Optical Glass

HOYA

HOYA CORPORATION USA OPTICS DIVISION

Notes.

1.Properties tagged with an asterisk (*) have been measured in compliance with Japanese Optical Glass Industrial Standards (JOGIS).

2. Système International d'Unités (SI) units are used throughout this catalog unless otherwise noted. Special symbol designations found in JIS Z 8202-1985 are used where applicable (as when referring to quantities, units or chemical symbols).

1. Designation of Glass Type

1.1 Group Designation

Optical glasses are classified by their main chemical components and are identified by refractive index (n_d) and Abbe-number (ν_d). They are divided into groups. Each glass type within a group is designated by the abbreviated group symbol and a number. For example, **B**oro-**S**ilicate **C**rown **7** glass is designated as **BSC 7** (BK7 in SCHOTT designation).

Table 1 Group / Designation Collation

Group	HOYA	SCHOTT	Group	HOYA	SCHOTT
Fluor Crown	FC	FK	Extra Light Flint	FEL	LLF
Dense Fluor Crown	FCD	FK	Barium Flint	BaF	BaF
Phosphate Crown	PC	PK	Light Flint	FL	LF
Special Phosphate Crown	PCS	PK	Flint	F	F
Dense Phosphate Crown	PCD	PSK	Dense Barium Flint	BaFD	BaSF
Boro Silicate Crown	BSC	BK	Dense Flint	FD	SF
Light Barium Crown	BaCL	BaLK	Special Dense Flint	FDS	SFS
Crown	C	K	Fluor Flint	FF	TiF
Zinc Crown	ZnC	ZK	Light Lanthanum Flint	LaFL	LaF
Barium Crown	BaC	BaK	Lanthanum Flint	LaF	LaF
Dense Barium Crown	BaCD	SK	Niobium Flint	NbF	LaF
Extra Dense Barium Crown	BaCED	SSK	Tantalum Flint	TaF	LaF, LaSF
Light Lanthanum Crown	LaCL	LaK	Dense Nobium Flint	NbFD	LaF, LaSF
Lanthanum Crown	LaC	LaK	Dense Tantalum Flint	TaFD	LaSF
Tantalum Crown	TaC	LaK	Abnormal Dispersion Crown	ADC	—
Crown Flint	CF	KF	Abnormal Dispersion Flint	ADF	KzFS
Antimony Flint	SbF	KzF	Athermal Crown	ATC	—
Light Barium Flint	BaFL	BaLF	Athermal Flint	ATF	—

1.2 Code

In addition to our glass type designation, a six-digit code number is listed in this catalog. The first three digits indicate the n_d after the decimal point, and the last three digits represent the ν_d. In **BSC 7**, for example, the n_d is **1.<u>51680</u>**, the ν_d is **<u>64.20</u>**, which we indicate as **517-642**.

A n_d–ν_d diagram is included in Appendix to this catalog.

2. Optical Properties

2.1 Refractive Index*

Refractive indices to five decimal places are given for the following standard spectral lines:

Table 2 Wavelengths of Spectral Lines for Determining Refractive Indices

Wavelength (nm)	Spectral Line	Element
1,013.98	t	Hg
852.11	S	Cs
768.19	A'	K
706.52	r	He
656.27	C	H
643.85	C'	Cd
632.8	632.8	He-Ne Laser
589.29	D	Na
587.56	d	He
546.07	e	Hg
486.13	F	H
479.99	F'	Cd
435.83	g	Hg
404.66	h	Hg
365.01	i	Hg

2.2 Dispersion* and Abbe-number*

The main dispersion is expressed by (n_F-n_c) and ($n_{F'}$-$n_{c'}$). The Abbe-number is defined:

$$\nu_d = \frac{n_d - 1}{n_F - n_c} \qquad \textbf{(1)}$$

Also listed is the ν_e value:

$$\nu_e = \frac{n_e - 1}{n_{F'} - n_{c'}} \qquad \textbf{(2)}$$

2.3 Dispersion Formula

The refractive index at a wavelength other than those covered in this catalog can be calculated from a dispersion formula. For practical approximation, the following dispersion formula, derived from a series expansion of the theoretical formula, is available:

$$n^2 = A_0 + A_1\lambda^2 + A_2\lambda^{-2} + A_3\lambda^{-4} + A_4\lambda^{-6} + A_5\lambda^{-8} \qquad \textbf{(3)}$$

where λ is the wavelength in μm, and A_0, A_1, ..., A_5 are coefficients to be determined in each glass, using the method of least squares.

The accuracy of a calculated refractive index at a wavelength between the range of 365~1,014nm is $\pm 5 \times 10^{-6}$ for typical glass with refractive indices denoted in this catalog.

