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An Examination of Keyes Universal Chart: 50 Years Later

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ABSTRACT

From the late 1940's to the late 1960's, significant efforts were made by ASHVE and then ASHRAE to evaluate and quantify the impact of window shading. In the context of the now defunct Shading Coefficient, well known researchers such as Parmelee, Ozisik, Schutrum, Farber, Yellott, and Keyes laid the groundwork for much of the work that followed decades later. Of particular interest are the efforts of Keyes. In his work, he produced a method of classifying fabric based either on visible inspection, or on property measurements. The result was the Keyes Universal Chart, which was first published in the 1965 ASHRAE Guide and Data Book, and has been part of the Fenestration Chapter of the ASHRAE Handbook of Fundamentals since its inception. The chart compares fabric transmittance, reflectance, and openness. It also permits estimation of these properties by making generalized fabric classifications based on a subjective analysis of how light or dark the fabric is, and how open or closed the fabric weave is. More recently, significant efforts have been made to produce window shading models for use in building simulation and daylighting analysis. As part of this research, shading materials have been analyzed using modern and highly accurate spectrophotometric equipment. Unfortunately, that data has revealed inaccuracy in Keyes Universal Chart. The present work examines this inaccuracy.

INTRODUCTION

With increasing energy demand and dwindling energy supply, the attention given to designing and constructing energy efficient buildings is ever present. Despite all the good things they do, windows are a potential weak point in any energy efficiency strategy. Thermally, they provide less resistance than wall construction, which is a detriment both in a heating and cooling climate. From a solar heat gain perspective, they have the potential to either offset heating or drive up cooling demand. As buildings become better insulated, and as one moves to a more cooling dominated climate, increased cooling demand becomes a serious concern. A window design that is able to transition from high to low solar heat gain would be a great asset. Simple shading devices can be used to make a window 'switchable'.

Called a Complex Fenestration System (CFS), it is well recognized how important these switchable window systems could be. Fittingly, since the mid 1990's, ASHRAE Technical Committee 4.05: Fenestration (TC4.05) and others have paid significant attention to quantifying the benefits of shading devices placed on window. Several are worth mentioning.

- While not part of the TC4.05 efforts, one must include the work of Van Dyck and Konen (1982) who produced solar/optical models of shades and CFS for implementation into the WIS software.
- McCluney and Mills (1993) modeled solar/optical properties of shade materials, and then used this to determine window system solar/optical behavior.
- Klems (1994a, 1994b) developed the Matrix Layer Calculation. The method has great potential to accurately quantify CFSs both from energy and daylighting perspectives. The complexity of this approach is a problem as it relies on difficult to obtain measurements (Klems and Warner, 1995) and is computationally intensive. Still the approach laid the groundwork for the efforts that followed (Klems 2001), and in particular, introduced the use of the Indoor Attenuation Coefficient (IAC).

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- Collins and Wright have made significant strides towards not only producing accurate models of CFS performance (Kotey et al. 2009a-d, 2011), but also producing and implementing a methodology that allowed for these calculations to be included in building simulation software where computational speed is important (Wright and Kotey 2006, Collins and Wright 2006, Wright et al. 2008, Foroushani et al. 2015). This most recent work was largely supported by ASHRAE Research Project 1311 (Wright et al. 2009).

Looking beyond energy considerations:

- Tzempelikos (Chan et al. 2015a-b) has been carefully studying the complex issue of balancing the combined impact of windows on energy, daylighting, and comfort.

Great strides have been made, and continue to be made in this area, and building designers now have the tools to quantify the benefits of CFSs of many forms.

It would be incorrect, however, to assume that all CFS research has occurred over the past 20 years. In the period from the late 1940's to the late 1960's significant efforts were also made in this area.

