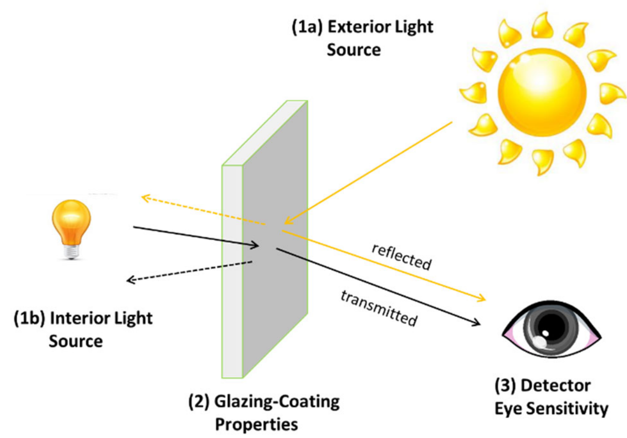
Solarban® Solar Control Low-E Glass Color Uniformity

The purpose of this technical document is to describe the basics of color and how it relates to various glazing types and applications in the commercial building design, fabrication and installation process. The following information outlines Vitro Flat Glass recommendations for glazing color uniformity based on the ASTM C1376 Standard.

Commercial buildings encompass many different end use segments including office, mercantile, multi-family housing, education, food service, lodging, healthcare and many others. Current design trends of all of these segments include more expansive glazing area, larger glazing units, and improved energy performance attributes. Balancing these trends with the always present need of a pleasing aesthetic appeal has led to the use of more complex glazing constructions. In many buildings, the goal of improved energy performance is met by incorporating solar control low-e coated glass into the design.

The responsible parties including Building Owners, Architects, Glazing Contractors, Fabricators, and Flat Glass Producers have much to consider given this design trend and the complex nature of the high tech glass products being used in buildings today. Balancing the performance requirements and the aesthetic desires is no easy task.

Vitro Flat Glass has a long standing history of providing quality *Solarban®* and *Sungate®* low-e glasses for the architectural building industry. These glasses are comprised of clear, ultra-clear, or tinted glass substrates of varying thicknesses with an additional micro-thin coating deposited onto the glass surface. The high tech coating process used to accomplish this is called magnetron sputter vacuum deposition (MSVD). This process requires a level of vacuum equivalent to outer space and deposits multi-layers of various metals and metal oxides one atom at a time. This requires a lot of energy, accurate gas flow controls, and precise process monitoring to successfully deposit coatings that are measured in angstroms (10^{-10} meters). Relative to the glass thickness the total coating stack is only 0.0002 times as thick. However even at this thickness, low-e coatings have an impact on light that passes through, absorbs in, or reflects off the coating. ***It is this interaction between light, the coated glass, and the eye of the observer that is directly related to color uniformity as illustrated in the following graphic.***



Color uniformity of coated glass in an architectural application can be defined as the variation in appearance of the color and/or shade within one glazed unit or between two or more glazed units of the same type on a typical elevation of a building. Color of coated glass, or any object for that matter, can be described by a mathematical model that was developed by CIE (International Commission on Illumination). Color space is based on one coordinate L* for *Luminance* (lightness-darkness) and two *Color* coordinates a* & b* and is therefore three dimensional as illustrated in the graphic on the following page.

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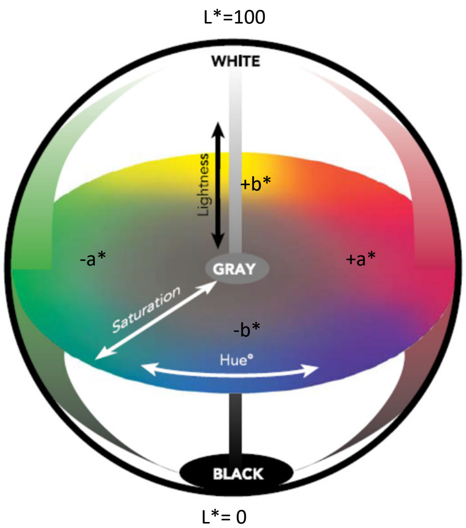
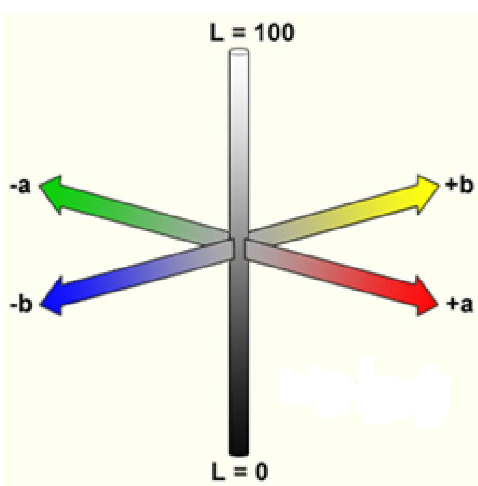


