

# Index of Refraction of Fused-Quartz Glass for Ultraviolet, Visible, and Infrared Wavelengths<sup>1</sup>

William S. Rodney and Robert J. Spindler

The index of refraction of fused-quartz glass was determined for 24 wavelengths from 0.34669 to 3.5078 microns, using the minimum-deviation method. The whole range was covered with a single instrument. The variation in index between samples was determined; no definite variations in dispersion were observed. Possible relations between purity and index are discussed.

## 1. Introduction

The physical and optical properties of fused-quartz glass make its increased use in the optical industry highly desirable whenever it can be readily produced in optical quality. In composition it is definitely reproducible as compared with optical glasses, it is extremely stable, and its coefficient of thermal expansion is remarkably low. Its transmission limits, both in the ultraviolet and the infrared, are nearly the same as for the crystalline material and in addition it is free from double refraction. Some specimens of this material, particularly from European range finders, are of excellent optical quality.

The refractive index of fused-quartz glass has been investigated in the ultraviolet and visible regions by Gifford and Shenstone and by Trommsdorff; also some measurements were made in the visible region by Riedel, by Rinne, and by Watson. All of these data, together with some *D*-line indices by other observers, are referenced, compared, and analysed by Sosman [1].<sup>2</sup> For the infrared region some indices of fused quartz have been computed from reflection data but experimentally determined data seem limited to three-decimal-place values [2]. Some published data [3] indicate different indices for specimens obtained from different sources, presumably made by somewhat different methods. However, very little precise and self-consistent information has previously been obtained by use of identical procedures for different wavelength regions and for different specimens.

## 2. Samples Investigated

Seven prisms of fused-quartz glass were used in this investigation. One was made over 20 years ago from fused-quartz glass produced by the General Electric Co. Its indices in the visible region and its degree of homogeneity were carefully investigated [3], and it is used as a refractive-index standard for the precise calibration of refractometers. A second prism was made of domestic fused-quartz glass of

recent origin, also produced by the General Electric Co. Two other prisms, A and B, were made from the product of the Heraeus Co. in Germany and obtained by Stanley S. Ballard, who made them available for this investigation. A fifth prism was made by grinding and polishing windows on the periphery of a 6-in. disk recently manufactured by the Nieder Fused Quartz Co., Babson Park, Mass. Another prism was made by placing windows on the periphery of a cylinder of Heraeus fused quartz (sample C), approximately 4 in. long and 2 in. in diameter. The seventh sample was made available by the Corning Glass Works; it is known to have extremely good ultraviolet transmission characteristics but has a stronger absorption band around 2.6  $\mu$  than the other samples. All seven specimens are of near optical quality and free of noticeable striae and bubbles, except the disk, which has considerable striae. Even in this case, however, precise data were obtainable.

## 3. Instruments Used in Measurements

The Watts precision spectrometer was used for the visible region and the Gaertner precision spectrometer for the ultraviolet and infrared. The visible-region measurements were also repeated on the Gaertner spectrometer for calibration purposes. Descriptions of these instruments, with photographs, are given in previous publications by the authors [4, 5]. Figure 1 is a schematic diagram of the Gaertner spectrometer showing some changes. On both instruments the minimum-deviation method, with its desirable features of high accuracy and simplicity of index computations, was used.

The spectra used in these measurements were the mercury and cadmium emissions for wavelengths out to approximately 2.5  $\mu$  and the absorption bands of polystyrene beyond this region to approximately 3.5  $\mu$ .

A lead-sulfide detector was used for the emission-line spectra and a Golay pneumatic detector for wavelengths in the absorption spectra of polystyrene. The incident flux was chopped at approximately 10 c/s to stabilize the zero, and the resulting signals were amplified in both cases by a gated amplifier supplied for the Golay detector. The amplified signal was recorded on a recording potentiometer.

<sup>1</sup> An account of this work containing less experimental detail but giving the essential results is published in *J. Opt. Soc. Am.* **44**, 677 (1954).

