New Primary Standard for Specular Gloss Measurements

María E. Nadal and E. Ambler Thompson—National Institute of Standards and Technology*

A new primary specular gloss standard has been developed at the National Institute of Standards and Technology to overcome the disadvantages of black glass. This new standard is a high-purity BaK50 glass with good mechanical durability and homogeneity. In addition, the index of refraction n_D = 1.5677 is close to the value specified for the theoretical standard, and the dispersion characteristics are similar to black glass.

INTRODUCTION

Specular gloss is the perception by an observer of the mirror-like appearance of a surface. This appearance cannot be measured; only the specific reflectance characteristics of the surface are measured. Gloss is a commercially important attribute of many materials such as paints, papers, plastics, and textiles, and is affected by the production, storage, and use of these products. Several documentary standards describe the proper measurement conditions to determine specular gloss for specific surfaces. Particularly, the International Organization for Standards' ISO 2813[1] and the American Society for Testing Materials' ASTM D 523[2] describe the measurement procedure that best correlates with visual ranking of specular gloss for nonmetallic samples. These standards specify the geometrical and spectral conditions of measurement. The incident beam, either collimated or converging, has a spectral flux distribution of Commission International de l'Eclairage (CIE)[3] Illuminant C and incident angles of 20, 60, or 85°. These angles are referred to as the standard geometries. The reflected beam is measured with a detector having the CIE luminous efficiency function V_λ.[3] *Figure* 1 shows a graphical representation of CIE illuminant C and the luminous efficiency function. The angular dimensions of the apertures for the source and detector are also specified for each incident angle.

For practical reasons, the specular gloss of a sample is measured relative to that of a primary standard, whose specular gloss is in turn determined relative to that of the theoretical standard.[4] This theoretical standard is specified to be a highly polished plane black glass with an index of refraction at the wavelength of the sodium D line, 589.3 nm, of n_D = 1.567. The specular reflectance of unpolarized light for this index of refraction is calculated using the Fresnel equations and assigned a specular gloss value of 100 for each of the three standard geometries.

Since there is no black glass with exactly n_D = 1.567, national metrology institutes use primary standards to realize their scales of specular gloss. Two such primary standards have been in use: Carrara black glass[5] and quartz.[6] A new primary standard for specular gloss developed by the National Institute of Standards and Technology (NIST) using barium crown glass BaK50,[7] which has several advantages over other primary standards is reported here. This new primary standard and the recently refurbished NIST reference goniophotometer[8] will provide accurate specular gloss measurements. The theory of specular gloss standards and measurements is

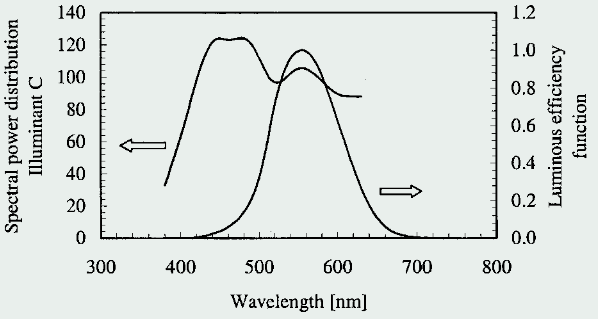

Figure 1—Graphical representation of the spectral power distribution of the CIE Illuminant C and the luminous efficiency function.

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*Optical Technology Division, Gaithersburg, MD 20899.

Table 1—Specular Reflectance $\rho_0(\theta, \lambda_D)$ of the Theoretical Gloss Standard for Each Standard Geometry

Standard Geometry	$\rho_0(\theta, \lambda_D)$
20°	0.049078
60°	0.100056
85°	0.619148

presented first, followed by a discussion of other primary standard materials. The selection criteria for the new NIST primary standard are described, along with the index of refraction, specular gloss, and luminous reflectance properties of the standard. Finally, the new primary standard is compared to other standards.

THEORY

Determining the specular gloss of a test sample involves measuring the luminous reflectance of the sample and a primary standard and determining the specular gloss value of the primary standard relative to that of the theoretical standard. The equations describing these measurements are presented in this section.