2.4 Relative Partial Dispersion and Abnormal Dispersion

The relative partial dispersion $P_{x,y}$ and the alternate relative partial dispersion $P'_{x,y}$ are defined by the following equation:

$$P_{x,y} = \frac{n_x - n_y}{n_F - n_C} \qquad P'_{x,y} = \frac{n_x - n_y}{n_{F'} - n_{C'}} \tag{4}$$

where subscripts x and y denote the standard spectral line assignments associated with specific refractive index values.

The dispersive characteristics of various glasses may be compared by plotting the relative partial dispersion $P_{x,y}$ versus the Abbe-number ν_d (or, alternatively, $P'_{x,y}$ versus ν_e). These quantities share a linear correspondence for most optical glasses and therefore plot along a single straight line. Glasses exhibiting this behavior are referred to as "normal dispersion glasses". The partial dispersion of these glasses can be approximately described by the following equation:

$$P_{x,y} \approx a_{x,y} + b_{x,y} \bullet \nu_d \tag{5}$$

where $a_{x,y}$ and $b_{x,y}$ are constants. Glasses which deviate significantly from the line described by equation (5) are called "abnormal dispersion glasses". For any glass, the deviation of the partial dispersion from the "normal line" can be represented by the quantity $\Delta P_{x,y}$. A more general expression for $P_{x,y}$ is then given by the following equation:

$$P_{x,y} = a_{x,y} + b_{x,y} \bullet \nu_d + \Delta P_{x,y} \tag{6}$$

$\Delta P_{x,y}$ values listed in this catalog are referenced to a straight line defined by the $P_{x,y}$ values found for the glass types C7 and F2.

$\Delta P_{C,t}$, $\Delta P_{C,A'}$, $\Delta P_{g,d}$, $\Delta P_{g,F}$ and $\Delta P_{i,g}$ for each glass type are presented herein.

2.5 Temperature Coefficient of Refractive Index (Δn/ΔT)

The refractive index of optical glass changes with the temperature. The temperature coefficient of the refractive index, (Δn/ ΔT) abs., is measured at 20°C intervals between –40~80°C in a vacuum, using an interference-dilatometer to detect changes in both optical path length and dilation of the specimen. The light source used is a He-Ne gas laser (632.8nm).

For calculation of the temperature coefficient of the relative refractive index (Δn / ΔT) rel. in air at 101.325 kPa, the following equation is given:

$$\left(\frac{\Delta n}{\Delta T}\right)_{rel.} \approx \left(\frac{\Delta n}{\Delta T}\right)_{abs.} - n_{rel.} \bullet \frac{\Delta n_{air}}{\Delta T} \tag{7}$$

where $\Delta n_{air} / \Delta T$ is the temperature coefficient of the refractive index of air. Reference should be made to Table 3.

Note: 101.325 kPa = 1 atm

Table 3 Temperature Coefficient of the Refractive Index of Air

Temperature (°C)	$\frac{\Delta n_{air}}{\Delta T}$ (10^{-6}/K)
-40~-20	-1.35
-20~ 0	-1.15
0~ +20	-1.00
+20~ +40	-0.87
+40~ +60	-0.76
+60~ +80	-0.68

2.6 Temperature Coefficient of Optical Path Length (ds / dT)

The optical path length also changes with the temperature. The degree of the change is expressed as the "temperature coefficient of optical path length (ds / dT)" and is given by the following equation:

$$\frac{ds}{dT} = (n - 1)\alpha + \frac{dn}{dT} \qquad \textbf{(8)}$$

where n is the refractive index of the glass, α is the coefficient of linear thermal expansion of the glass, and dn / dT is the temperature coefficient of the refractive index of the glass.

In ordinary optical glass, the ds / dT is fairly large with a positive sign, as dn / dT is positive. Thus the optical path length will vary with the temperature to cause wave front distortion, which may present serious problems in high resolution optical systems.

The glasses with negative dn / dT, nearly zero ds / dT are called "Athermal Glasses". "ATC1, ATF2 and ATF4 (included in "custom-made glass types") are Athermal Glass Types.

2.7 Stress-Optical Coefficient (B)

Ideally, the optical properties of glass are isotropic through fine annealing. Birefringence may be observed, however, when external forces are applied or when residual stresses are present (commonly the result of rapid cooling).

The optical path difference δ (nm) associated with birefringence is linearly proportional to both the applied tensile or compressive stress, σ (10^5 Pa) and the thickness d (cm) of the specimen and is given by the following equation:

$$\delta = B \cdot \sigma \cdot d \qquad \textbf{(9)}$$

The proportionality constant, B (10^{-12} / Pa), in this equation is proper constant of each glass type and referred to as the stress-optical coefficient.

Stress-optical coefficents are obtained by measuring the optical path difference caused at the center of a glass disk with He-Ne laser light, when the disk is subject to a compressive load in a diametral direction.