<sup>2</sup> Figures in brackets indicate the literature references at the end of this paper.

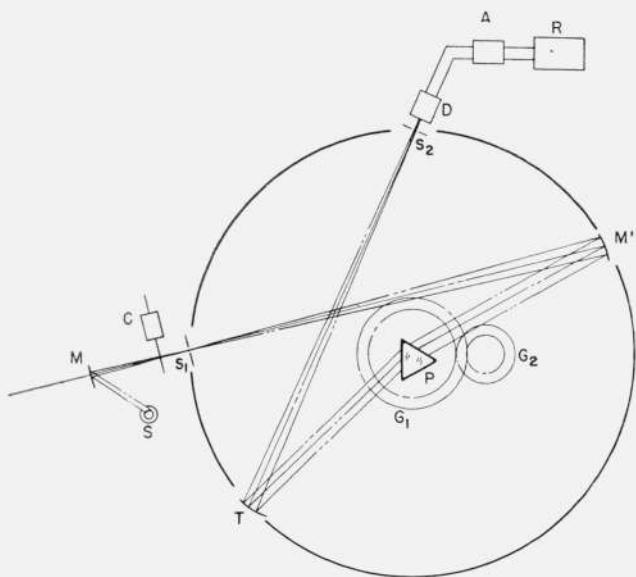


FIGURE 1. Modified Gaertner infrared spectrometer.

$S_1$  and  $S_2$ , entrance and exit slits, respectively; S, globe source; M, condensing mirror;  $M'$ , collimator mirror; T, telescope mirror; C, chopper; D, detector; A, amplifier; R, recorder. The prism P is rotated at one-half the rotation rate of T by use of the gears  $G_1$  and  $G_2$ .

#### 4. Experimental Procedure

The index of refraction for visible wavelengths is first determined on the Watts instrument by the usual minimum-deviation method. The errors for these data do not exceed  $\pm 1 \times 10^{-5}$ . The deviation angles are observed and recorded. With the aid of an auxiliary telescope the prisms are then leveled and centered with respect to the optical axes of the Gaertner instrument. A second telescope is used to set the prism, for a given line, usually the  $0.6438 \mu$  line of cadmium, at its minimum-deviation position. The table is now clamped in this position. The mirror acting as the telescope objective is brought into the beam so that an image of this line falls on the exit slit, causing a deflection of the potentiometer pen. The scale position corresponding to maximum deflection of the pen is observed for several pointings. The instrument is now set and clamped at the average of these readings. A system of gears, designed to maintain minimum deviation by causing the prism table to rotate at one-half the rotation rate of the telescope and detector, is now engaged and the prism table clamps released.

The design of the Gaertner spectrometer, as adapted for nonvisible radiation, does not allow double deviation, or even the position of the undeviated beam, to be measured. Consequently, it is necessary to compute the average reading for the undeviated beam. This is done by applying a few deviations, as observed visually on the Watts instrument, to the scale readings on the Gaertner for minimum-deviation settings of the corresponding

lines of the visual spectrum as determined by the use of the detector.

The spectra are then scanned to identify other wavelengths and to determine the approximate scale position of the minimally deviated beam for each known wavelength. Once an approximate position is determined, hand settings are made by observing the scale position for maximum or minimum deflection of the recorder pen. The scale readings are averaged for greater precision.

#### 5. Data

Index determinations were made on Heraeus prisms A and B at or very near  $24^\circ$  and  $31^\circ$  C. The average temperature of the room was controlled within  $\pm 0.2$  deg C and was determined frequently by means of a thermometer having its bulb near the prism. Temperature coefficients were then computed and small corrections were made to adjust to exact temperatures of  $24^\circ$  and  $31^\circ$  C. On the other prisms, index determinations were made near  $24^\circ$  C only.