Color defined in terms of three dimensional L*a*b*

In this color model, the L* values range from (0) darkest to (100) lightest. Positive a* values are more red while negative a* values are more green. Positive b* values are more yellow while negative b* values are more blue. Another way to look at the L*a*b* color space is shown in the diagram below.



Most glass and coated glass products with the exception of painted spandrels are fairly neutral in color and have L* values that range from 20 to 97 and a* & b* values that range from -20 to +20. For example, ¼" Solarblue® tinted glass has transmitted color of L*=80.0, a*=-4.8, b*=-10.0 and therefore appears light blue. In comparison, Clear glass has L*=95.4, a*=-1.8, b*=0.1 and appears slightly green. Take this same Clear glass and put a low-e coating such as *Solarban®* R100 on the #2 surface and now L*=74.1, a*=-4.7, b*=-3.2 and the glass appears somewhat darker bluish-green when looking through the glass in transmission.

Low-e coatings can also increase the amount of reflection which adds to the perceived color especially as viewed from the building exterior. Under certain lighting conditions (overcast sky) and/or viewing angles (45 to 60 degrees), the reflected color appearance can dominate especially against the dark background of an unfinished interior. Once the building is completed inside and outside, the appearance of the glazing will change and previously perceived color differences become muted. ***Perceived color differences due to changing site conditions and/or viewing conditions further illustrates the need for measuring color and utilizing data along with visual observations to assess color uniformity.***

Measuring color can be accomplished by using a spectrophotometer. This type of instrument has a light source, a sample holder or port, an integrating sphere to collect light, and a detector. It also typically has built-in software to calculate the measured color and display values in L*, a*, and b* or other color systems.

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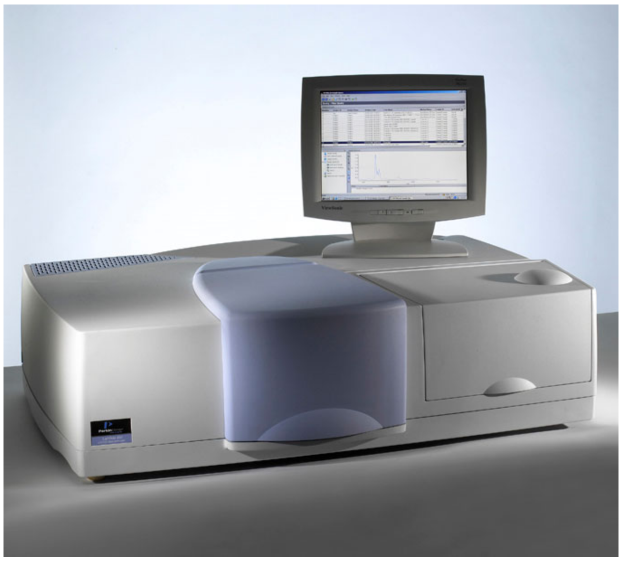
Typical Spectrophotometers –



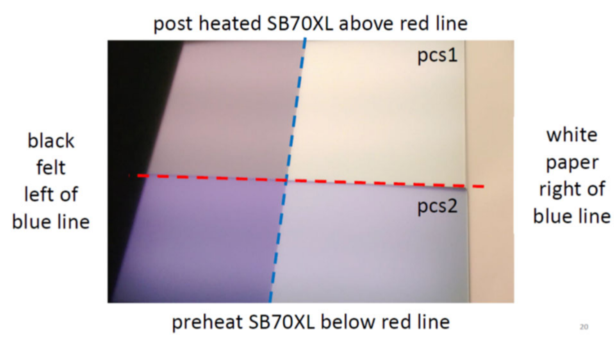
Laboratory Unit w/ closed sample chamber

Larger bench top spectrophotometers are typically used in the laboratory and are the most accurate and precise and therefore costly (>$100,000 USD).
They are used to set color reference standards and where more accurate color measurements are required in both transmitted and reflection mode.