For unpolarized light, the specular reflectance ρ from the surface of a dielectric sample depends on the incident angle θ relative to the normal of the sample and the wavelength λ. The specular reflectance as a function of these variables is given by the Fresnel equations, namely

$$\rho(\theta,\lambda)=\frac{1}{2}\left[\frac{\sin^2(\theta-\theta')}{\sin^2(\theta+\theta')}+\frac{\tan^2(\theta-\theta')}{\tan^2(\theta+\theta')}\right] \tag{1}$$

where θ′ is the angle of refraction given by

$$\theta'=\arcsin(\sin(\theta)/n(\lambda)). \tag{2}$$

In general, the luminous flux Φ_v is given by

$$\Phi_v=K_m\cdot\int S(\lambda)\cdot V_\lambda(\lambda)\cdot d\lambda, \tag{3}$$

where K_m = 683 lm/W is the maximum spectral luminous efficacy for photopic vision, S(λ) is the spectral flux distribution, and $V_\lambda(\lambda)$ is the spectral luminous efficiency function. The luminous flux incident on a sample Φ_i is given by equation (3), while the luminous flux reflected by a sample Φ_r is given by

$$\Phi_r=K_m\cdot\int S(\lambda)\cdot\rho(\theta,\lambda)\cdot V_\lambda(\lambda)\cdot d\lambda, \tag{4}$$

Therefore, the luminous reflectance $\rho_v(\theta)$ of a sample is given by the ratio of equation (4) to equation (3),

$$\rho_v(\theta)=\frac{\int S(\lambda)\cdot\rho(\theta,\lambda)\cdot V_\lambda(\lambda)\cdot d\lambda}{\int S(\lambda)\cdot V_\lambda(\lambda)\cdot d\lambda}.$$

The specular gloss of a sample under test, $G_t(\theta)$, is given by

$$G_t(\theta)=G_s(\theta)\cdot\frac{\rho_{v,t}(\theta)}{\rho_{v,s}(\theta)}, \tag{6}$$

where $G_s(\theta)$ is the specular gloss of the primary standard and $\rho_{v,t}(\theta)$ and $\rho_{v,s}(\theta)$ are the specular luminous reflectances of the test sample and primary standard, respectively. Furthermore, the specular gloss of the primary standard is given by

$$G_s(\theta)=G_0(\theta)\cdot\frac{\rho_s(\theta,\lambda_D)}{\rho_0(\theta,\lambda_D)}, \tag{7}$$

where $G_0(\theta)$ is the specular gloss of the theoretical standard and $\rho_s(\theta, \lambda_D)$ and $\rho_0(\theta, \lambda_D)$ are the specular reflectances of the primary and theoretical standards, respectively, at wavelength λ_D=589.3 nm. Combining equations (6) and (7), the specular gloss of the sample being tested is given by

$$G_t(\theta)=G_0(\theta)\cdot\frac{\rho_{v,t}(\theta)}{\rho_{v,s}(\theta)}\cdot\frac{\rho_s(\theta,\lambda_D)}{\rho_0(\theta,\lambda_D)}. \tag{8}$$

From the documentary standards, the index of refraction of the theoretical standard at wavelength λ_D is $n(\lambda_D)$ = 1.567, from which the specular reflectance $\rho_0(\theta, \lambda_D)$ is calculated using equations (1) and (2). These specular reflectances are listed in *Table* 1 for the angles of incidence specified in the documentary standards. For each angle of incidence, the specular gloss of the theoretical standard is defined as $G_0(\theta)$ = 100. Thus, for example, a specular reflectance $\rho_0(60°, \lambda_D)$ = 0.100056 corresponds to a specular gloss value of 100. Similarly, the specular reflectance of the primary standard $\rho_s(\theta, \lambda_D)$ is determined from its $n(\lambda_D)$ using equations (1) and (2). These values for the new primary standard are presented in this paper.

