains.

Currently, WINDOW 5.2 calculates the SHGC and VT for direct irradiance only. The proposed ASTM Standard (see Task 3 below) includes spectra separately for direct and diffuse solar irradiance for both vertical and 20º-tilted surfaces. [The 20º tilt angle has been standardized by NFRC to define the tilt of skylights used on roofs.]

There is ongoing discussion related to the importance of considering the diffuse radiation incident on fenestration. The PI has been in negotiation with LBNL concerning the implementation of this desirable new capability in WINDOW (i.e., addressing the calculation of SHGC and VT for incident diffuse radiation, in addition to direct radiation). Unfortunately, LBNL’s staff was not able to implement that modification in time to be included in this research project.
The proposed spectra separate direct and diffuse irradiance because it is anticipated that WINDOW and other fenestration analysis software will eventually calculate the transmission of diffuse radiation. This would be particularly important for diffusing fenestration systems (i.e., frits, frosted glass, etc.), and for an eventual annual energy rating, since most windows are exposed to significant diffuse radiation for long periods during the year. The total diffuse irradiance might even have to be separated into \textit{sky diffuse} and \textit{ground-reflected diffuse}, because both their spectral \textit{and} angular distributions are different. This might come into play in a future version of WINDOW, per our discussions with LBNL.

Since WINDOW cannot currently consider point sources of diffuse radiation, each associated with a different incidence angle, the only possible way to use a diffuse or global spectral weighting function is by assimilating them to a direct spectrum, i.e., by ignoring the multidirectional aspect of diffuse radiation. This normally does not introduce too much error because diffuse irradiance is generally a small fraction of direct irradiance, as mentioned above (Fig. 4). The notable exception, however, is in the UV and at blue wavelengths, where the diffuse fraction is significant. As mentioned earlier, the European methodology uses a global spectrum as if it were purely direct radiation. Until a true calculation of diffuse SHGC and VT calculations can be done reliably, we think this pragmatic approach is the best compromise.

A provision is made in the proposed ASTM standard that the tabulated \textit{diffuse} spectral irradiance can be used solely to represent cases when a surface is shaded from the sun, and therefore no direct radiation impinges on fenestration. This is a very common case under realistic conditions.
Alternate Spectra
The comparison between the existing NFRC spectrum (i.e., ASTM E891) and the proposed direct and global spectra for vertical and 20° tilts are presented in Figures 5–7. Interestingly, these figures show that the four proposed spectra are less different from the current NFRC weighting function than the two existing ASTM G173 standard spectra.

![Fig. 5 Direct and global reference spectral irradiance distributions from ASTM G173 compared to the current NFRC distribution, per ASTM E891](image)

![Fig. 6 Direct and global reference spectral irradiance distributions for vertical surfaces from the proposed ASTM standard compared to the current NFRC distribution, per ASTM E891](image)
Fig. 7 Direct and global reference spectral irradiance distributions for 20°-tilted surfaces from the proposed ASTM standard compared to the current NFRC distribution, per ASTM E891

U-Factor and Tilt Effects
This study considers the spectral effects affecting both vertical fenestration and roof-mounted skylights. Although it is likely that not all of the 37 selected specimens would constitute good skylights, we have simulated them all anyway for both a 90° and a 20° tilt. Note, however, that a change in tilt also affects the convection heat transfer, and hence the U-factor. Our results show that, for our 37 specimens, the U-factor increases by 8–34% when moving from a 90° tilt to a 20° tilt (Figure 8). The largest percent changes normally correspond to the lowest U-factors.

Fig. 8 Percent change in U-factor for a 20°-tilt vs. a 90°-tilt, for varying U-factor (left) or LSG (right).
To serve as the base case for all 20°-tilt simulations, we have first evaluated SHGC with the default E891 spectrum at a 20° tilt, and have calculated the percent change in SHGC from the more usual results at the 90° tilt. These results are illustrated in Figure 9 and show that, even without modifying the default spectrum, increases in SHGC of up to 20% occur because of the tilt effect alone. The largest increase occurs with specimen #11, a film-on-glass system, whose response to various environmental changes will be singled out and discussed further in what follows.

![Change in SHGC vs LSG for E891, from 90° to 20° tilt](image)

**Fig. 9** Percent change in SHGC for a 20°-tilt compared to a 90°-tilt, with the default spectrum

**Methodology**
For each of the 37 specimens of Table 1, the WINDOW software has been run in “non-standard” mode, once for each of the six alternate spectra defined above. Such runs require some tweaking since WINDOW does not currently store these spectra, and does not offer a user-friendly way to switch from one spectrum to another, while at the same time transparently change the environmental conditions (which include the tilt and the total irradiance corresponding to the spectral weighting function). Files in the appropriate format had to be prepared and added to the appropriate folders.

WINDOW is currently limited in the number of wavelengths a spectral file can contain. The original files prepared with the SMARTS radiative code (Gueymard, 2001) for Task 3 and the proposed ASTM standard were of too high resolution for WINDOW. Therefore, degraded spectra (down to only 671 wavelengths from the original 2002 wavelengths) were obtained, at 1 nm resolution (rather than 0.5 nm) between 300 and 400 nm, at 5 nm resolution (rather than 1 nm) up to 2500 nm, and 10 nm beyond (rather than 5 nm). The “environmental conditions” setting in WINDOW, which particularly includes the total integrated irradiance in the spectrum,
also had to be changed consistently. In particular, this means that the calculations involving the two 20°-tilt spectra were done for the geometry of a 20°-tilt roof. In these two instances, the base case spectrum was also used with a 20°-tilt geometry.

Instructions for glazing and coating manufacturers to calculate the solar and optical properties of any glazing system using these six alternate spectra in WINDOW are provided in Appendix 1 and as a separate document. The intent is to allow NFRC to post a folder containing these files and instructions on their website so that NFRC Members can perform these calculations on their own.