Note. 1×10^{-12} / Pa = 0.980 7 (nm / cm) / (kgf / cm^2)
10^5Pa = 1.019 7 kgf / cm^2 = 1 bar

2.8 Transmittance

The transmittance characteristics of optical glasses in this catalog are expressed by two terms. One is "Internal Transmittance" and the other is "Coloration Code".

2.8.1 Internal Transmittance* (τ)

Internal transmittance (τ) refers to transmittance obtained by excluding reflection losses at the entrance and exit surfaces of the glass. Internal transmittance values over the wavelength range from 280 to 1,550nm are calculated from transmittance measurements on a pair of specimens with different thicknesses.

Internal transmittance values obtained for 5mm and 10mm thick glasses are given as τ5mm and τ10mm.

The internal transmittance τ for glass with arbitrary thickness d can be obtained from these values by using:

$$\tau = \tau_0^{\,d/d_0} \qquad \textbf{(10)}$$

where τ_0 refers, to the internal transmittance given in the tables for glass with thickness d_0 equal to either 5 mm or 10 mm.

2.8.2 Coloration Code* (λ_{80}/λ_5)

Optical glasses exhibit almost no light absorption over a wavelength range extending through the visible to the near infra-red. The spectral transmittance characteristics of optical glasses can be simply summarized with the coloration code λ_{80}/λ_5.

The coloration code is determined in the following way. The internal transmittance of a specimen with thickness 10 $\pm$ 0.1mm is measured from 280nm to 700nm. Wavelengths are rounded off to the nearest 10nm and expressed in units of 10nm. λ_{80} is the wavelength for which the glass exhibits 80% transmittance while λ_5 is the wavelength at which the glass exhibits 5% transmittance. For example, a glass with 80% transmittance at 398 nm and 5% transmittance at 362nm has a coloration code 40 / 36, as shown in Fig. 1.

The coloration code is generally applied for transmittance control of optical glasses.

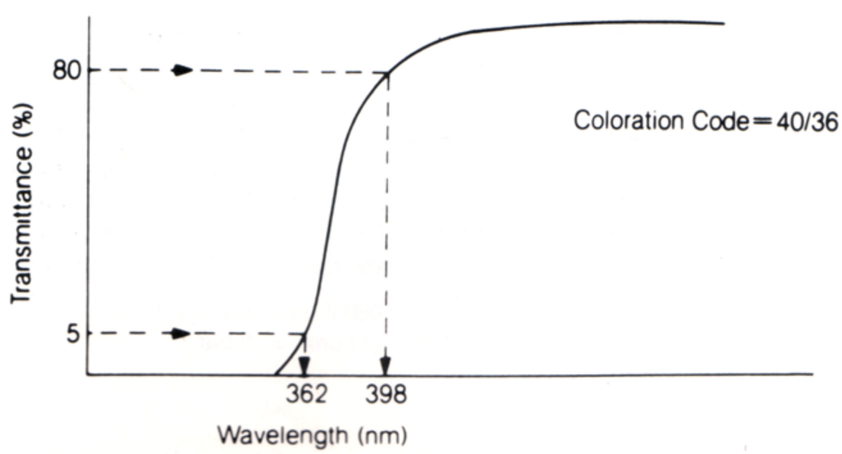

Fig. 1 Designation of the Coloration Code in Spectral Transmittance curve.

3. Chemical Properties

In various processes of fabricating optical components such as lenses and prisms, surface deterioration is often encountered and recognized as dimming, staining and latent scratching. These surface defects are caused by chemical reactions of the glass constituents with water in the surrounding environment or with detergents in the cleaning fluids.

Dimming

Polished glass exposed to high humidity and rapid temperature variations may "sweat". Water vapour may condense to form droplets on the glass surface. Some of the glass components that dissolve in the droplets may in turn attack the glass surface and react with gaseous elements in the air (CO_2, for example). Reaction products form as white spots or a cloudy film as the glass surface dries. We call this phenomenon "dimming".

The resistivity of glass to dimming is expressed in term of "water durability by the powdered method* (D_w)".

Staining

Water contact causes chemical reactions (ion exchange between cations in the glass and hydronium ions (H_3O+) in water) which result in a silica-rich surface layer that causes an interference color on that layer. We call this phenomenon "staining".

The resistivity of glasses to staining has been conventionally expressed in terms of "acid durability by the powdered method* (D_A)". It has often been suspected that the acid durability test may not necessarily correctly represent the ion exchange reaction to be encountered between glass and water in the actual lens polishing processes, and that the test may sometimes indicate higher resistivity to staining than is actually experienced in work. To cope with the shortcomings of this test method, this catalog has introduced "staining resistivity by the surface method (T_{Blue})". The conventional "acid durability by the powdered method* (D_A)" is also presented for the purpose of comparison only.