Hand held spectrophotometer for field measurements

Smaller hand held spectrophotometers function in a similar fashion and are effective in taking color measurements in the field since they are easily portable. A disadvantage is related to the fact that the sample being measured is not held in a closed and dark chamber but rather is exposed to ambient light which can influence the readings somewhat. Also the hand held unit will only measure reflected color. However, the hand held unit is still a valuable tool for measuring color at various points within a glazing unit as well as between multiple glazing units, including large sizes, and is also fairly affordable (~$10,000 - $15,000 USD).

Color Shift Explained: The color of *Solarban*® and *Sungate*® heatable glass designated as VT (vacuum temperable) is designed to change during a typical heat treatment process. These heat treatable low-e coatings start out one color as produced in the monolithic form by Vitro. The color is further modified during the subsequent heating process used by the fabricator to heat strengthen or fully temper the glass as shown in the picture below.



Two pieces of Solarban® glass showing the color shift due to the typical heat treatment by a fabricator

When the coated glass is assembled into an IGU or laminate along with other lite(s) of glass, coated or uncoated, the color is now a blending of these components as light interacts with the various materials including the air gap(s) and/or PVB interlayer.

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During the development of *Solarban®* or *Sungate®* coatings, Vitro Flat Glass goes to great lengths to design, engineer, and test the coating to consider all of these variables and in the end provide the color uniformity to meet or exceed requirements for commercial, residential and specialty glazing applications.

Color Differences and Tolerance

Based on the unique color target for each type of coated glass product, the ASTM C1376 Standard requirements for color uniformity can be applied. Note the comments in this standard in regards to what the impact of varying lighting conditions (i.e. differences between factory lighting conditions and jobsite conditions) will have on perceived color.

Should jobsite color uniformity concerns arise, the color data measured with a spectrophotometer for the glazing in question in comparison to glazing with acceptable appearance can be used to determine whether or not the color uniformity requirements have been meet.

Color Difference Equation is used to calculate the differences between two color measurements for comparative purposes [reference ASTM D2244].

The color difference equation is referred to as ΔE^*_{ab} and is calculated using the following:

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

For example, the reflected color of a low-e coated sample #1 is L*=33.0, a*=4.0, b*=2.0 and sample #2 is L*=33.5, a*=5.0, b*=4.0. The color difference between them is calculated as follows:

$$\Delta E^*_{ab} = \mathrm{SQRT}((33.5-33.0)^2+(5.0-4.0)^2+(4.0-2.0)^2) = 2.3$$

The calculation between a color target and a color measurement taken on a piece of glass can be done in a similar fashion. ASTM C1376 describes how the color target can be obtained and used to determine color uniformity. ASTM D2244 goes into more details regarding how color tolerances are defined along with various calculations.

Color Uniformity Considerations in Glazing Design should be reviewed during the early stages of glazing design and material selection for a given building project. The following list provides many of the known considerations but is not an exhaustive list. Thus, the glazing manufacturer should be consulted. Also it is strongly recommended to perform a full size mock-up early on in the project under actual (or simulated) finished building and project site location conditions. Review the mock-up under various viewing conditions (i.e. exterior, interior, straight on, at angle, cloudy, sunny, blinds, no blinds, reflections of adjacent structures & trees, shading devices, etc.) with all stakeholders of the particular project. Recommend that actual color data be provided on the glazing used for the mock-up. The mock-up should be retained throughout the project as a reference of what was reviewed and approved for visual appearance. Keep in mind that a mock-up done on the ground level with limited number of glazing units may still appear somewhat different than the completed glazing curtain wall some thirty stories above the ground due to angular color considerations.

- Use of tinted glass on the outer lite, especially darker tints, will mask much if not all of the color differences in the low-e coating. Caution must be used when placing darker tinted glass behind *Solarban®* glass as this contrast acts to highlight color variation. When using a non-coated dark tinted glass as the outer lite, ensure consistent tin

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side & air side orientation in the IGU and/or laminate assemblies (refer to TD-122 "Surface Orientation of Low Light Transmittance Glasses").