**SHGC Sensitivity Results**

A statistical analysis of the data has been performed to determine whether the change in SHGC ratings of any glazing system resulting from a change in spectral weighting function can be predicted. Such a prediction would be easy if a relationship could be shown to exist between the glazing system’s degree of spectral selectivity (usually described by LSG) and the expected relative change in SHGC and VT ratings.

Percent changes in SHGC have been calculated for each specimen and alternate spectrum. They are consolidated in Table 3, which is extracted from a detailed spreadsheet. The latter is also made available separately for further reference. The columns in Table 3 correspond to the alternate spectra listed on p. 10.

Among the four newly proposed ASTM spectra, the 20°-tilt global spectrum is the one that deviates most from the base case (Figure 7), nearly as much as the global G173 spectrum (#3, Figure 5). The percent change in SHGC due to using the 20°-tilt global spectrum rather than the current E891 is illustrated in Figure 10. All specimens are color coded per their category in Table 1. There is no clear dependence of the change in SHGC on the specimen category, except that electrochromics display little change, and triple glazings consistently display moderate to high changes (5–8%). Double low-e systems exhibit a linear increase of the change in SHGC with increasing LSG. Below an LSG of about 1, all specimens exhibit very limited changes, in the range -2 to +3%. This is the case, for instance, of specimen ID #11 with a 3.1% change. Changes tend to be larger at higher LSGs, up to +11% for double low-e specimens.

Figure 11 is similar to Figure 10, but for the global vertical spectrum (#7). The changes in SHGC are significantly less than in Figure 10. This could be expected since this spectrum is closer to the base case (Figure 6). The magnitude of the changes is nearly half of that in Figure 10, for all specimens. It ranges from -1 to +7%. For low LSGs (<1), the changes are very limited, from -1 to 2%, and do not seem to depend on LSG. Changes are also only marginally affected by LSG for LSGs greater than 1.8. The main sensitivity area is clearly for glazing systems that have LSGs between 1 and 1.8.

Figure 12 shows the percent change in SHGC for all alternate spectra and all specimens. System #11 deviates again from the general trend, but is not alone. An upward trend of increasing percent change in SHGC with increasing LSG clearly appears, but the scatter is relatively large. This scatter precludes the possibility of accurately predicting, from LSG alone, by how much the SHGC of any glazing system would change. Considering, however, the wide range of optical
properties in the specimen list, it is unlikely that excursions beyond -3 and +11% would result from such a change.
Table 3  Percent change in U-factor, SHGC, Tvis and LSG due to a change in the spectral weighting function and tilt. The six alternate spectra are defined on p. 10.

<table>
<thead>
<tr>
<th>Spectra</th>
<th>U-Fact.</th>
<th>Percent change in SHGC</th>
<th>Percent change in Tvis</th>
<th>Percent change in LSG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window Films on Glazing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BRONZE 6AG + Sunbelt LowE</td>
<td>1.357</td>
<td>34.0</td>
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<td>GRAY 6AG + Gold</td>
<td>0.302</td>
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<td>28.9</td>
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<td>CLEAR 6PPG + REFSSARM</td>
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<td>CLEAR 6PPG + SunClear</td>
<td>0.144</td>
<td>34.0</td>
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Laminates and Laminated Glazing

<table>
<thead>
<tr>
<th>Spectra</th>
<th>U-Fact.</th>
<th>Percent change in SHGC</th>
<th>Percent change in Tvis</th>
<th>Percent change in LSG</th>
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<tr>
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<tr>
<td>09 650 9 SOL</td>
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</tbody>
</table>

Reference Glazing

<table>
<thead>
<tr>
<th>Spectra</th>
<th>U-Fact.</th>
<th>Percent change in SHGC</th>
<th>Percent change in Tvis</th>
<th>Percent change in LSG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylate</td>
<td>1.073</td>
<td>34.0</td>
<td>34.0</td>
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</tr>
<tr>
<td>Polycarbonate</td>
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<tr>
<td>Glass</td>
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</tr>
<tr>
<td>Glass</td>
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</tr>
<tr>
<td>Glass</td>
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</tr>
<tr>
<td>27 Amrol 6PPG + VE785</td>
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</tr>
<tr>
<td>28 Exponent CP + VE855</td>
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<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>57 CLEAR 3 DF</td>
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<td>34.0</td>
<td>34.0</td>
<td>34.0</td>
</tr>
</tbody>
</table>

Double Glazing - Low-E

<table>
<thead>
<tr>
<th>Spectra</th>
<th>U-Fact.</th>
<th>Percent change in SHGC</th>
<th>Percent change in Tvis</th>
<th>Percent change in LSG</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRONZE 6AG + Sunbelt LowE</td>
<td>1.530</td>
<td>34.0</td>
<td>34.0</td>
<td>34.0</td>
</tr>
<tr>
<td>CLEAR 3 CIG + VE785</td>
<td>1.743</td>
<td>34.0</td>
<td>34.0</td>
<td>34.0</td>
</tr>
<tr>
<td>CLEAR 2 CP + Gango 1000</td>
<td>2.374</td>
<td>34.0</td>
<td>34.0</td>
<td>34.0</td>
</tr>
<tr>
<td>CLEAR 2 CIG + Gango 500</td>
<td>1.121</td>
<td>34.0</td>
<td>34.0</td>
<td>34.0</td>
</tr>
<tr>
<td>CLEAR 2 CIG</td>
<td>1.050</td>
<td>34.0</td>
<td>34.0</td>
<td>34.0</td>
</tr>
</tbody>
</table>

Double Glazing - Elctrochromic

<table>
<thead>
<tr>
<th>Spectra</th>
<th>U-Fact.</th>
<th>Percent change in SHGC</th>
<th>Percent change in Tvis</th>
<th>Percent change in LSG</th>
</tr>
</thead>
<tbody>
<tr>
<td>58 Unknown + SageGlass EC</td>
<td>0.343</td>
<td>34.0</td>
<td>34.0</td>
<td>34.0</td>
</tr>
<tr>
<td>59 Unknown + SageGlass EC</td>
<td>1.034</td>
<td>34.0</td>
<td>34.0</td>
<td>34.0</td>
</tr>
</tbody>
</table>