At this point, three of the five quantities on the right-hand-side of equation (8) are known. The other two quantities are the luminous reflectances of the primary standard and test sample, which are generally not measured separately. Rather, the ratio of these reflectances is measured, given by the ratio of the luminous fluxes reflected from the test sample and primary standard, $\Phi_{r,t}$ and $\Phi_{r,s}$, respectively. Therefore,

$$\frac{\rho_{v,t}(\theta)}{\rho_{v,s}(\theta)}\cdot\frac{\Phi_{r,t}(\theta)}{\Phi_{r,s}(\theta)}=\frac{\int S(\lambda)\cdot\rho_t(\theta,\lambda)\cdot V_\lambda(\lambda)\cdot d\lambda}{\int S(\lambda)\cdot\rho_s(\theta,\lambda)\cdot V_\lambda(\lambda)\cdot d\lambda}. \tag{9}$$

Using the definition for $G_0(\theta)$ and equation (9), equation (8) becomes

$$G_t(\theta)=100\cdot\frac{\Phi_{r,t}(\theta)}{\Phi_{r,s}(\theta)}\cdot\frac{\rho_s(\theta,\lambda_D)}{\rho_0(\theta,\lambda_D)}. \tag{10}$$

This equation expresses the gloss value of the test sample as a function of the measured reflected luminous fluxes for the test sample and primary standard and the specular reflectances of the primary and theoretical standards.

From the previous discussion, the specular gloss value of the primary standard is determined using the monochromatic radiant flux from equations (1), (2), and (7), while the luminous flux reflected from the primary standard is used to calibrate the specular gloss of the test sample, from equation (10). This ambiguity produces differences in practical gloss measurements of up to 0.5% since this recommendation ignores the dispersion characteristic of the material represented by changes in refractive index as a function of wavelength. It has been suggested in reference 9 that this ambiguity be removed by defining the specular gloss of the primary standard from its luminous reflectance given by equation (5). There are two methods for determining the luminous reflectance of the primary standard, one from measurements of the index of refraction over the wavelength range of visible light, the other from direct measurements of this reflectance. Results from both methods are presented in the following.

OTHER PRIMARY STANDARDS

The primary specular gloss standard previously used at NIST was a commercial Carrara black glass with n_D = 1.527.[5] A recent evaluation of this type of glass and its constituents was performed, and no match to any commercially available optical glass could be determined. The National Research Council (NRC) of Canada investigated the stability of highly polished black glasses used as specular gloss standards.[10] They found that surface chemical contamination of these standards results in variations of 0.3 to 0.5% in the index of refraction over a time period of three to four years. These variations correspond to changes of about two percent and one percent in the specular gloss values for the 20° and 60° standard geometries, respectively. Repolishing the surface with cerium oxide recovered the original specular gloss values of these standards. They also investigated the uniformity of the index of refraction, which varied across the surface by approximately 0.5%, and concluded that these variations were a result of inhomogeneities in the glass.

In general, there are a number of disadvantages to using black glass as a primary specular gloss standard, primarily inhomogeneity and aging of the glass as well as easy damage to the front surface, which requires frequent repolishing and recalibration. The ISO 2813 suggests an alternative to black glass—a clear glass with roughened edges and back surface, with the back surface painted black to absorb any transmitted light. A difficulty with such a primary standard is finding a black paint that provides a good match to the index of refraction of the clear glass. Otherwise, some scattered light from the back surface will enter the detector and cause an error in the measured flux. An alternative to the black paint is to cut the clear glass at an angle so that back reflections are not incident on the detector, but this option is not feasible for small, portable instruments commonly used in industry. In 1980, the NRC developed wedged quartz samples as their primary standards. Quartz was selected because of its high optical quality, stability, and durability. However, it does not have the same dispersion characteristics as the crown black glass standards used previously at NIST and commonly in industry.

NEW PRIMARY STANDARD

Description

The disadvantages of the previously described primary standards for specular gloss motivated a search for a new primary standard. A good standard should be smooth, stable, cleanable, durable, uniform, and homogeneous with known optical properties. The selection criteria for the new primary standard were threefold. First, the standard would be a commercially available, high-purity optical glass with high chemical and mechanical durability. Second, the index of refraction n_D should be as close to 1.567 as possible to conform to the documentary standards. Third, the material should be homogenous and have dispersion characteristics similar to black glass.