- Low-e coatings developed and optimized for surface #2 of the IGU can be placed on #3 surface but may have more color variation especially if the outer lite is Clear or *Starphire* Ultra-Clear™ glass. For solar control applications, Vitro suggests using a dark tinted outer lite to mask color variations when surface #3 coatings are desired by design. Note: An IGU with designated surface #2 coating that is manufactured or installed backwards will have noticeable color difference since the coating is now on the #3 surface as installed.
- Coatings on multiple surfaces will have combined color effects. For example, the colors of a low-e coating on #2 surface and on #4 surface may be additive. Another example would be low-e coatings on multiple surfaces of triple IGU's.
- Surrounding conditions (overhangs, shadows and reflections from trees or adjacent buildings) affect perceived color and can have a dramatic effect even if all glazing meets color uniformity requirements.
- Different perceived color on different elevations can occur due to different viewing conditions. Building orientation to North-South and East-West will impact how direct and indirect sunlight shines on the glazing. For example, North elevations tend to have less direct sunlight and therefore more shadows which can affect the perceived color.
- During the glazing installation, units with exposed edges (w/o frames or adjacent rows of windows) can appear different to the eye due to edge lighting effects.
- Time of day and year effects ambient lighting (polarized light effect) and perceived glass color.
- Overcast versus sunny skies can affect the perceived color sometimes quite dramatically.
- Interior shading devices and shadow boxes can affect perceived color.
- Relative sizes (very large versus small) of adjacent windows can make perceived color appear slightly different due to the amount of continuous glass surface the eye views. Similar to why Curtain Wall designs tend to be more critical than punched openings for perceived color uniformity. For more details, search online for "field size metamerism".
- Types of glazing (spandrel, laminated, glass with dot/line patterns or some other decorative pattern) will affect perceived color and add variation. Reference ASTM C1376 Appendix X1 for additional information.
- Attic stock is recommended for best color match if replacements are needed for subsequent glass breakage of installed glazing units.
- Effects of glazing on color appearance of interior design elements when looking through the glass or how exterior objects appear when looking from the inside of the building out is beyond the scope of this technical document.

Color Influencing Factors: Due to all of the above listed factors that can and do influence perceived glazing color on a building, one must exercise caution when visually judging glazing color uniformity. In reaching a conclusion about the visual appearance of the glazing, take into consideration all the influencing factors that may be affecting the perceived color observed at any given time.

One may conclude that there appears to be something "wrong" with the glazing when in fact the color differences observed are not due to the glass

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itself but rather due to the viewing and/or surrounding conditions.

This can be particularly true early on in the build cycle just after the glazing is installed. Because the building interior is unfinished, the background behind the glazing, when viewed from the exterior, is dark with minimal light coming from behind the glass (the black hole effect). Therefore, primarily what one sees is the reflected color of the glazing which is further enhanced by the angle of view.

Once the building interior structure and decor (i.e. walls, furniture, blinds, drapes, lights, etc.) are completed, light from outside has opportunity to pass through the glass and then bounce off this internal structure and combine with any man-made interior lighting that results in a transmitted color. This transmitted color blends with the reflected color and tends to mute the overall exterior appearance of the glazing color. This phenomenon gives further credence to performing a complete full size mock-up reviewed under various conditions as previously stated. ***Also this points out the need for measuring glazing color with a spectrophotometer to remove the subjectivity when assessing glazing color uniformity.***

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HISTORY TABLE		
ITEM	DATE	DESCRIPTION
0	2016-08-03	Initial Release of architectural version
1	2016-10-04	Updated to Vitro Logo and format
2	2018-03-27	Updated Vitro Logo and format
3	2019-06-06	Revised bullet items 1&2 on pgs 4&5
4	2020-06-01	Transfer to TD-155

KEYWORDS: color, glazing, appearance, uniformity, aesthetic, low-e, coated glass, luminance, transmitted, reflection, color difference equation, spectrophotometer, color shift, color monitoring, color target, color plot, color tolerance, glazing design, metamerism, color influencing factors, mock-up

REFERENCES: ASTM C1376 & D2244, CIE, LBNL, IGDB, US DOE, TD-122