Triple Glazing - Clear, Heat Mirror & Low-E

<table>
<thead>
<tr>
<th>Spectra</th>
<th>U-Fact.</th>
<th>Percent change in SHGC</th>
<th>Percent change in Tvis</th>
<th>Percent change in LSG</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRONZE 6CIG + VE785</td>
<td>1.730</td>
<td>34.0</td>
<td>34.0</td>
<td>34.0</td>
</tr>
<tr>
<td>CLEAR 2 CP + Gango 1000</td>
<td>1.432</td>
<td>34.0</td>
<td>34.0</td>
<td>34.0</td>
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<tr>
<td>CLEAR 2 CIG</td>
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<td>34.0</td>
<td>34.0</td>
<td>34.0</td>
</tr>
<tr>
<td>CLEAR 2 CIG + Gango 500</td>
<td>1.423</td>
<td>34.0</td>
<td>34.0</td>
<td>34.0</td>
</tr>
<tr>
<td>CLEAR 2 CIG + Gango 1000</td>
<td>1.534</td>
<td>34.0</td>
<td>34.0</td>
<td>34.0</td>
</tr>
<tr>
<td>CLEAR 2 CIG + Gango 500</td>
<td>1.688</td>
<td>34.0</td>
<td>34.0</td>
<td>34.0</td>
</tr>
</tbody>
</table>
Fig. 10 Percent change in SHGC vs LSG for each specimen of Table 1, using the proposed 20°-tilt global spectrum. Results are color coded by specimen category.

Fig. 11 Same as Fig. 10, but for the proposed 90°-tilt global spectrum.
Interestingly, the calculated changes are normally the lowest (between about -2 and +7%) for spectra #6 and 7, which are the ASTM-proposed direct and global spectra for vertical tilts, respectively. These numbers are comparable to, if not lower than, the percent differences typically obtained when comparing modeled and experimentally measured SHGC values. This finding supports the notion that, for better agreement between modeled and measured data, the variable effect of the incident spectrum should be taken into account. See Appendix 2 for a discussion of a theoretical methodology to adjust test results from solar calorimeters for differences in the source spectrum, provided that the source spectrum can be identified.

**Predicting Changes in SHGC**

Figure 12 shows the upward trend of the change in SHGC vs. LSG. The curves indicate least-squares fits using simple quadratics. The scatter around these curves complicates the prediction of the change in SHGC. Although nothing would replace the actual calculation of SHGC with WINDOW, we have investigated the prediction possibilities a little further. Much can be gained by analyzing the reason behind the very presence of outliers. Since the only change in this case is in the incident spectrum, the reason must be spectral in nature, even though it does not appear to be related to LSG. Figure 13 compares the spectral transmittances of two different systems: ID #11 (film-on-glass) and ID #73 (double glazing with low-E). For the latter specimen, the change in SHGC is 5.3% in the case of Fig. 10 and 4.0% in the case of Fig. 11, compared to 3.1% and 1.2%, respectively, for the former (Table 3). The figure also shows the relative distributions of the current spectral weighting function (E891) and of the alternate spectrum #7, after normalization to 0.3 at 555 nm, for clarity. Whereas the peak of the transmittance of specimen #73 (at 560 nm) is close to that of the incident spectra, the peak of #11’s transmittance is at a far
smaller wavelength, namely 400 nm. The transmittance of specimen #73 is typical of the advanced systems that try to maximize VT while minimizing SHGC. From Table 1, these numbers are 0.378 and 0.247, respectively. These numbers change to 0.049 and 0.162 for specimen #11. It is likely that a bivariate fit, using both LSG and the peak-to-peak distance as the independent variables, would predict the change in SHGC with relatively better accuracy than a fit based on LSG alone, but this has not been attempted yet.

![Glazing System Transmittance](image)

Fig. 13  Spectral transmittance of two specimens (ID#11 and ID#73), compared to two spectral weighting functions, normalized to 0.3 at 555 nm for clarity.

**Visible Transmittance and LSG Sensitivity**
The Work Statement specifically called for an analysis of the change in VT induced by a change in the spectral weighting function. After this analysis started, it became clear that the VT ratings would not be affected by a change in the solar spectrum since NFRC 300 specifies another spectral weighting function for VT, namely CIE’s standard illuminant (D65). The latter attempts to reproduce the typical spectral distribution of daylight at a correlated color temperature of 6500 K. It is based entirely on spectral measurements obtained in the early ‘60s (Judd et al., 1964).
Having to rely on two different spectra for the calculation of SHGC and VT appears as a source of inconsistency. The visible spectrum (300–830 nm in D65) is obviously a significant part of the solar spectrum used for SHGC (300–2500 nm), and should not be a separate entity. Furthermore, this discrepancy translates into an inconsistent definition of LSG = VT/SHGC.

![Relative spectral distributions of some solar spectra and of CIE D65. All spectra are normalized to their value at 555 nm, which is the peak of CIE’s photopic response curve, also shown.](image)

After discussion with the PMTG, it was agreed that this part of Task 2 would be modified to analyze what changes in VT would occur if D65 was replaced by the same solar spectra weighting function as for SHGC.

Preliminary calculations showed that, in the visible, there were noticeable differences between the spectral distribution in D65 and some other solar spectra considered here (Figure 14). It can be hypothesized that these differences are in great part the result of the correlated temperature constraint. Close examination of Figure 14 reveals that the largest difference is between D65 and the current NFRC 300 solar weighting function. This can be explained by the fact that D65 is a daylight spectrum, which mixes direct and diffuse radiation, whereas the E891/NFRC 300 spectrum is for direct radiation only. If D65 could be used as a weighting function for SHGC in replacement of E891, it is obvious that far larger SHGC changes than those reported in the previous section would occur. Nevertheless, it can be argued that the role of the photopic curve is essential here to attenuate these differences.
VT is obtained by convolving the glazing’s spectral transmittance results with both the spectral weighting function (e.g., D65) and the photopic response curve (also shown in Fig. 14). Since the latter is highly peaked, it remains to be seen whether the spectral discrepancy observed in Figure 14 would survive the latter convolution. The result of convolving all spectra in Figure 14 with the photopic curve appears in Figure 15. The resulting “reduced” spectral distributions now appear in relatively close agreement, although D65 is perceptibly shifted towards bluer wavelengths than the other distributions.