- Parmelee (Parmelee and Aubele 1952, Parmelee et al. 1953) examined the effect of slat type sun shades on heat gain to the indoors using both mathematical analysis and solar calorimetry. Later, Ozisik and Schutrum performed similar measurements for roller shades (Ozisik and Schutrum 1959) and drapes (Ozisik and Schutrum 1960). Both of these studies were limited to single-glazed windows.
- Farber et al. (1963) performed a theoretical analysis of solar heat gain through double pane glazing units with both Venetian blinds and draperies. A parallel experimental study was also carried out to validate the theoretical treatment (Pennington et al. 1964).
- Yellott experimentally determined the solar performance of draperies using the ASHRAE solar calorimeter (Yellott 1965). He also measured the solar optical properties of fabrics and glass-drape combinations using custom-made instruments. In that work, Yellott makes frequent reference to the work of Keyes, and together they propose that fabric properties be rated based on yarn reflectance and fabric openness (the percent open area between fibers in a fabric). This approach was dubbed the *yarn reflectance-openness system*. They also state that visual estimation of fabric properties is accurate enough for this application.
- Moore and Pennington (1967) measured the solar optical properties of fabrics, draperies, and glass-drapery combinations using various techniques. They recommended that drapery classifications be designated by fabric solar optical properties using what they called the *fabric reflectance-transmittance system*, instead of the *yarn reflectance-openness system* proposed by Yellott and Keyes. They argued that openness needed to be properly determined, and that visual estimation may not be good enough depending on the fabric material, its thickness, and other characteristics such as color, which may be misleading as to its reflective characteristics.

THE DEVELOPMENT OF KEYES UNIVERSAL CHART

Although Keyes chart was first published in the 1965 ASHRAE Guide and Data Book (ASHRAE 1965), and referred to in the work of Yellott (1965), Keyes work itself was not published by ASHRAE until 1967 (Keyes 1967). In that work, Keyes not only discussed the solar control abilities of drapes, but also their impact on other factors related to thermal comfort and daylighting concerns. Further, he reasoned through the usefulness of the *yarn reflectance-openness system*. He mentioned that if the *fabric reflectance-transmittance system* proposed by Moore and Pennington (1967) were the only one employed, one would a) have no fundamental understanding of what is physically happening between the yarn and radiant input, b) move into complete dependence on instruments, and c) give up the ability to predict other performance characteristics of the drape fabric. He advocated, therefore, that both systems are needed; the *fabric reflectance-transmittance system* for accurate prediction of shading effect, and the *yarn reflectance-openness system* for approximating shading effect, and for evaluating other fabric characteristics.

To develop his Universal Chart, Keyes needed three pieces of information: the fabric reflectance, fabric transmission, and openness. He was able to obtain this data for various fabric materials, colors and weaves from four sources: the Yellott Solar Energy Laboratory (Yellott), the University of Florida (Pennington), Pennsylvania State University (Pass), and from the Pittsburgh Plate Glass Company (Schutrum, Stewart, and Keyes) (Keyes 1967). Keyes started by plotting fabric transmittance versus fabric reflectance. To place openness lines, Keyes would plot on this chart all data points within a range of the target openness. For example, all fabrics with openness between 0.15 and 0.25 were plotted. A curve fit to this data was set to be the 0.20 openness line (Figure 1). As openness and fabric transmission should be nearly the same at zero fabric reflectance, the line was anchored at that point. Note that, even with zero openness (i.e., one cannot see through fabric), a certain amount of radiation can still penetrate the fabric by transmittance through "transparent" fibers or by multiple reflections among fibers. In other words, zero openness does not necessarily mean zero transmission. Figure 1 shows this effect as each line of constant openness curves up, indicating increased fabric transmission as fabric reflectance increases to the right. Next, the line connecting 100% reflectance at zero transmittance and 100% transmittance at zero reflectance is a limit, so the plot takes on a triangular shape. Following this, yarn reflectance was included. It was calculated as the fabric reflectance divided by one minus the openness. The resulting yarn reflectance lines curve toward the theoretical boundary limit. The stronger the openness lines curve upwards, the more the yarn reflectance lines curve toward the boundary limit line. Note that, again, yarn reflectance cannot be measured, but the openness concept offers a way to estimate its value. As a final step, Keyes produced general fabric classifications on this chart. Fabrics were classified by weave as Open (I), Semi-open (II), and Closed (III), and by color as Dark (D), Medium (M), and Light (L). Table 1 summarizes the classification system. Figure 2 shows the Keyes Universal Chart along with lines of fabric reflectance and examples of fabric classifications. The process of developing the Keyes Universal Chart is fully described in Keyes (1967).