Latent Scratch

Fine scratches created on the glass surfaces during polishing will sometimes grow to a large visible size when the surfaces are exposed to corrosive ions out of inorganic builders in a detergent used for cleaning. This grown scratch is customarily called a "latent scratch".

The inorganic builders such as Na_2CO_3, $NaHCO_3$ or polymerized phosphate (mostly $Na_5P_3O_{10}$) may attack glass: Through hydrolysis of the builders in the solution, the builders form corrosive ions which attack the glass: hydroxyl ions, (OH- out of Na_2CO_3, $NaHCO_3$), or polymerized phosphoric ions out of polymerized phosphate.

Corrosion resistivity to hydroxyl ions is expressed in terms of "latent scratch resistivity (D_{NaOH})" and it is designated as "latent scratch resistivity (D_{STPP}**)" to polymerized phosphoric ions.

STPP is the abbreviation for **Sodium **T**ri-**P**oly **P**hosphate, $Na_5P_3O_{10}$.

Intrinsic Chemical Durability to Water

The entire surface of glass, when immersed in water, may be susceptible both to leaching of soluble ions in the glass and simultaneously to disintegration of its network, (SiO_2, B_2O_3), through hydrolysis.

The resistivity of glass to these reactions (leaching + disintegration) is directly related to the intrinsic chemical durability of glass to water. In this catalog, this resistivity is expressed as the "intrinsic chemical durability to water (D_0)".

3.1 Dimming Resistivity (Water Durability by the Powdered Method* (D_w))

The water durability is rated into 6 classes according to the percentage of mass loss, using the following method.

Glass is powdered and sieved to select particle sizes of 420~590μm. Powdered glass, weighed by its specific gravity, is placed in a platinum net basket and soaked in 80mℓ pure water (pH 6.5~7.5) that is contained in a fused silica flask. The glass is then boiled for 60 minutes. The percentage of mass loss is measured and listed in this catalog, along with its class, rated by Table 4.

Table 4 Classes of "Water Durability by Powdered Method* (D_w)"

Class	1	2	3	4	5	6
Mass loss(%)	≤0.04	0.05 ~ 0.09	0.10 ~ 0.24	0.25 ~ 0.59	0.60 ~ 1.09	≥1.10

3.2 Staining Resistivity

3.2.1 Acid Durability by the Powdered Method* (D_A)

The acid durability rating employs a method of testing which is similar to the water durability by the powdered method*, D_A, except that a 0.01 mol / ℓ nitric acid solution is used. The percentage of mass loss is measured and listed in this catalog, along with its class, rated by Table 5.

Table 5 Classes of "Acid Durability by the Powdered Method* (D_A)"

Class	1	2	3	4	5	6
Mass loss(%)	≤0.19	0.20 ~ 0.34	0.35 ~ 0.64	0.65 ~ 1.19	1.20 ~ 2.19	≥2.20

3.2.2 Staining Resistivity by the Surface Method (T_{Blue})

A glass specimen with a 43.7mm diameter and approximately 5mm thickness, polished on both surfaces (with a total surface area of 30cm^2) is immersed in pure water at 50°C, pH = 7.0±0.2. The pure water is well stirred and circulated at a rate of 1 ℓ / min through layers of ion exchange resin. The specimen is then taken out of the water to examine the interference color in the stained surface under a 100W tungsten-filament lamp at predetermined intervals of time. The time required to form a bluish stained layer (n•d≅120~130nm) is listed in this catalog, along with its class, rated by Table 6.

Table 6 Classes of "Staining Resistivity by the Surface Method (T_{Blue})"

Class	1	2	3	4	5	†
Criteria [length of time (h) required for stained layer observed]	>45	45	25	10	5	See Note***

Note*** Glasses in which the dissolution of the entire surface dominates and thus to prevents observation of the bluish layer or glasses where an irregular shift of the interference color is observed.

3.3 Latent Scratch Resistivity

3.3.1 Latent Scratch Resistivity (D_{NaOH})

A glass specimen with a 43.7mm diameter and approximately 5mm thickness, polished on both surfaces (with a total surface area of 30cm^2) is immersed in a 0.01 mol/ ℓ NaOH solution at 50°C which is well stirred for 15 hrs. Mass loss per unit area is then measured and listed in this catalog, along with its class, rated by Table 7.

Table 7 Classes of "Latent Scratch Resistivity (D_{NaOH})"

Class	1	2	3	4	5
Mass loss [mg / (cm^2•15h)]	≤0.01	0.02 ~ 0.10	0.11 ~ 0.20	0.21 ~ 0.30	≥0.31

3.3.2 Latent Scratch Resistivity (D_{STPP})

The latent scratch resistivity, D_{STPP}, is measured in terms of mass loss per unit area. A glass specimen of with a 43.7mm diameter and approximately 5mm thickness, polished on both surfaces (with a total surface area of 30cm^2), is immersed for 1 hr. in a 0.01 mol / ℓ $Na_5P_3O_{10}$ (STPP) solution, at 50°C which is well stirred. Mass loss per unit area is then measured and listed in this catalog, along with its class, rated by Table 8.