![Normalized spectra of Fig. 10, after convolution with the photopic curve.](image)

As could be expected from the findings just described, the effect of changing from D65 to any one of the six alternate spectra defined above is significantly reduced compared to the effect on SHGC, due to the strong filtering effect of the photopic curve. As shown in Figure 16, these changes are typically well within ±2% for most specimens, with specimen #11 right at the limit of -2%. There are three outliers (two laminates and an electrochromic) in the -5 to +5% range. Curiously, these two laminates display significant and unmatched variability in VT from one spectrum to the other. Since many glazing systems have a VT lower than 0.5, a change in VT less than ±2% results in an absolute change of less than 0.01, which would only affect the third decimal.
Change in Tvis vs LSG

Fig. 16 Percent change in Tvis vs LSG for each specimen of Table 1, for each alternate spectrum

Change in LSG vs LSG

Fig. 17 Percent change in LSG vs current LSG for each specimen of Table 1, for each alternate spectrum
Finally, Figure 17 shows how the adoption of an alternate spectrum would affect LSG. VT being significantly less sensitive to the weighting function than SHGC, and LSG being inversely proportional to SHGC, it is clear that the spectral effect on LSG is close to be the reverse of what it is on SHGC (Figure 12).

During our discussions with the PMTG, it has been argued that VT was a variable to consider in colorimetry. Colorimetric calculations are based on D65 and are not likely to change soon. To respect the integrity of this application, it has been proposed that the color properties continue to be based on D65. This implies that new columns be added to the “Color Properties” tab in WINDOW to report the visible transmittance and reflectances based on D65.

Task 2 Deliverables: The original Work Statement requires that a minimum of four spectra be selected for analysis. It also stipulates that a method to adjust calorimeter test results for spectral effects be explored.

In actuality, the PI produced results for six alternate spectra. The effect of changing the spectral weighting function for the calculation of VT (currently disconnected from that of SHGC) was investigated. The relationship between the glazing system’s degree of spectral selectivity and the expected relative change in SHGC and VT ratings was analyzed and reported. A methodology of adjusting solar calorimeter test results based on a known source spectrum has been explored and presented (see Appendix 2).
Task 3 – Report ASTM Activities and Represent NFRC at ASTM G-03.09 Meetings

At the time the work statement was written, it was thought that the best venue for developing NFRC-oriented solar spectra would be through CIE TC 2.17. A general meeting in Europe was then being organized by the TC chairman. Various organizational problems occurred, however, and that meeting could not take place as anticipated.

Following the discussions we had at previous ASTM and CIE meetings and with confirmation from the PMTG, we finally elected to develop the new standard spectra through ASTM instead of CIE.

ASTM G-03.09 subcommittee on Radiometry had produced various reference spectra in the last few years (e.g., ASTM G173 and ASTM G177) with the help of the first PI, and therefore was considered the appropriate ASTM Subcommittee to develop this new standard.

ASTM Activity: ASTM G-03.09 was approached, and accepted, to develop standard direct normal and diffuse spectra for fenestration at vertical and 20° tilted orientations. The first PI prepared a draft standard, which he presented at the ASTM G-03.09 subcommittee meeting in Cleveland, Ohio in June 2007, chaired by Gene Zerlaut. The draft standard has some similarities with the existing G173 standard (adopted in 2003), but is tailored for fenestration applications. Spectral calculations are made with the same SMARTS code (Gueymard, 2001; Gueymard et al., 2002) that was used to develop G173, as well as a spectral heat gain calculation procedure for ASHRAE (Gueymard, 2007). The tabulated data include the direct and diffuse irradiance incident on vertical and 20°-tilted sun-facing planes, under predetermined atmospheric and environmental conditions. The global irradiance is simply obtained by summing the direct and diffuse components. The data tables extend from 280 to 4000 nm, with a total of 2002 wavelengths. Three spectral steps are used: 0.5 nm in the UV (280–400 nm), 1 nm between 400 and 1700 nm, and 5 nm beyond. The SMARTS code, which has been recognized as an adjunct standard by ASTM in 2003, can be used to degrade these spectra to accommodate a variety of lower spectral resolutions. It can also be used to separate the sky and ground-reflected diffuse components if so desired.

Shortly after this meeting in June 2007, a revised draft for this proposed ASTM standard was balloted at subcommittee level, under the ASTM Work Item number WK 17196. The single negative and the few editorial comments from that ballot were resolved by the first PI at the following ASTM meeting in Fort Lauderdale, Florida on January 22, 2008. The revised draft is now being finalized, and will be submitted for full G-03 Committee ballot shortly.

CIE Activity: Immediately following both ASTM G-03.09 meetings mentioned above, there were also CIE TC 2-17 “limited” meetings. The North American representation to CIE TC 2.17 is modest compared to the European one, but the latter does not attend the North American meetings such as these, thus creating a difficult situation. Gene Zerlaut has tried to convene a CIE TC 2.17 meeting in Europe, but this has not materialized yet. This state of affair appears to us as a confirmation that the projected “NFRC-friendly spectrum” will be standardized by ASTM much faster than it would have been by CIE. It is possible, however, that CIE eventually
adopts some variant of the draft ASTM standard for its own use, which would make these new reference spectra known by the glazing industry in Europe and elsewhere.

*Task 3 Deliverables:* The original Work Statement required that new spectrum standards be developed by CIE, and that the PI attend the NFRC meetings.