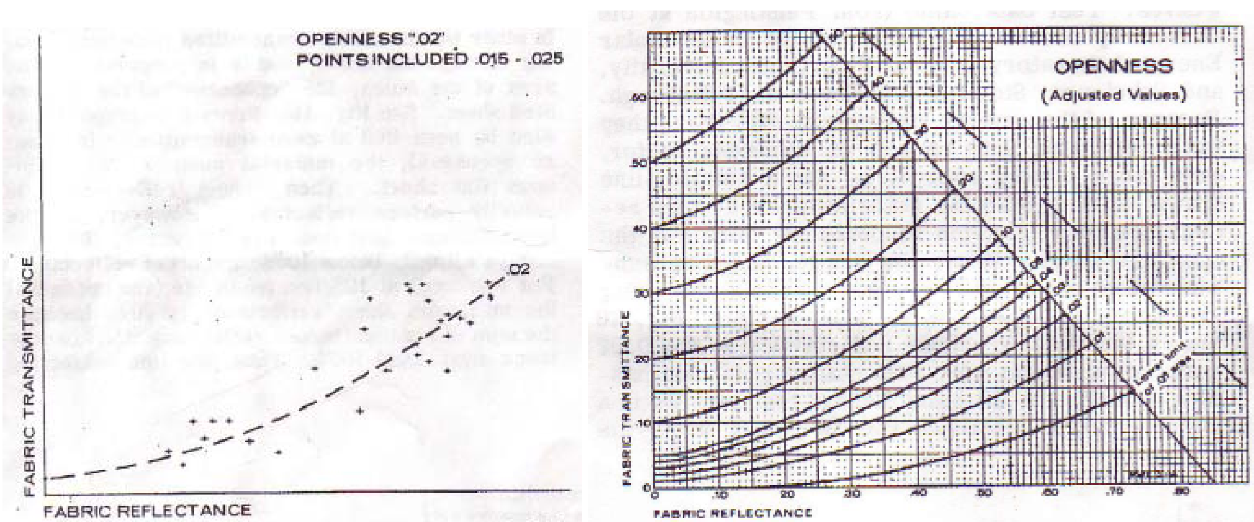

Figure 1 The development of Keyes Universal Chart (Keyes 1967).

Table 1. Fabric Classifications Outlined by Keyes (1967)

Classification	Region on Keyes Universal Chart
$\mathrm{I_L}$	Openness > 0.25, Yarn Refl. > 0.50
$\mathrm{II_L}$	0.07 < Openness < 0.25, Yarn Refl. > 0.50
$\mathrm{III_L}$	Openness < 0.07, Yarn Refl. > 0.50
$\mathrm{I_M}$	Openness > 0.25, 0.25 < Yarn Refl. < 0.50
$\mathrm{II_M}$	0.07 < Openness < 0.25, 0.25 < Yarn Refl. < 0.50
$\mathrm{III_M}$	Openness < 0.070.25 < Yarn Refl. < 0.50
$\mathrm{I_D}$	Openness > 0.25, Yarn Refl. < 0.25
$\mathrm{II_D}$	0.07 < Openness < 0.25, Yarn Refl. < 0.25
$\mathrm{III_D}$	Openness < 0.07, Yarn Refl. < 0.25