An optical quality barium crown glass BaK50 was selected as the new NIST primary standard, since it possesses high chemical and mechanical durability and n_D = 1.5677. In addition, this glass has a better homogeneity of the index of refraction than does black glass. The manufacturer's specifications are as follows: no bubbles, index of refraction homogeneity within 5×10^{-6} over an area of 70 mm^2. Three pieces of BaK50 with dimensions of 98 mm × 98 mm × 20 mm were purchased, and the NIST optical shop fabricated these pieces into samples with a 6° wedge at the back surface. This angle is sufficient to reflect the light incident on the back surface out of the field of view of the detector for all of the standard geometries, as shown in *Figure* 2. The front and back surfaces were polished to a roughness of 0.6 to 1.0 nm, and the edges were roughened. A black felt material was placed at the back and edges of the samples to eliminate reflections from the surrounding black anodized holder. Since October 1998, the stability of these three samples of BaK50 has been under investigation. As of December 1999, the refractive index and luminous reflectance measurements have not indicated any variability of this material.

Properties

INDEX OF REFRACTION: According to the documentary standards, primary standards for specular gloss are calibrated from measurements of the index of refraction.

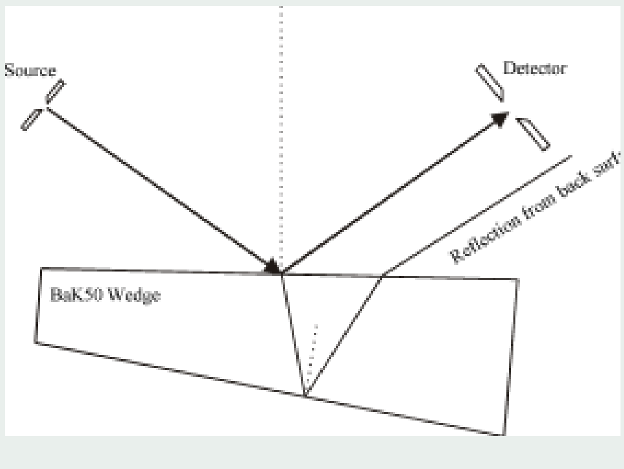

Figure 2—Schematic diagram of the new NIST primary standard showing the incoming and reflected beam at 60° specular geometry. The wedge deflects the reflection from the back surface away from the detector.

Table 2—Index of Refraction *n* of BaK50 Glass as a Function of Wavelength

Wavelength (nm)	*n*
435.8	1.5800
480.0	1.5753
546.1	1.5702
589.3	1.5677
643.9	1.5654

Table 3—Calculated Specular Reflectance $\rho_s(\theta, \lambda_D)$ and Specular Gloss Value $G_s(\theta)$ of the New Primary Standard at λ_D = 589.3 nm for Each Standard Geometry

Standard Geometry	$\rho_s(\theta, \lambda_D)$	$G_s(\theta)$
20°	0.049172	100.19
60°	0.100167	100.11
85°	0.619204	100.01

The index of refraction of BaK50 was measured on a prism-shaped sample prepared from the same melt as the wedge samples. The minimum deviation technique[11] was used to determine the index of refraction at five different wavelengths with a standard uncertainty of 4×10^{-5}. The index of refraction as a function of wavelength is given in *Table* 2. The data was inter/extrapolated using a cubic spline to give the dispersion curve for wavelengths from 380 to 780 nm at 10 nm interval shown in *Figure* 3. In addition, the refractive index at the wavelength of the sodium D line was measured for each of the three wedge pieces of BaK50 at their four corners using an Abbe refractometer. These measurements show that the samples are homogeneous. The maximum variations of n_D for the three samples result in changes in gloss of 0.1.

Specular Reflectance: Specular gloss values for the primary standard were determined from the index of refraction n_D, as specified in the documentary standards. From *Table* 2, n_D = 1.5677 at wavelength λ= 589.3 nm, and using equation (1), the specular reflectance for each standard geometry was calculated. These reflectances and their corresponding gloss values from equation (7) and *Table* 1 are listed in *Table* 3.

Luminous Reflectance: The discussion at the end of the second section suggested that the specular gloss value of the primary standard be defined from its luminous reflectance and noted that there are two methods for determining this reflectance. The first calculates the luminous reflectance from the index of refraction as a function of wavelength, while the second measures the luminous reflectance directly. The luminous reflectances and specular gloss values from these different methods are listed in *Table* 4, with the details of the calculations and measurements given in the following.