The refractive indices of the Heraeus B prism at  $24^\circ$  C have been represented by means of the dispersion formula [6] ( $\lambda$  expressed in microns)

$$n^2 = 2.979864 + \frac{0.008777808}{\lambda^2 - 0.010609} - \frac{84.06224}{96.00000 - \lambda^2} \quad (1)$$

and the goodness of fit of the formula is shown by the small residuals, B-c, as tabulated in table 1, and by their nearly random distribution. The predominance of negative residuals for the region 3 to  $3.5 \mu$  indicates that further improvement can be made. However, no least-squares solution was attempted because at  $\lambda = 3.4188 \mu$ , where the maximum negative residual was obtained, there is observational uncertainty because of the very broad nature of this absorption band, which tends to make the wavelength of the minimum difficult to determine. Note that a positive residual was obtained for the Corning prism at this wavelength (last column, table 1).

The indices computed by formula (1) are, in general, better than the observed values, and accordingly table 2 gives such indices for selected regular intervals of wavelength.

In order to compare the indices for the various prisms, the indices as computed by formula (1) have been subtracted from all others. These differences are listed in table 1 and plotted in figure 2. From the variation shown in this figure, the differences in index of different samples seem clearly established. It will be noticed that the Heraeus, Nieder, and Corning samples agree in general in refractivity with the data of Trommsdorff and of Gifford. Gifford's data were taken on the fused-quartz glass made by Gifford and Shenstone, with particular attempts at purity of material. It seems that the Heraeus B and Corning samples, may possibly be freer of traces of other substances, because the common basic impurities would tend

TABLE 1. Computed indices of refraction of fused-quartz glass (Heraeus B) and residuals  $(o-c) \times 10^5$  for temperature of 24° C.

Source	Wavelength	Computed index Eq (1)	Heraeus			Nieder disk N-c	General Electric		Corning silica glass S-c
			A-c	B-c	C-c		G1-c	G2-c	
Cadmium	$\mu$ 0.34669	1.47757		-1				+22	-5
Do	.36117	1.47522	+6	0		+6	+31	+23	-6
Mercury	.365015	1.47465	+5	-3		+6	+26	+21	-9
Do	.404656	1.46971	+6	-2	+21	+8	+31	+21	-6
Do	.435835	1.46677	+7	0	+23	+6	+33	+21	-5
Do	.546074	1.46014	+7	+1	+24	+8	+34	+22	-4
Do	.578012	1.45887		+5	+25				
Cadmium	.643847	1.45676	+9	0	+25	+9	+34	+24	-5
Mercury	1.01398	1.45030	+9	0		+10	+35	+23	-6
Do	1.12866	1.44893		+1					
Do	1.36728	1.44622		+1					
Do	1.39506	1.44590		-1					
Do	1.52952	1.44434	+9	0		+10	+35	+24	-7
Do	1.6932	1.44234		+1					
Do	1.81307	1.44078		+1					
Do	1.97009	1.43861	+8	-1		+8	+36	+25	-8
Do	2.24929	1.43431		+1					
Do	2.32542	1.43303	+9	-1		+7	+39	+28	-10
Polystyrene absorption	3.2432	1.41326		-5					-5
Do	3.2666	1.41263		0					-5
Do	3.3033	1.41164		0					-1
Do	4.3293	1.41092		0					-6
Do	3.4188	1.40839		-12					+3
Do	3.5978	1.40577		-4					-7

NOTE: All residuals in this table are based on results obtained with a physical detector. For wavelengths in the visible range the residuals would be smaller if the visually observed data were used. In particular, the residual  $+5 \times 10^{-4}$  for  $\lambda = 0.578012 \mu$  becomes zero because the physical detector did not effectively resolve this mercury doublet. Such differences among residuals for the visible region emphasize the advisability of relying only on data computed by means of an adequate dispersion equation with parameters properly adjusted to an adequate number of observed points whenever best values of refractive index are required in nonvisible regions of the spectrum.