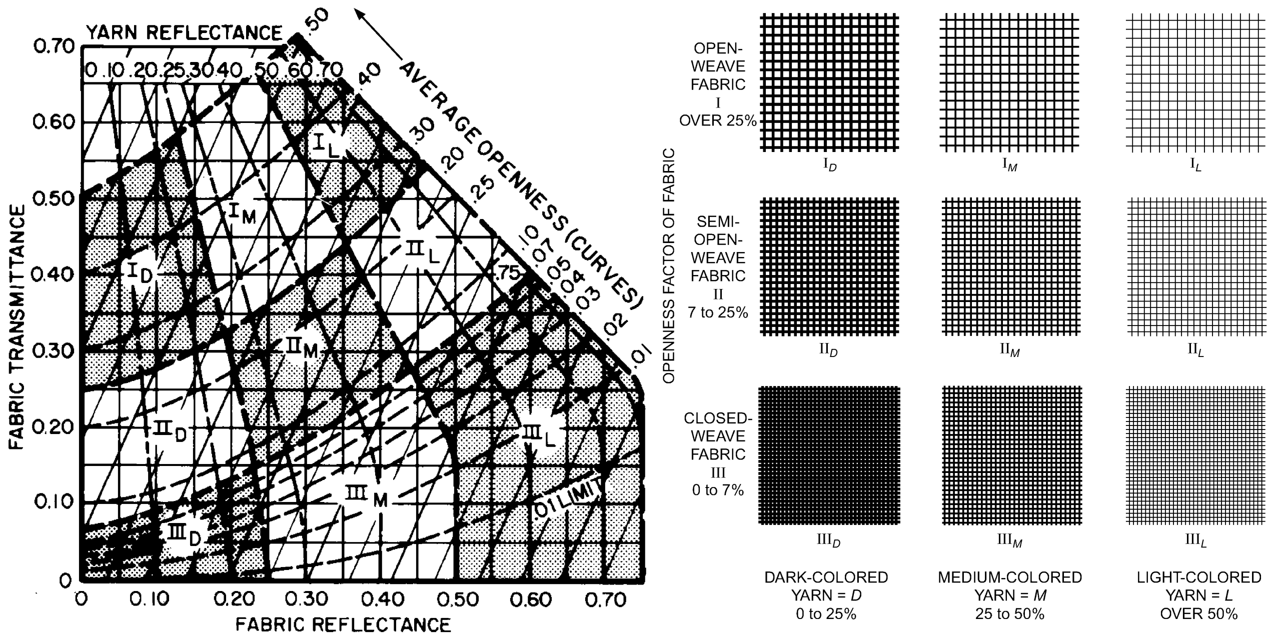

Figure 2 Keyes Universal Chart and fabric classifications (ASHRAE 2013).

This Keyes Universal Chart, has remained virtually unchanged for 50 years, and has been published in the Fenestration Chapter of every Handbook of Fundamentals. The only significant change was the replacement of shading coefficients with IACs in the 2001 Handbook of Fundamentals [ASHRAE 2001].

Issues with the Universal Chart

ASHRAE Research Project 1311 recently developed new solar optical and thermal models, and a new solution methodology by which window and shade combinations can be modeled in building simulation software (Wright et al. 2009). As part of that work, the link between the solar optical properties of shades and the solar optical properties of the materials from which they were made was required. In several cases, those models had already been developed. For example, drapery models for determining the solar optical properties of a drapery layer based of fabric properties had already been developed by Ozisik and Schutrum (1960), and by Yellott (1965). The accuracy and limitations of these models needed to be established, and in the case of drapery, this required the measurement of solar optical properties of several new fabrics.

In total, Kotey et al. (2009a) examined 9 fabrics, representing 8 of the 9 Keyes fabric classifications, and a sheer. A III_D sample was not included. He did so by using a highly accurate UV/VIS/NIR spectrophotometer. First, the specular (beam-beam) transmission, or openness, was measured. Then, with the help of an integrating sphere attachment, the total (beam-hemispherical or beam-total) reflectance and transmission were determined. Complete details of the measurement methods were documented in that work, and the results are reproduced in Table 2.