With permission from the PMTG, these standard spectra were developed and balloted at ASTM G-03.09 instead of CIE. If the next G-03 ballot goes smoothly as anticipated, the new standard should be adopted by ASTM later this year.

The second PI attended all NFRC meetings. In addition, the first PI (Chris Gueymard) attended the NFRC Meeting in Tempe, Arizona in November 2007, as also stipulated by the Work Statement.
Task 4 – Reports on CIE Activities, Final Report, and Technical Paper

Three status reports (including this final report), and three presentations, were given at all of the NFRC Research Subcommittee meetings since the initiation of this research project. These reports and presentations described the status of the project, as well as our activities within ASTM and CIE.

The peer-reviewed paper will be derived from this final report upon its approval by the PMTG. The current plan is to submit it to Solar Energy. This journal already published important papers on NFRC-related methodologies (e.g., Karlsson et al., 2001; Rubin et al, 1998, 1999).

Task 4 Deliverables: The original Work Statement required that the status of the project and the activities within CIE be reported to the PMTG and the NFRC Membership. In addition, a peer-reviewed paper describing the project and conclusions had to be developed and submitted for publication.

The PI indeed reported the progress and standardization activities to the PMTG and NFRC meetings (see also Task 3 Deliverables). Although the required reports and presentations have been delivered, the peer-reviewed paper is still under development. An important step in the process will be the acceptance of this Final Report by the PMTG.
Recommendations

Based on the results from this research project, the PI recommends that the NFRC peruse the following future activities.

*Adopt the new (draft standard) ASTM G-03.09 Spectrum for Global Irradiance on Vertical Surfaces for Windows*

Not only is this new standard spectrum more accurate than the current default spectrum, it does not significantly change the listed solar and optical properties of most glazing systems. By adopting this new spectrum, it will also become easier to correct spectrum-induced discrepancies between modeled and experimentally determined SHGC data.

If this new spectrum is adopted, the spectral weighting functions in future versions of WINDOW, OPTICS (NFRC 200), and the ASTM E 903 Test Method (NFRC 300) will need to be modified. These modifications should be balloted and approved for each calculation methodology and test method by the NFRC Membership.

*Adopt the new (draft standard) ASTM G-03.09 Spectrum for Global Irradiance on 20°-Tilt Surfaces for Skylights*

For consistency, the SHGC procedure for skylights should adopt the global 20°-tilt spectrum draft standard, which has been developed specifically for that application. The change in SHGC would be slightly larger than with the 90°-tilt spectrum recommended above, but on the other hand, this change would most likely lead to more accurate numbers, and better agreement between modeled and experimental data.

*Use Identical Solar and Visible Spectrum in WINDOW*

NFRC 300 currently specifies that the visible transmittance be calculated using a different spectrum (CIE D65) than SHGC (ASTM E891). This discrepancy is confusing, and does not permit the Light-to-Solar-Gain (LSG) ratio to be properly determined. To remove this inconsistency and to simplify and update the procedure, we recommend that the spectral weighting function for VT be identical to that for SHGC.

*Upgrade WINDOW to Use the ASTM G-03.09 Spectrum for Direct & Diffuse Irradiance*

Once the WINDOW software is capable of performing SHGC calculations using direct and diffuse irradiance separately, the Direct and Diffuse spectral irradiance standards should be adopted and specified. Fortunately, the adoption of this methodology and spectra should not produce significant variations in the solar and optical performance in all but a few glazing systems as compared with the results from the current spectral weighting function or the recommended global spectrum.
References


Lawrence Berkeley National Laboratory, WINDOW 5.2.17a, Berkeley, CA (2005), http://windows.lbl.gov/software/window/window.html.


Appendix 1 — Instructions for Calculating Solar and Optical Properties of Select Glazing Systems Using Alternate Spectra in WINDOW 5.2

Overview—Researchers, window and glazing manufacturers may want to determine whether the solar and optical properties of any glazing system are significantly affected by the use of any of the alternate spectra presented in the NFRC SWF Research Project. These instructions provide guidance on how to create a separate WINDOW 5.2 Glazing System Library that will reference alternate environmental conditions, namely Spectral Data and Standard files (*.ssp & *.std) within WINDOW. The differences in the solar and optical properties using different spectra can then be easily determined by comparing the results from repetitive calculations on the same Glazing System Library. Comprehensive step-by-step instructions are provided in this document.

1. Create Glazing System Library

Although it is not essential, it is recommended that a separate WINDOW database be created that contains only those glazing systems in the Glazing System Library to be considered for comparison. This can be performed in two different ways. One is to save the entire database as another name (click on File|Save As in the menu bar). This will copy all the records from the original database into the new database. Another option is to make a separate “Project” database, by exporting records from one database into another. To make a Project database from a master database from the Glazing System Library, create the desired glazing systems, and then use the “Ctrl” and “Shift” keys to highlight those glazing systems in the [List] view of the WINDOW Glazing Library. As shown in Fig. 1, use the [Export] button to copy those selected glazing systems into a new WINDOW database file (*.mdb) with a different name and/or location.
Click on the [New] button to create a new file.

Figure 1 - Select Glazing Systems for Export to New WINDOW database
2. Copy Spectral Data and Standard Files into the WINDOW Standards Folder

Copy the following pairs of files\(^1\) from the attached folder to the WINDOW Standards folder\(^2\):

**ASTM G 173-03, Air Mass of 1.5, Direct Normal Irradiance**
- “ASTM G173 AM1_5 Direct Normal.ssp”
- “W5_NFRC_2003 G173 AM1_5 Direct Normal.std”

**ASTM G 173-03, Air Mass of 1.5, Global Irradiance on a Surface at a 37° Tilt**
- “ASTM G173 AM1_5 37 Tilt Global.ssp”
- “W5_NFRC_2003 G173 AM1_5 37 Tilt Global.std”

**ASTM WK17196, Air Mass of 1.5, Direct Irradiance on a Surface at a 20° Tilt**
- “ASTM WK17196 AM1_5 20 Tilt Direct.ssp”
- “W5_NFRC_2003 WK17196 AM1_5 20 Tilt Direct.std”