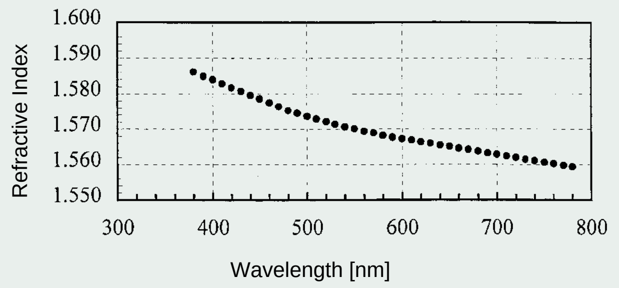

Figure 3—Fitted refractive index, n(λ), for new primary standard (BaK50) as a function of wavelength.

For the first method, the index of refraction as a function of wavelength, from *Table* 2 and *Figure* 3, is used in equations (1) and (2) to calculate $\rho_s(\theta, \lambda)$ for each of the standard geometries from 380 to 780 nm every 10 nm. The luminous reflectance $\rho_{v,s}(\theta)$ is calculated from equation (5) using $\rho_s(\theta, \lambda)$, CIE Illuminant C for $S(\lambda)$, and the CIE 1931 2° Observer for $V(\lambda)$. Finally, the specular gloss value $G_s(\theta)$ for the primary standard is given by equation (7) but with $\rho_{v,s}(\theta)$ in place of $\rho_s(\theta, \lambda_D)$. The relative expanded uncertainty (k=2) for the luminous reflectance is <0.002%.

The second method measures luminous reflectance by an absolute technique using the NIST reference goniophotometer.[8] For a fixed specular geometry, the following steps are followed for absolute luminous reflectance measurements. The sample is manually removed from the path of the incident beam, the detector is rotated into the beam path, and the net incident signal is measured. The sample is then placed into the beam path, the sample table and detector arm are rotated to the desired geometry, and the net reflected signal is measured. The net incident signal is measured again, and the two values are averaged to obtain the final incident signal. The luminous reflectance is calculated from the ratio of the net reflected signal to the net incident signal. From the measured luminous reflectance of the primary standard, the specular gloss value was calculated as described in the previous paragraph, and these quantities are listed in *Table* 4. The listed values represent the average values for two NIST BaK50 samples. The third sample requires additional polishing. The 85° geometry was not measured due to limitations in the source aperture and the signal to noise level. The relative expanded uncertainty (*k*=2) for the luminous reflectance of BaK50 at the specular geometries of

Table 4—Average Luminous Reflectance $\rho_{v,s}(\theta)$ and Specular Gloss Value $G_s(\theta)$ for the New Primary Standard for Each Standard Geometry and Method of Calculation or Measurement

	Standard Geometry					
	20°		60°		85°	
Method	$\rho_{v,s}(\theta)$	$G_s(\theta)$	$\rho_{v,s}(\theta)$	$G_s(\theta)$	$\rho_{v,s}(\theta)$	$G_s(\theta)$
Index of refraction	0.049464	100.8	0.100510	100.5	0.619375	100.0
Luminous reflectance	0.049587	101.0	0.100743	100.7		

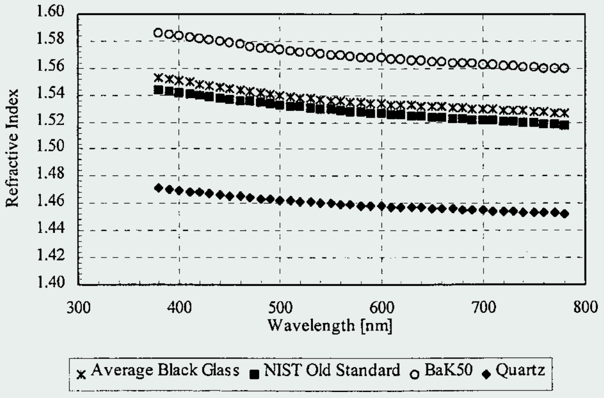

Figure 4—Fitted refractive index, $n(\lambda)$, for Carrara black glass, quartz, and black glass working standards as a function of wavelength.