While the validity of the older drapery models proved to be very good, the same could not be said for Keyes Universal Chart. For each classification shown in Table 2, one could plot three different points on the chart: Openness–Reflectance, Openness–Transmittance, and Reflectance-Transmittance. These three points would form a right triangle on the chart with the reflectance-transmittance point located at the right angle. Given the Keyes had to approximate the openness curve from several points representing a range of measured openness values, it was not expected that these 3 points would overlay one another. They should, however, be in close proximity: the triangles should be small. Furthermore, it was expected that in the absence of bias, that upward pointing and downward pointing triangles would be seen. This, however, was not the case. Not only are some of the triangles large, indicating chart inaccuracy, but all of the triangles point in the same direction, indicating bias. Also concerning is the fact that some points lie significantly beyond the physical limits of the chart.

Table 2: Fabric Properties. Reproduced from Kotey et al. (2009a).

Classification	Openness (Beam-Beam Transmission)	Fabric Reflectance (Beam-Total Reflectance)	Fabric Transmittance (Beam-Total Transmittance)
Sheer	0.45	0.19	0.80
I_L	0.26	0.42	0.56
II_L	0.01	0.56	0.43
III_L	0.01	0.68	0.30
I_M	0.33	0.23	0.64
II_M	0.02	0.32	0.28
III_M	0.01	0.38	0.20
I_D	0.23	0.15	0.32
II_D	0.05	0.21	0.23