Table 8 Classes of "Latent Scratch Resistivity (D_{STPP})"

Class	1	2	3	4	5
Mass loss [mg / (cm^2•h)]	≤0.01	0.02 ~ 0.20	0.21 ~ 0.40	0.41 ~ 0.60	≥0.61

3.4 Intrinsic Chemical Durability to Water (D_0)

The intrinsic chemical durability to water, D_0, is evaluated in terms of mass loss per unit time per unit area [10^{-3}mg / (cm^2•h)] for a given period of time. Other test conditions are similar to those in T_{Blue}. Mass loss per unit area is then measured and listed in this catalog, along with their class, rated by Table 9.

Table 9 Classes of "Intrinsic Chemical Durability to water (D_0)"

Class	1	2	3	4	5
Mass loss [10^{-3}mg / (cm^2•h)]	≤0.3	0.4 ~ 5.0	5.1 ~ 10.0	10.1 ~ 15.0	≥15.1

4. Thermal Properties

4.1 Transformation Temperature* (Tg)

The glass transformation temperature 'T'g refers to the temperature at which the glass transforms from a lower temperature glassy state to a higher temperature super-cooled liquid state.

This behavior is illustrated in Fig. 2 which shows thermal expansion measured as a function of temperature. A differential thermal dilatometer is used for the measurement as it maintains a uniform temperature distribution within the furnace to ±1°C. As illustrated in the figure, the transformation temperature is determined by the intersection point of the two tangents of the high and low temperature ranges of the thermal expansion curve. The glass viscosity at Tg corresponds to about $10^{13.3}$dPa•s. Tg serves as a useful benchmark for annealing.

Note. 1 dPa•s = 1 poise

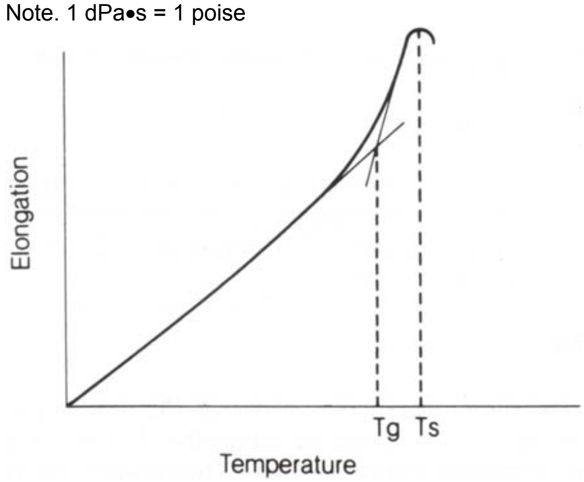

Fig. 2 Thermal Expansion Curve.

4.2 Sag Temperature (Ts)

In the thermal expansion curve shown in Fig. 2, the Sag Temperature (T_s) is defined as temperature at which thermal expansion stops increasing and actually begins to decrease with increasing temperature. This behavior is not due to an intrinsic property of the glass but is rather due to deformation of the glass under the load applied in these measurements. The viscosity of the glass at T_s corresponds to about 10^{10} to 10^{11} dPa•s.

4.3 Strain Point ($T_{10^{14.5}}$)

The strain point, $T_{10^{14.5}}$, represents a temperature at which internal stresses in a glass are relieved after a few hours. The viscosity of the glass at that temperature corresponds to about $10^{14.5}$ dPa•s.

4.4 Annealing Point ($T_{10^{13}}$)

The annealing point, $T_{10^{13}}$, represents a temperature at which internal stresses in a glass are relieved after a few minutes. The viscosity of the glass at that temperature corresponds to about 10^{13} dPa•s.

4.5 Softening Point ($T_{10^{7.6}}$)

The softening point, $T_{10^{7.6}}$, represents a temperature at which a glass begins to remarkably soften and deform under its own weight. The viscosity of the glass at that temperature corresponds about $10^{7.6}$ dPa•s.

In this catalog, the softening point is determined by the method specified in JIS R 3104-1970 and ASTM C338-73.

Note. The softening point is also called the "Littleton Point".

4.6 Mean Coefficient of Linear Thermal Expansion* (α)

4.6.1 $\alpha_{-30/+70°C}$

The mean coefficient of linear thermal expansion from -30°C to 70°C, $\alpha_{-30/+70°C}$, is obtained by using the interference-dilatometer mentioned in the preceding paragraph 2.5 "Temperature Coefficient of Refractive Index ($\Delta n / \Delta T$)" and expressed in 10^{-7} / K.