**ASTM WK17196, Air Mass of 1.5, Global Irradiance on a Surface at a 20° Tilt**
- “ASTM WK17196 AM1_5 20 Tilt Global.ssp”
- “W5_NFRC_2003 WK17196 AM1_5 20 Tilt Global.std”

**ASTM WK17196, Air Mass of 1.5, Direct Irradiance on a Surface at a 90° Tilt (Vertical)**
- “ASTM WK17196 AM1_5 90 Tilt Direct.ssp”
- “W5_NFRC_2003 WK17196 AM1_5 90 Tilt Direct.std”

**ASTM WK17196, Air Mass of 1.5, Global Irradiance on a Surface at a 90° Tilt (Vertical)**
- “ASTM WK17196 AM1_5 90 Tilt Global.ssp”
- “W5_NFRC_2003 WK17196 AM1_5 90 Tilt Global.std”

As shown in Fig. 2, the default location for the WINDOWS 5.2 Standards folder is:

```
C:\Program Files\LBNL\LBNL Shared\Standards
```

---

**Figure 2 - Copy Spectral Data and Standard Files to WINDOW Standards Folder**

\(^1\) Although it is recommended that all the files be copied into the WINDOW 5.2 Standards folder, one can limit their selection to specific spectra from the list. Make sure that the Spectral Data files (*.ssp), and the associated Standard files (*.std) are copied in pairs, as the Standards file calls upon a specific Spectral Data file.

\(^2\) Copy all these files directly into the Standards folder without making a subfolder.
3. Open the Glazing System Glazing Library in the Newly Created WINDOW Database

Open WINDOW, and then use the [Glazing System Library] toolbar button (or the Libraries/Glazing System menu choice) to open the new Glazing System Library that was previously created in Step 1 (Fig. 3).

![Figure 3 - Open New Glazing System Library for Analysis](image)

4. Change the WINDOW Standards File Reference

Open the Preferences box in WINDOW (on the Menu Bar, click on File>Preferences), and then click on the “Optical Data” Tab. Click on the [Browse] button under the “Standards File” section near the bottom (Fig. 4). Select the Standards file (*.std) representing the spectrum in question. Click on the [Open] button to select the file, and then click on the [OK] button to close the Preferences box. The WINDOW Spectral Data file (*.ssp) is referenced by the WINDOW Standards file, and so the Spectral Data file reference is not directly specified within WINDOW.

![Figure 4 - Specify Location of the New Standards File in Preferences](image)
5. Change the WINDOW Environmental Conditions

Click on the [Environmental Conditions Library] button to open that library (on the Menu Bar, click on Libraries|Environmental Conditions). From within the [List] view of the Environmental Conditions Library, highlight the first ID record, titled “NFRC 100-2002,” and use the [Copy] button to make a copy of that environmental condition (Fig. 5). Select this new environmental condition, and click on the [Detailed View] button to edit this condition.

![Environmental Conditions Library](image)

**Figure 5 - Copy NFRC 100-2002 Environmental Conditions to Edit**

By editing a copy of the NFRC 100-2002 Environmental Conditions, all of the specific environmental parameters (i.e., temperatures, emissivity, wind speed and direction, solar irradiance, and surface conductance coefficient models) for U-factor and SHGC will be initially defined. Only two fields need to be modified. First, change the environmental condition Name to reflect the use of the new spectrum, (i.e., “NFRC/ASTM G173 Global37”). Second, click on the “SHGC Outside” Tab, and change the Direct Solar Radiation value based on the last column of Table 1 (Fig. 6).

---

3 If the NFRC 100-2002 Condition is not available, use the [Import] button to copy it from the original “w5.mdb” file initially supplied with WINDOW 5.2.

4 The term “Direct Solar Radiation” is not exactly correct since some new spectra refer to global radiation, but is used in these instructions to be consistent with the current version of WINDOW.
Table 1 – *Direct Solar Radiation* Values for WINDOW 5.2 Standards Files

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Standards File</th>
<th>Direct Solar Radiation, W/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM E 891 (NFRC 300)</td>
<td>W5_NFRC_2003.std</td>
<td>783.0</td>
</tr>
<tr>
<td>ASTM G 173, Direct Normal</td>
<td>W5_NFRC_2003 G173 AM1_5 Direct Normal.std</td>
<td>900.1</td>
</tr>
<tr>
<td>ASTM G 173, Global, 37° Tilt</td>
<td>W5_NFRC_2003 G173 AM1_5 37 Tilt Global.std</td>
<td>1000.4</td>
</tr>
<tr>
<td>ASTM WK17196, Direct, 20° Tilt</td>
<td>W5_NFRC_2003 WK17196 AM1_5 20 Tilt Direct.std</td>
<td>791.1</td>
</tr>
<tr>
<td>ASTM WK17196, Global, 20° Tilt</td>
<td>W5_NFRC_2003 WK17196 AM1_5 20 Tilt Global.std</td>
<td>889.0</td>
</tr>
<tr>
<td>ASTM WK17196, Direct, 90° Tilt</td>
<td>W5_NFRC_2003 WK17196 AM1_5 90 Tilt Direct.std</td>
<td>669.7</td>
</tr>
<tr>
<td>ASTM WK17196, Global, 90° Tilt</td>
<td>W5_NFRC_2003 WK17196 AM1_5 90 Tilt Global.std</td>
<td>810.3</td>
</tr>
</tbody>
</table>

Figure 6 – Rename and Edit Copy of Existing NFRC 100-2002 Environmental Conditions

Click on the [Save] button to save the changes to this new Environmental Conditions file.
Once new Environmental Conditions have been created, the referenced Environmental Conditions must be individually changed for each glazing system by selecting the appropriate Environmental Conditions designation in the [Detailed View] of the Glazing System Library (Fig. 7). All of the Environmental Conditions entries in the Glazing System Library can be easily changed by scrolling through each glazing system using the [Next Record] button. This also a convenient time to change the tilt angle as described in the next step if necessary. To speed up the process of changing multiple records, press the [Calc] and [Save] button after each record is changed.