TABLE 2. Most probable values of refractive indices of pure fused-quartz glass at 24° C for various wavelengths

Computed from eq (1)

Wave-length	Index	Wave-length	Index
$\mu$		$\mu$	
0.34	1.47877	0.67	1.456066
.35	1.47701	.68	1.455818
.36	1.47540	.69	1.455579
.37	1.47393	.70	1.455347
.38	1.47258	.80	1.453371
.39	1.47135	.90	1.451808
.40	1.470208	1.00	1.450473
.41	1.469155	1.10	1.449261
.42	1.468179	1.20	1.448110
.43	1.467273	1.30	1.446980
.44	1.466429	1.40	1.445845
.45	1.465642	1.50	1.444687
.46	1.464908	1.60	1.443492
.47	1.464220	1.70	1.442250
.48	1.463573	1.80	1.440954
.49	1.462965	1.90	1.439597
.50	1.462394	2.00	1.438174
.51	1.461856	2.10	1.436680
.52	1.461346	2.20	1.435111
.53	1.460863	2.30	1.433462
.54	1.460406	2.40	1.431730
.55	1.459973	2.50	1.429911
.56	1.459561	2.60	1.428001
.57	1.459168	2.70	1.425995
.58	1.458794	2.80	1.423891
.59	1.458437	2.90	1.421684
.60	1.458096	3.00	1.41937
.61	1.457769	3.10	1.41694
.62	1.457456	3.20	1.41440
.63	1.457156	3.30	1.41173
.64	1.456868	3.40	1.40893
.65	1.456591	3.50	1.40601
.66	1.456324		

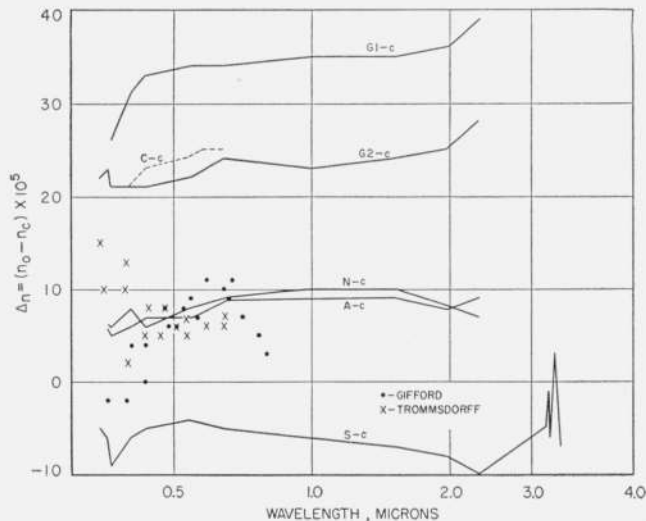


FIGURE 2. Variations in index between samples of fused-quartz glass.

G1 and G2 refer to the indices of two General Electric samples; A and C, Heraeus samples; N, a Nieder sample; S, a Corning sample. The reference index of refraction,  $c$ , is that computed from eq (1), which was fitted to data on Heraeus sample B. The Gifford and Trommsdorff data were taken from Sosman's book.