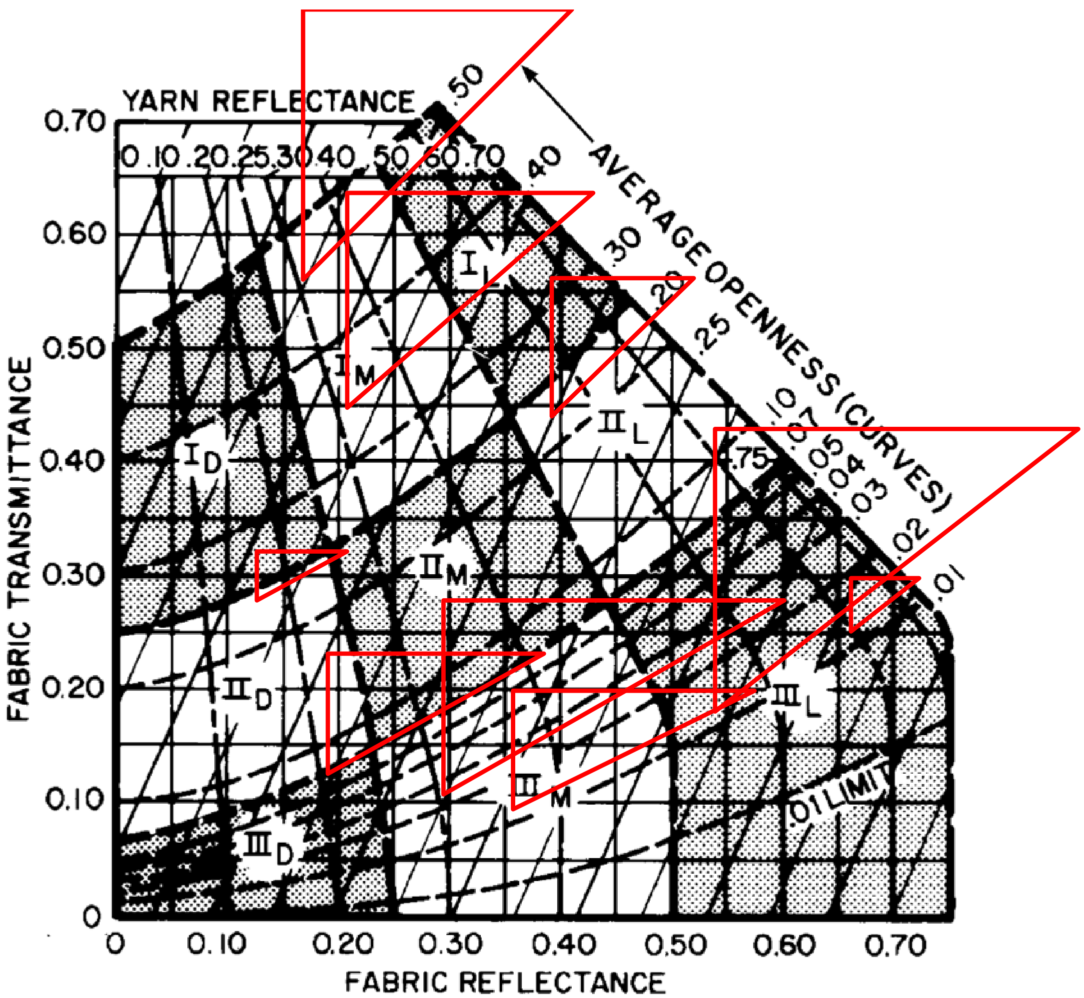

Figure 3 Universal Chart (ASHRAE 2013) including data from Kotey et al. (2009b).

It is unlikely that one could definitively show the origin of this error. Keyes (1967) obtained data from four sources, but at no point provides a detailed listing of the numbers or types of samples used. Concerning the methods by which each measurement was obtained; he refers to Pennington et al. (1965) for determining total reflectance and transmittance, and describes a custom built apparatus consisting of a slide projector, collimating tube, and photocell for measuring the openness (Figure 4). A photocell reading is taken both with and without the sample in place, and the ratio of these readings is the openness. Reliance on the referenced data sources is also not helpful. In the paper by Ozisik and Schutrum (1960), 9 samples are described, but no mention is made of the openness. The tests are only briefly described as being done outdoors using a pyroheliometer. In Pennington et al. (1965), only 2 samples are listed, also without openness data, and a brief reference is made to spectrophotometric measurement. To the authors knowledge, the work of Pass was never published, and it is unknown how many samples were tested, or how. Yellott's work (1965) is perhaps the best documented. Yellott describes all three properties for 17 fabrics, although fabric designations suggest he tested about 100 samples in total. He also describes his measurement procedure in great detail. To measure total reflectance and transmittance, he uses the TRA-Scope (Figure 5). It consists of two frames rotating about the same axis, using the sun as a light source. One contains a fabric or glass sample, while the other contains a radiometer. To measure openness, an apparatus similar to the one described by Keyes was used, except the illumination source was the sun (Figure 5).

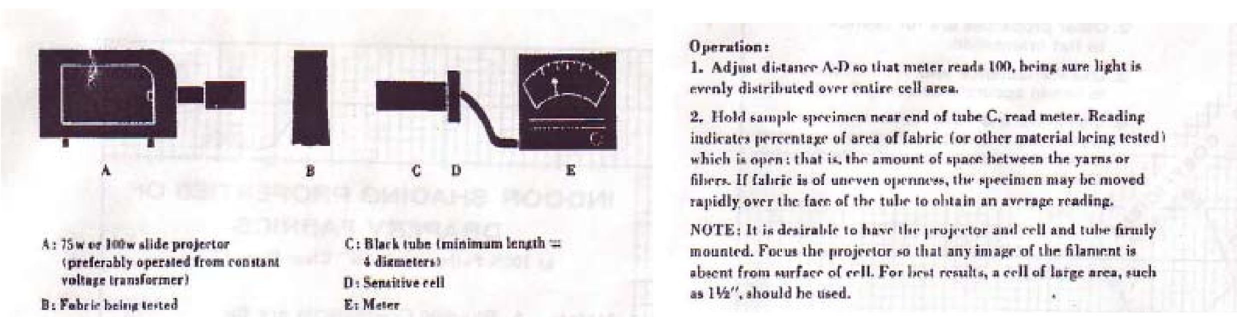

Figure 4 Keyes openness measurement apparatus (Keyes 1967).