4.6.2. $\alpha_{100/300°C}$

The mean coefficient of linear thermal expansion from 100°C to 300°C, $\alpha_{100/300°C}$, is obtained by using the differential thermal dilatometer mentioned in the preceding paragraph 4.1 "Transformation Temperature* (Tg)" and expressed in 10^{-7} / K.

4.7 Thermal Conductivity (λ)

The thermal conductivity λ is the quotient obtained by dividing the density of heat flow rate by the temperature gradient, that is, the quotient obtained by dividing the heat quantity transferring through a unit area in a unit time, by the temperature difference per unit distance, and expressed in W / (m•K).

Note. 1 W / (m•K) = 8.600 0 x 10^{-1} kcal / (h•m•°C) = 2.388 89x 10^{-3} cal / (s•cm•°C)

4.8 Specific Heat (Specific Heat Capacity) (c_p)

The specific heat, c_p, is the quotient obtained by dividing the heat capacity of a substance by the mass, that is, the heat quantity required for increasing the temperature of a substance of unit mass by one unit (1K or 1°C) and expressed in kJ / (kg • K).

Note.1 kJ / (kg•K) = 2.388 89 x 10^{-1} cal / (g•°C)

5. Mechanical Properties

5.1 Knoop Hardness* (H_K)

Knoop hardnes is used to characterize the hardness of the surface of optical glass against penetration.

For this measurement a pyramidal diamond indenter with vertex angles 172°30' and 130°00' and with a rhombic base is applied to the polished specimen surface. Indentation loads of up to 0.9807N are applied for 15 seconds. The size of the resulting indentation is then measured.

Knoop hardness H_K is calculated using:

$$H_K = 1.451 \frac{F}{\ell^2} \qquad \textbf{(11)}$$

where F(N) denotes the applied load and ℓ (mm) is the length of the longer diagonal of the resulting indentation.

Notes.
1. The knoop hardness is expressed in terms of MPa or N / mm^2 which is omitted herein according to the usage.
2. The H_K value obtained by the above equation using SI units is equal to that which is obtained by the calculation equation using kgf units.
3. 1N = 1.019 72 x 10^{-1} kgf

Knoop hardness measurements are classified into the groups shown in the table below.

Table 10 Classes of "Knoop Hardness* (H_K)"

Class	1	2	3	4	5	6	7
Knoop Hardness	≤149	150 ~ 249	250 ~ 349	350 ~ 449	450 ~ 549	550 ~ 649	≥650

5.2 Abrasion Factor* (F_A)

The abrasion factor*, F_A, is a relative measure for lapping. A glass specimen with a surface area of 9cm^2 is placed at 80mm from the center of a cast iron circular plate. The plate is then rotated horizontally at 60 r.p.m., and a 9.807N lapping weight is vertically loaded on the specimen. Lapping is continued for 5 minutes, with a continuous supply of a lapping compound composed of 10g aluminum oxide (grain size 20μm) in 20ml of water. The mass loss of the specimen, m, is then measured and compared to that of the standard reference material (BSC 7), m_0, specified by JOGIS. The abrasion factor is then determined by the following equation:

$$F_A = \frac{m / d}{m_0 / d_0} \text{ X } 100 \qquad \textbf{(12)}$$

where d is the specific gravity of the test specimen and d_0 is the specific gravity of the standard reference material (BSC 7).

A H_K—F_A diagram is included in Appendixes to this catalog.

5.3 Elastic Properties (E, G and μ)

Young's modulus E and the modulus of rigidity, G, are measured by an acoustic method on a well-annealed 20 x 20 x 100mm specimen placed in an isothermal chamber.

The velocity of both the longitudinal and transverse waves of 5 MHz ultrasonic waves are measured.

Young's modulus E and the modulus of rigidity G are then calculated by the following equations:

$$E = \frac{4G^2 - 3G \bullet V_\ell{}^2 \bullet \rho}{G - V_\ell{}^2 \bullet \rho} \qquad \textbf{(13)}$$

$$G = V_s{}^2 \bullet \rho$$

where V_ℓ = velocity of the longitudinal wave
V_s = velocity of the transverse wave
ρ = density of the glass

The measured values are expressed in GPa with precision of $\pm$1%. From these E and G, Poisson's ratio μ is obtained by the following equation:

$$\mu = \frac{E}{2G} - 1 \qquad \textbf{(14)}$$

Notes.
1. Young's modulus is termed the modulus of longitudinal elasticity. The modulus of rigidity is also termed the modulus of transverse elasticity or shear modulus.
2. 1 GPa = 1.019 72 x 10^2 kgf / mm^2

5.4 Flexural Strength (Modulus of Rupture) (σ_b)

A well-annealed specimen of 4mm in width, 3mm in thickness, and 40mm in total length with polished upper and lower surfaces and a chamfered edge of C0.2 is used to measure its breaking load P(N) by the "3-point bending test" according to JIS R 1601-1981 and the flexural strength, σ_b, is calculated by the following equation:

$$\sigma_b = \frac{3P \bullet L}{2w \bullet t^2} \qquad \textbf{(15)}$$

where L is the support span (mm), w is the width (mm) of the specimen and t is the thickness (mm) of the specimen. The measured value is expressed in MPa.