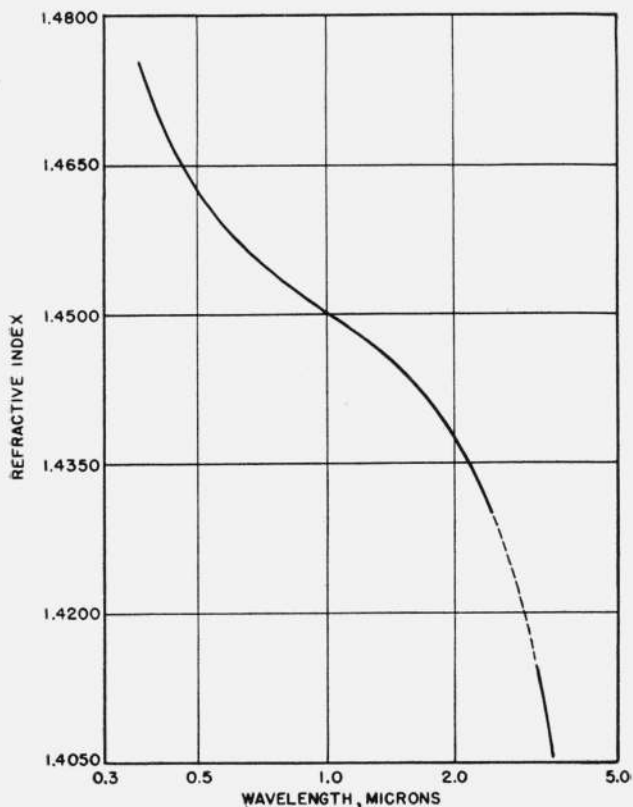


FIGURE 3. Index of refraction of fused-quartz glass (Heraeus B) as a function of wavelength.

Wavelength scale is logarithmically graduated.

to make the index higher.<sup>3</sup> The possible effects of other impurities cannot, of course, be altogether ignored. On this assumption of relative purities, it seems possible that formula (1) and table 2 express probable values for nearly pure fused-quartz glass. Further, it seems advisable to add 2 or  $3 \times 10^{-4}$  for probable values of some specimens of such glass.

Although the index of refraction is given in the infrared out to  $3.5 \mu$ , there is a region at wavelengths shorter than this where no index values were satisfactorily determined. This region is shown in figure 3 as a dashed line from approximately 2.4 to approximately  $3.2 \mu$ . This is a result of the strong absorption in this region in all samples used. There is some variation between samples in the strength of this absorption band. The absorption band was resolved into four components, and the deviations of these were measured, but the wavelengths of these absorption bands are not known. By assigning a value of  $2.5 \mu$  as wavelength for the average of the computed indices, such an observed point would fall on the dashed line.

<sup>3</sup> No information is available about the annealing temperatures used for any of these quartz glasses. It was found by Frost and Klauer [7] that the density of silica glass is rather insensitive to annealing. Also, Tool and Tilton [8] found it possible to produce only very small changes in index of silica glass by annealing at different temperatures. However, it cannot be assumed that the differences observed for these various samples are entirely independent of their thermal history.

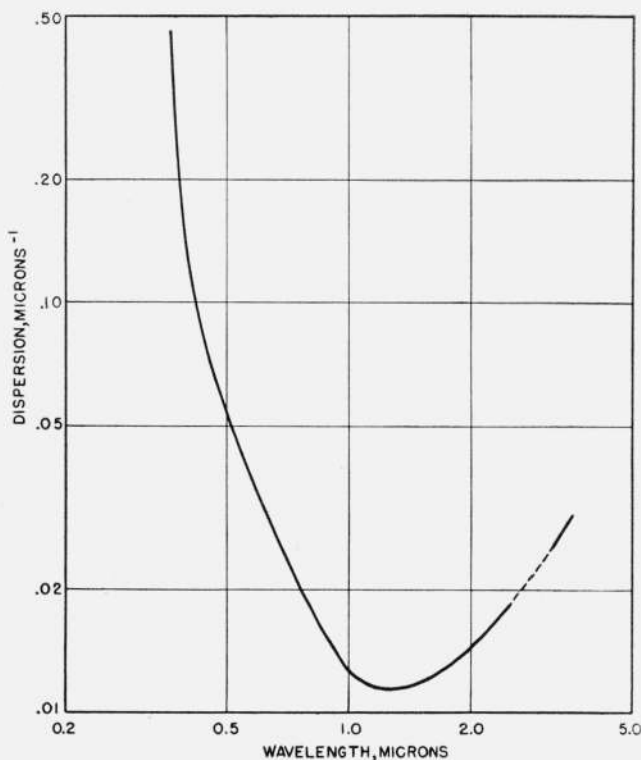


FIGURE 4. Dispersion of fused-quartz glass as a function of wavelength.