20° and 60° is 0.22%. The random effects, which include the source stability and detector noise, result in a relative expanded uncertainty (k=2) of 0.1% for both geometries. The systematic effects, which include the DVM accuracy, amplifier gain, detector linearity, source polarization, angular scale, and spectral product, result in a relative expanded uncertainty (k=2) of 0.2% for both geometries.

Several important conclusions can be drawn from the results presented in *Tables* 3 and 4. The specular gloss value of this standard is nearly 100 for all three standard geometries, as shown in *Table* 3, which is a consequence of n_D of the new primary standard being close to the theoretical value of 1.567. Comparing *Tables* 3 and 4, the specular gloss values calculated from the luminous reflectance are greater than those calculated using only n_D for the 20° and 60° standard geometries and are approximately equal for the 85° standard geometry. Finally, the luminous reflectances and corresponding specular gloss values obtained from each of the two methods from *Table* 4 agree well with each other, the maximum difference in $G_s(\theta)$ being only 0.2. The uncertainty analysis shows that the calculated gloss value following the two different procedures agree within the uncertainties.

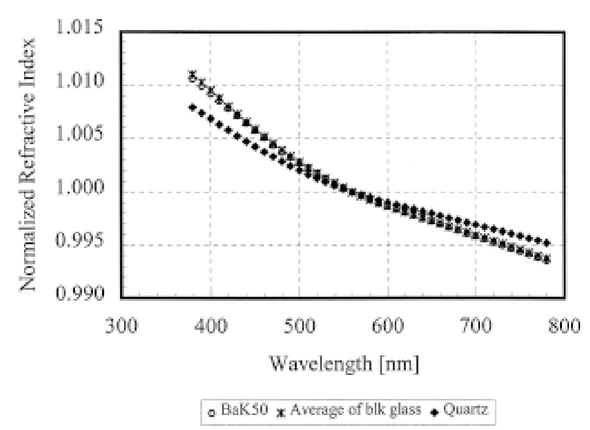

Figure 5—Normalized index of refraction as a function of wavelength for the samples indicated in the legend.

COMPARISONS OF SPECULAR GLOSS STANDARDS

The dispersion characteristics of BaK50 were compared to those of black glass and quartz gloss standards. Three different types of highly polished black glasses were investigated—the gloss standard previously used at NIST and two currently used in industry. Neither black glass nor quartz are a good match for n_D = 1.567. The refractive indexes for the black glass samples were measured using an Abbe refractometer at three different wavelengths and fit with a cubic spline function to give the dispersion curves from 380 to 780 nm at 10 nm intervals shown in *Figure* 4. The uncertainty of these measurements is 0.0005. The refractive indexes for quartz listed in reference 12 was inter/extrapolated using a cubic spline to give the dispersion curve for wavelengths from 380 to 780 nm at a 10 nm interval (*Figure* 4).

The normalized dispersion curves of BaK50, black glass, and quartz standards are shown in *Figure* 5. The index of refraction is normalized at a wavelength of 560 nm and plotted as a function of wavelength. The average of the dispersion curves for the black glass samples is plotted. The relative dispersion characteristic of BaK50 closely resembles that of the black glass samples studied in this paper, while quartz has a different characteristic. The international and national standards define the specular gloss value for the theoretical and working standards based upon a single refractive index, n_D, but the instruments are specified for polychromatic radiation and broad spectral range detectors. This ambiguity leads to a situation where the gloss value of the sample under test depends on the dispersive characteristics of the secondary-working standard, such as black glass. This is particularly important for instruments whose spectral characteristics are in poor agreement with those specified by the documentary standards. Ideally, the calibration of a test sample should not be affected by the properties of the working standard.

CONCLUSIONS

The new NIST primary standard for specular gloss has three important advantages over other materials used as primary standards. First, BaK50 is a commercially available high-purity glass with good homogeneity. Second, since n_D of BaK50 is close to the value of 1.567 specified for the theoretical standard, the specular gloss values for this glass differ from 100 by less than 0.2 for all three standard geometries. Third, the relative dispersion of BaK50 is similar to that of black glass, which is important for calibrating samples with instruments whose spectral characteristics are not in good agreement with those specified by the documentary standards. This new standard and the NIST reference goniophotometer provide an accurate calibration facility for specular gloss measurements.

ACKNOWLEDGMENTS

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