Note. 1 MPa = 1.019 72x 10^{-1} kgf / mm^2

6. Electrical Properties

6.1 Relative Permittivity (ϵ_r)

The relative permittivity, ϵ_r, is defined by the ratio of the capacitance C/C_0.

The capacitance C_0 of a parallel-plate capacitor in a vacuum is given by the following equation:

$$C_0 = \frac{Q}{V} = \frac{\epsilon_0 \bullet A}{d} \tag{16}$$

where V is the potential difference between the plates, Q is the charge on the plates, ϵ_0 is the permittivity of vacuum (= 8.854×10^{-12} F/m), A is the area of the plates and d is the distance between the plates.

When an insulator is introduced between the plates of a capacitor, the capacitance increases and its value, C, is given by the following equation:

$$C = \frac{\epsilon_r \bullet \epsilon_0 \bullet A}{d} = \epsilon_r \bullet C_0 \tag{17}$$

ϵ_r in the above equation is called the relative permittivity which can be obtained from the ratio C/C_0. In this catalog, it is measured at 20°C and at 1 MHz by the method specified in JIS C 2141-1978.

6.2 Volume Resistivity (ρ_v)

The volume resistance between the two electrodes forming the two opposite sides of a cube with 1cm edges is called the volume resistivity, ρ_v, or simply the resistivity.

In this catalog the volume resistance, $R_v(\Omega)$, is measured with D.C. 500V by the method specified in JIS C 2141-1978 and the volume resistivity, ρ_v (Ω•cm), is calculated by the following equation:

$$\rho_v = \frac{A}{d} \bullet R_v \tag{18}$$

where A is the effective area (cm^2) of the main electrode of the disklike specimen and d is the thickness (cm) of the specimen.

In this catalog, the volume resistivity is measured at 20°C and 200°C and the measured values are expressed in terms of $\rho_{V20°C}$ and $\rho_{V200°C}$.

7. Other Property

7.1 Specific Gravity* (d)

Specific gravity of a glass is defined as the ratio of the glass density to the density of pure water at 4°C and 101.325 kPa (1 atm) pressure. Specific gravity is measured using the buoyancy method prescribed in JIS Z 8807-1976.

8. Quality Definitions

8.1 Tolerance of Refractive Index* and Abbe-number*

Since the listed refractive indices and Abbe-numbers are the mean of several melts, those for an individual melt will differ from the mean. The tolerances are generally as follows:

Refractive index n_d : $\pm$ 50 x 10^{-5}
Abbe-number ν_d : $\pm$ 0.8%

When you order, please specify the tolerance with respect to against our nominal values given in this catalog.

Upon special request, we can select an n_d up to $\pm$ 20 x 10^{-5} and a ν_d to $\pm$ 0.3 %.

Upon delivery of the ordered materials, melt data will be attached to report the specific refractive indices at the C, d, F and g spectral lines and the Abbe-number. The precision of standard measurements is $\pm$ 3 x 10^{-5} for the refractive index and $\pm$ 2 x 10^{-5} for dispersion. Upon request for precision measurement, we can furnish a refractive index with a precision up to $\pm$ 2 x 10^{-5} for the i and t lines, and up to $\pm$ 1 x 10^{-5} for the rest of the lines, as well as a dispersion with a precision up to $\pm$ 3 x 10^{-6}.

8.2 Optical Homogeneity

For large-sized glass blanks used in extremely high-precision optical systems, variations in the refractive index within a single piece must be controlled within very narrow limits.

Such large glass blanks with tight index control, or with very high optical homogeneity control, are manufactured by special manufacturing processes followed by interferometric inspection. Several grades of homogeneity can be supplied and are listed as follows:

Table 11 Grades of "Optical Homogeneity"

Grade	Variation of n_d
H1	$\pm$ 2 x 10^{-5}
H2	$\pm$ 5 x 10^{-6}
H3	$\pm$ 2 x 10^{-6}
H3	$\pm$ 1 x 10^{-6}

8.3 Striae*

Striae are inspected by a striae-scope equipped with a point light source and an optical lens system. For inspection, striae are first identified in a selected direction which facilitates good viewing, then rated in one of HOYA's own striae grades. With respect to standard reference samples, the MIL-G-174B striae grade is compared to HOYA's own grade, as shown in Table 12.