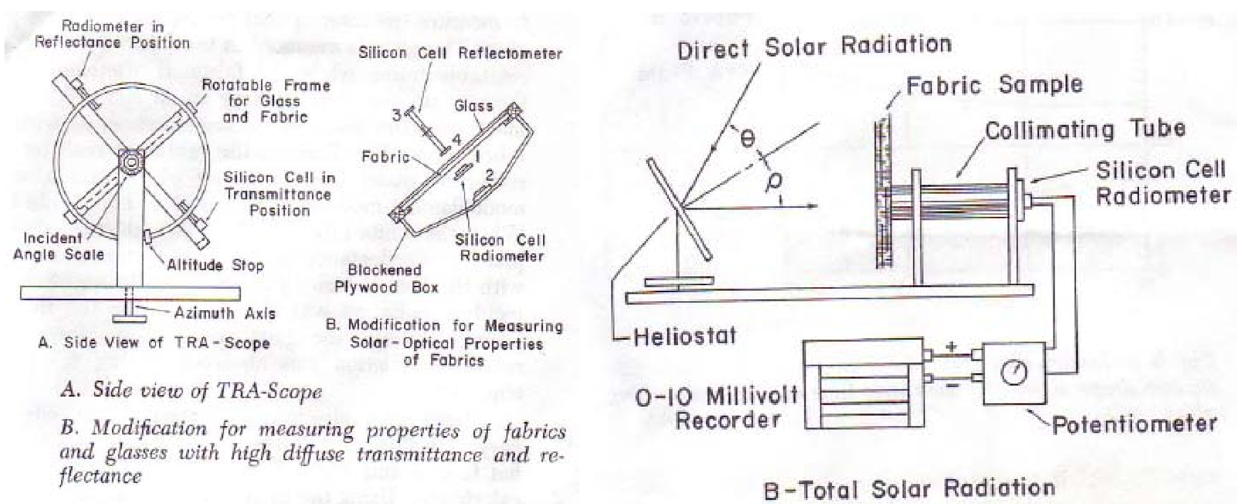

Figure 5 Yellott's measurement setup. The TRA-scope (Left) and openness reading (right). Taken from Yellott (1965).

Despite the lack of detail, the source of this error most likely lies with the data used by Keyes, and not with the current measurements. Either Keyes transmittance data was too low, his reflectance data too high, or his openness data was too high. The total transmittance and reflectance measurements shown in Table 2 were obtained using the same spectrophotometric process referred to by Pennington et al. (1965) and endorsed by Keyes (1967). The modern shading studies described earlier endorse this approach. In deference to the older studies, however, is the fact that the current spectrophotometric measurements come from far more accurate and reliable equipment. Still, one must presume that this would not have a significant impact on the data. Regarding openness, the beam-beam transmittance measurement obtained from the spectrophotometer is fundamentally no different from the one described by Keyes or Yellott and shown in Figures 4 and 5. In the case of the spectrophotometric equipment, however, the equipment is far better designed and calibrated. What is most likely the problem with the openness measurements, however, is the acceptance angle of the sensor. Ideally, a measurement of beam-beam transmission would only include those light rays that pass directly through the fabric weave without changing direction. Unfortunately, if a single ray direction could be chosen, it would contain no energy, and the sensor would not pick up a reading. The measurement system must therefore be designed to accept all radiation within a cone that emanates from the sample. As the size of this cone increases, more scattered radiation is sensed, and the measured openness value becomes inflated. It is not known how large the acceptance angle was in the original experiments, but it is most definitely greater than the acceptance angle of the spectrophotometer used by Kotey et al. (2009b). No matter where the error lies, it is clear that the openness lines shown on the Keyes Universal Chart are not placed accurately.

Correcting the errors in the Keyes Universal Chart is beyond the scope of the present discussion. It will require a thorough investigation of the interrelation between fabric properties, and the subsequent production of a corrected chart. Until that time, however, the openness data shown on the current Keyes Universal Chart should be ignored, and users should rely on measurements of fabric transmittance and reflectance. New versions of the ASHRAE Handbook of Fundamentals should make note of this fact.

CONCLUSION

The Keyes Universal Chart has been published by ASHRAE for 50 years. Keyes melding of the yarn reflectance-openness and fabric transmittance-reflectance approaches has produced a useful approach to estimating the properties of shading and their impact on solar heat gain in buildings. However, the placement of the openness lines on the chart is clearly inaccurate. Given heavy reliance on the chart in recent years, it is the authors' position that it is time to revisit this exercise, and produce a modern replacement as soon as possible.

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