![Glazing System Library](image)

**Figure 7 - Select Environmental Conditions for Each Individual Glazing System**

6. **Change the Tilt of the Glazing System (20° Tilted Spectra Only)**

The outdoor and indoor surface heat transfer coefficients and the effective conductivity of glazing cavities vary with the tilt of the glazing system. Their effect on SHGC may appear small in many cases, but they can be of the same magnitude as those that result from a change in spectral distribution. Proper calculation of the SHGC therefore requires that the tilt of each glazing system be changed from 90° to 20° when using spectra for surfaces tilted at 20°. This modification must be performed individually for each glazing system by changing the Tilt value to 20 in the [Detailed View] (Fig. 8). All of the Tilt values in the Glazing Library can be easily changed by scrolling through each glazing system using the [Next Record] button. Remember to press the [Calc] and [Save] button after each record is changed.
Figure 8 – Change the Tilt Angle for Each Glazing System

7. Calculate

If you have not recalculated the results for all of the glazing systems while modifying the Environmental Conditions or tilt, then results may need to be calculated. From the Glazing Library [List] view, click on the [Calc] button, and check the All records option before clicking on the [OK] button to calculate new solar and optical properties of all the glazing systems in the library. This will calculate new results for all the glazing systems using the new Spectral Data file referenced by the Standards file specified in the Preferences box. Changing the Standards file is a program setting, so all records are affected by those settings.

Use the [Report] button to create a text file of the results (Fig. 9). After deselecting Use default column widths, and Wrap column boxes in the “Text file options” section, press [OK] in the Report box to generate the report for All records. This report can then be saved as a comma delimited file (*.csv) using a name identifying the spectrum by pressing the [Save] button in the Report window. The comma delimited file needs to be specified in the Save as type field in the Save As box before pressing the [Save] button.

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5 The variations in the ultra-violet (UV) results calculated by WINDOW in the “Optical Data” tab are not reported in this research project. By specifying the Standards files provided with these instructions, the spectra used to calculate the Krochman Damage Weighted Average (Tdw-K), the UV Damage Weighted Transmittance based on CIE 89/3 (Tdw-ISO), and the Unweighted UV Average (Tuv) are all calculated using the new spectra instead of ASTM E891.

6 For this reason, it is important that the new Standards file be replaced with the original “W5_NFRC_2003.std” file once this analysis is complete as this initial Standards file will not be restored when opening your original database.
8. Compare

Repeat Steps 4 through 7 for each spectrum under consideration. The results from calculations of all the spectra can be easily compared by opening each of the comma-delimited files (*.csv) in a spreadsheet (Fig. 10), and copying the appropriate data from each file into the same worksheet.

Figure 9 - Create Text File Using WINDOW 5.2 [Report] Button

Figure 10 - Open Exported Text File in Spreadsheet
Appendix 2 — Proposed Methodology to Adjust Solar Calorimeter Test Results Based on a Known Source Spectrum

**Overview** – Although the calculation of SHGC is typically performed using a unique standard spectrum, the measurement of the SHGC of windows, door and skylights using solar calorimeters is seldom—if ever—performed using a light source emitting a spectrum that is the same as this standard spectrum. This is often a source of discrepancy when comparing simulated SHGC with measurements from solar calorimeters. In the process of performing this research project, the investigators cultivated a methodology to correct the differences between test and simulation results. If the spectral characteristics of the light source are known, such as with an electric artificial light source, or by measurement or inference of the incident solar spectrum outdoors, it becomes possible to adjust the solar calorimeter test results to more closely match simulation at a standard spectrum. This Appendix outlines a methodology to perform that adjustment.

**Characterize Source Spectrum** – Measurement or estimation of the actual spectrum emitted from a light source such as the sun or an electric light is not a trivial task. A discussion of methods of obtaining the spectral response curves of light sources that might be used to illuminate solar calorimeters follows:

**Indoor Solar Calorimeters – Electric Artificial Light Source**: The spectral output from an electric light may be the easiest to obtain, especially if it can be provided by the manufacturer of the lamp. Manufacturers of large-scale lamps, like those used to simulate sunlight, are often able to provide the spectral output from their lamps in sufficient detail. For instance, Figure A2 shows the output from a Vortek Lamp used by Bodycote Materials Testing for their indoor solar calorimeter compared with the ASTM E891 spectrum and the proposed ASTM Global 90°-tilt spectrum.

If the spectral response of the electric light source cannot be provided by the manufacturer, or the source has been altered by additional lamps or filters, then the spectrum of the incident irradiation on the face of the indoor solar calorimeter may need to be directly measured. Although instrumentation and testing methodologies are available to perform this measurement, it is not an easy or inexpensive task.

**Outdoor Solar Calorimeters – Natural Sunlight**: The spectral composition of the irradiance from the sun, the sky or the ground is considerably more variable than that of indoor lamps, but it can be measured or estimated. As in the measurement of the spectral characteristics of electric lamps, the measurement of the spectrum of incident solar and diffuse irradiation is difficult and expensive to perform. The sensors must be rugged enough to withstand exposure to the outdoor environment, and the angular distribution of the diffuse irradiation from the ground and the sky must be taken into account. Accurate,

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7 Bodycote Materials Testing Canada, Inc. 2395 Speakman Drive, Mississauga, ON L5K 1B3, Contact: Alfred Brunger (905) 822-4111 Ex 544
laboratory-grade equipment can be expensive to purchase and maintain. Nevertheless, acceptable measurements can generally be performed by commercially available sensors and software that may be adequate for this task.

Another way to estimate the spectral composition of the incident spectrum is to use SMARTE software\(^8\) to calculate the direct irradiance from the sun, and the diffuse irradiance emanating from the sky or reflected by the ground. This can be done for a specific time, date and location, given that certain atmospheric parameters can be determined or estimated. Some of these atmospheric parameters may be measured by

\(^8\) Available from http://www.nrel.gov/rrredc/smarts/.
nearby airports, universities or government laboratories, and are generally available to the public. In addition, these atmospheric parameters may be estimated from other sources (such as satellite data) by qualified technicians and scientists.