Table 12 Grades of "Striae"

HOYA striae grade	MIL-G-1741B striae grade
1	A
2	B
3	B
-	C,D

8.4 Stress Birefringence*

Optical glass retains slight residual stresses even after being well annealed. Internal stresses cause birefringence, which is represented in terms of differences in the optical path in nm / cm.

For disc-shaped products, the stress birefringence is measured at a distance 5% of the diameter from the circumference, and for rectangular plates, at a distance 5% of its width from the edge in the middle of the longer side. Stress birefringence is graded as follows:

Table 13 Grades of "Stress Birefringence"

Grade	Stress birefringence (nm / cm)	
1	≤ 4	(Precision annealing)
2	5 ~ 9	(Fine annealing)
3	10 ~ 19	(Commercial annealing)
4	≥ 20	(Coarse annealing)

For articles shaped differently than rectangles or discs, birefringence measurements at significantly meaningful locations may be arranged, if so requested.

8.5 Bubbles and Inclusions*

Bubbles and inclusions in our glasses, though not entirely absent, are very scarce owing to our development of melting methods. The size and number of bubbles varies with the glass composition and melting conditions.

Bubbles are counted to obtain the total cross sectional area (mm^2) of bubbles present in every 100ml of glass. Inclusions such as small stones or crystals are treated together with bubbles. The total cross-sectional area of bubbles and inclusions with diameter greater than 0.05mm is measured. This measurement is used to classify the glass according to Table 14.

The permissible number of bubbles and inclusions with diameter or maximum dimension less than 0.05mm is described per unit volume or mass by our class.

Table 14 Classes of "Bubbles and Inclusions"

Class	1	2	3	4
Total cross sectional area per 100ml of glass (mm^2)	≤ 0.11	0.12 ~ 0.24	0.25 ~ 0.49	0.50 ~ 0.99

8.6 Coloration Code*

The extent of coloration varies slightly from one melt to another, and therefore the coloration code listed in the catalog is the mean of several melts. Coloration between lots is controlled within ± 10nm of the listed nominal values.

Even when intensive care is taken in preparation and manufacturing, some types of optical glasses are prone to coloration, particularly noticeable in the FD and FDS types. Through the use of selected raw materials of high purity and by special melting methods, we can supply some types of glasses with less coloration. These types are affixed with "L" after the glass type and are shown in the remarks column. If the reduced coloration is desired for these types, it is advised that you specify this by adding "L" after the glass type designation on your order form.

Transmittance data can be furnished for delivered products upon request.

8.7 Cadmium and Thorium Free Glasses

As a result of pollution and environmental concerns, we have entirely eliminated both cadmium and thorium from our glass. Therefore, none of the glass presently manufactured by us contains any such materials, or other radioactive constituents.

9. Forms of Supply

9.1 Extruded Bar (E-Bar)

Two opposite sides, though not polished, may permit visual internal inspection, and the remaining sides are fire-polished or as cast. Bevels at the edges may vary depending on the dimensions of Extruded Bar.

9.2 Pressed Blanks

Pressed blanks refer to glass articles already formed in lens shapes or prism shapes. Forming is done either by automated direct-pressing (DP) or by manual reheated-pressing (RP). The DP blanks are superior in dimensional accuracy in outside diameter (O.D.), thickness etc., to RP blanks and can be supplied with edge thickness at a fixed dimension. Standard dimensional tolerances are given in the table below:

Table 15 Tolerance for the Outside Diameter and Thickness of Pressed Blanks

unit : mm

Outside Diameter of Pressed Blanks	Tolerance (in over-all range)			
	Direct-Pressing (DP)		Reheated-Pressing (RP)	
	O.D.	Thickness	O.D.	Thickness
~ 25.0	0.2	0.4	0.3	1.0
25.1~ 35.0	0.3	0.4	0.3	0.8
35.1~ 50.0	0.3	0.4	0.4	0.8
50.1~ 65.0	0.4	0.4	0.4	0.6
65.1~ 80.0	0.4	0.4	0.5	0.6
80.1~100.0	0.4	0.5	0.6	0.6
100.1~	Separately determined upon consultation			

On request tighter tolerance is acceptable with condition that customers furnish the final dimensions or drawings indicating the thickness of glass removal by grinding and polishing.

9.3 Gobs

Gobs are supplied in a fire-polished form in a given weight specified by the customer and are available only for selected glass types.

9.4 Special Shapes and Sizes

Special orders for sliced discs, large molded blanks, window or mirror blanks and other miscellaneous shapes with various dimensions for special applications are acceptable on request.

9.5. Polished Lenses

Polished, coated and assembled various lenses such as camera lenses and VTR-lenses are available on request.