Both abscissa and ordinate are logarithmically graduated.

TABLE 3. Most probable values of refractive indices of pure fused-quartz glass at various room temperatures for visual spectral ranges

Wave-length	$10^7 \times \frac{\Delta n}{\Delta t}$	$t=15^\circ \text{C}$	$t=20^\circ \text{C}$	$t=25^\circ \text{C}$	$t=30^\circ \text{C}$	$t=35^\circ \text{C}$
$\mu$						
0.40	95	1.47012	1.47017	1.47022	1.47026	1.47031
.41	95	1.46907	1.46912	1.46916	1.46921	1.46926
.42	95	1.46809	1.46814	1.46819	1.46824	1.46828
.43	96	1.46719	1.46723	1.46728	1.46733	1.46738
.44	96	1.46634	1.46639	1.46644	1.46649	1.46653
.45	96	1.46556	1.46560	1.46565	1.46570	1.46575
.46	96	1.46482	1.46487	1.46492	1.46497	1.46501
.47	97	1.46413	1.46418	1.46423	1.46428	1.46433
.48	97	1.46349	1.46353	1.46358	1.46363	1.46368
.49	97	1.46288	1.46293	1.46297	1.46302	1.46307
.50	97	1.46231	1.46236	1.46240	1.46245	1.46250
.51	98	1.46177	1.46182	1.46187	1.46191	1.46196
.52	98	1.46126	1.46131	1.46136	1.46140	1.46145
.53	98	1.46077	1.46082	1.46087	1.46092	1.46097
.54	98	1.46032	1.46037	1.46042	1.46046	1.46051
.55	98	1.45988	1.45993	1.45998	1.46003	1.46008
.56	99	1.45947	1.45952	1.45957	1.45962	1.45967
.57	99	1.45908	1.45913	1.45918	1.45923	1.45928
.58	99	1.45870	1.45875	1.45880	1.45885	1.45890
.59	99	1.45835	1.45840	1.45845	1.45850	1.45855
.60	100	1.45801	1.45806	1.45811	1.45816	1.45820
.61	100	1.45768	1.45773	1.45778	1.45783	1.45788
.62	101	1.45737	1.45742	1.45747	1.45752	1.45757
.63	101	1.45707	1.45712	1.45717	1.45722	1.45727
.64	102	1.45678	1.45683	1.45688	1.45693	1.45698
.65	102	1.45650	1.45655	1.45660	1.45665	1.45670
.66	103	1.45623	1.45628	1.45633	1.45639	1.45644
.67	103	1.45597	1.45602	1.45608	1.45613	1.45618
.68	103	1.45573	1.45578	1.45583	1.45588	1.45593
.69	103	1.45549	1.45554	1.45559	1.45564	1.45569
.70	103	1.45525	1.45531	1.45536	0.45541	1.45546

The dispersion of fused-quartz glass was calculated over the region measured and found to have its minimum at about 1.5, as shown in figure 4. The region between 2.4 and 3.2  $\mu$  is, of course, still represented as a dashed line. The region beyond 3.2  $\mu$  has dispersion good enough to enable one to resolve the polystyrene bands into six distinct parts.

The temperature coefficients of index were determined for each of the lines measured. The precision is not adequate to determine definitely the variation with wavelength; however, there is evidence of first a slight increase, then a lowering at the longer wavelengths. The average value at the shorter wavelengths was found to be  $10 \times 10^{-6}$  and this may fall to an average of about  $4.0 \times 10^{-6}$  near 3.5  $\mu$ . The values in the visible region agree with those of Tilton [3] and others. Table 3 lists the index at several different temperatures. These values were obtained by applying the temperature coefficients to value computed from formula (1).

## 6. References

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WASHINGTON, March 15, 1954.