Select Similar Glazing System Specimen – Select or construct a glazing system from the WINDOWS 5.2 Glazing System Library that most closely resembles the test specimen installed in the solar calorimeter. Most importantly, the spectral characteristics and the SHGC of the glazing system selected in the Glazing System Library must be as close as possible to the test specimen.

Methodologies to Calculate SHGC of Glazing System Using Measured and Standard Spectra

1. Approximate (Short) Method
   Use WINDOW to calculate the SHGC of the selected glazing system using the standard spectrum, \( SHGC_{STD} \). Since these calculations are attempting to mimic the conditions experienced during solar calorimeter tests, it may be necessary to change the Environmental Conditions within WINDOW from the standard NFRC conditions, to conditions that more closely resemble the actual environmental conditions experienced during testing.

   Using the same environmental conditions, recalculate the SHGC using WINDOW, but replace the standard spectrum with the source spectrum measured or estimated by the previously described methodology, \( SHGC_{ALT} \). The source spectrum will have to be converted into a WINDOW spectral file (*.ssp), which typically means that the resolution is degraded to 1 nm resolution between 300 and 400 nm, 5 nm resolution up to 2500 nm, and 10 nm beyond. Use the Instructions provided in Appendix 1 of this report as guidance in performing WINDOW 5.2 calculations with alternate spectra.

   Correct the Measured SHGC – Simply use the ratio of the SHGC calculated using the standard spectrum, \( SHGC_{STD} \) to the SHGC calculated using the actual spectrum, \( SHGC_{ALT} \), to adjust the measured SHGC. The corrected SHGC, \( SHGC_{SPEC} \), is a function of the measured SHGC, \( SHGC_{TEST} \), as follows:

   \[
   \frac{SHGC_{ALT}}{SHGC_{STD}} = \frac{SHGC_{TEST}}{SHGC_{SPEC}}
   \]  

2. Detailed (Long) Method
   This alternate method is derived from the technique known as “spectral mismatch correction” in the field of photovoltaic (PV) cell testing\(^9\). This method is more general and accurate than the short method above, but also involves more calculation.

\(^9\) See, e.g., D. Myers and C. Gueymard, Description and availability of the SMARTS spectral model for photovoltaic applications. 49th SPIE Annual Meeting, Denver, CO (2004).
The definition of $SHGC$ is

$$SHGC = T_s + A_s N_i$$

(2)

where $T_s$ is the fraction of incident flux transmitted through the glazing to the interior (i.e., its transmittance), $A_s$ is the glazing system’s absorptance, and $N_i$ is the fraction of the absorbed radiation that is re-emitted to the interior. For any glazing system, the calculation described by Eq. (2) is actually performed wavelength by wavelength in WINDOW. Therefore, for each wavelength $\lambda$,

$$SHGC_{\lambda} = T_{s\lambda} + A_{s\lambda} N_i.$$  

(3)

Note that $N_i$ does not depend on the wavelength of the incident shortwave (or “solar”) spectrum, since it is only a function of the convection, conduction and longwave (“infrared” or “thermal”) radiation heat transfer characteristics of the glazing system. The limit between the shortwave and longwave domains is 4–5 $\mu$m, approximately.

When all individual spectral calculations are completed, WINDOW performs the final step, by convolving the calculated SHGC spectrum defined by Eq. (3) with the standard SWF, i.e.,

$$SHGC_{STD} = \int SHGC_{\lambda} E_{STD\lambda} d\lambda / \int E_{STD\lambda} d\lambda$$

(4)

where $E_{STD\lambda}$ is the standard spectral solar irradiance at wavelength $\lambda$. The denominator in Eq. (4) simply represents the integrated incident solar irradiance, per the last column of Table A1 in Appendix 1.

Using Eq. (3), Eq. (4) can be developed into

$$SHGC_{STD} = \left[ \int T_{s\lambda} E_{STD\lambda} d\lambda + N_i \int A_{s\lambda} E_{STD\lambda} d\lambda \right] / \int E_{STD\lambda} d\lambda.$$  

(5)

If the actual spectral irradiance during the experimental tests is $E_{ALT\lambda}$ (obtained either by measurement or prediction with, e.g., SMARTS, as discussed above), the SHGC that WINDOW would predict under the spectral test conditions is

$$SHGC_{ALT} = \left[ \int T_{s\lambda} E_{ALT\lambda} d\lambda + N_i \int A_{s\lambda} E_{ALT\lambda} d\lambda \right] / \int E_{ALT\lambda} d\lambda.$$  

(6)

The $T_{s\lambda}$ and $A_{s\lambda}$ spectra are important characteristics of the glazing system, which can be exported from WINDOW. Therefore, $SHGC_{ALT}$ can be easily calculated from Eq. (6) in a spreadsheet if $N_i$ is known. Whenever $N_i$ is not known beforehand, it can be derived from Eq. (3), such as

$$N_i = (SHGC - T_s) / A_s.$$  

(7)
SHGC_{ALT} thus obtained from Eq. (6) should be the same as if WINDOW was actually used to calculate it when using the procedure described in Appendix 1 (to change the standard spectrum for an alternate spectrum—in this case, E_{ALT,\lambda}).

NOTES
1. Rather than correcting the measured value of SHGC as in the short method, the intent of the long method is, conversely, to obtain the theoretical SHGC that would correspond to the spectral test conditions.

2. The detailed methodology would also have to include cases where the tested fenestration system includes glazing layers whose spectral characteristics are close, but not necessarily identical to, the data in WINDOW. This case has not been discussed in the overview of the long method for conciseness.

3. The equations involving integrals are given in mathematical form for further reference, and may look intimidating. In practice, they are easily calculated as summations of columnar values in a spreadsheet.