# Optical Materials

## Important properties:

- **Optical**
  - **Wavelength range**
  - **Refractive index**
  - **Dispersion**
  - **dn/dT**
  - **Optical quality**
    - **transmission, bubbles, homogeneity, birefringence, ..**
- **Mechanical**
  - **CTE**
  - **Young's modulus**
  - **Density**
  - **Thermal conductivity**
  - **Specific heat**
  - **Hardness**
  - **Melting point**
  - **Fracture toughness**
  - **Climatic resistance**

## Glasses:

**Transmit from near UV to near IR**
**Wide variety for color correction**
**Low conductivity, fairly low CTE**
**Isotropic**
**Hard (cannot be diamond turned to optical finish)**

## Crystals

**Wider wavelength range**
**Wider range of mechanical properties**
**Can have severe anisotropy**
**Many can be diamond turned**

$n_d = 1.51680$ $\nu_d = 64.17$ $n_F - n_c = 0.008054$
$n_e = 1.51872$ $\nu_e = 63.96$ $n_F - n_{c'} = 0.008110$

**N-BK7 517642.251**

| Refractive indices | $\lambda$ [nm] | |
|---|---|---|
| $n_{2325.4}$ | 2325.4 | 1.48921 |
| $n_{1970.1}$ | 1970.1 | 1.49485 |
| $n_{1529.6}$ | 1529.6 | 1.50091 |
| $n_{1060.0}$ | 1060.0 | 1.50669 |
| $n_t$ | 1014.0 | 1.50731 |
| $n_s$ | 852.1 | 1.50980 |
| $n_r$ | 706.5 | 1.51289 |
| $n_C$ | 656.3 | 1.51432 |
| $n_{C'}$ | 643.8 | 1.51472 |
| $n_{632.8}$ | 632.8 | 1.51509 |
| $n_D$ | 589.3 | 1.51673 |
| $n_d$ | 587.6 | 1.51680 |
| $n_e$ | 546.1 | 1.51872 |
| $n_F$ | 486.1 | 1.52238 |
| $n_{F'}$ | 480.0 | 1.52283 |
| $n_g$ | 435.8 | 1.52668 |
| $n_h$ | 404.7 | 1.53024 |
| $n_i$ | 365.0 | 1.53627 |
| $n_{334.1}$ | 334.1 | 1.54272 |
| $n_{312.6}$ | 312.6 | 1.54862 |
| $n_{296.7}$ | 296.7 | |
| $n_{280.4}$ | 280.4 | |
| $n_{248.3}$ | 248.3 | |

| Constants of dispersion formula | |
|---|---|
| $B_1$ | $1.03961212 \cdot 10^{+00}$ |
| $B_2$ | $2.31792344 \cdot 10^{-01}$ |
| $B_3$ | $1.01046945 \cdot 10^{+00}$ |
| $C_1$ | $6.00069867 \cdot 10^{-03}$ |
| $C_2$ | $2.00179144 \cdot 10^{-02}$ |
| $C_3$ | $1.03580653 \cdot 10^{+02}$ |

| Constants of formula dn/dT | |
|---|---|
| $D_0$ | $1.86 \cdot 10^{-06}$ |
| $D_1$ | $1.31 \cdot 10^{-08}$ |
| $D_2$ | $-1.37 \cdot 10^{-11}$ |
| $E_0$ | $4.34 \cdot 10^{-07}$ |
| $E_1$ | $6.27 \cdot 10^{-10}$ |
| $\lambda_{TK}$[µm] | 0.170 |

| Internal transmittance $\tau_i$ | | |
|---|---|---|
| $\lambda$[µm] | $\tau_i$ [10mm] | $\tau_i$ [25mm] |
| 2500 | 0.67 | 0.36 |
| 2325 | 0.79 | 0.56 |
| 1970 | 0.930 | 0.84 |
| 1530 | 0.992 | 0.980 |
| 1060 | 0.999 | 0.997 |
| 700 | 0.998 | 0.996 |
| 660 | 0.998 | 0.994 |
| 620 | 0.998 | 0.994 |
| 580 | 0.998 | 0.995 |
| 546 | 0.998 | 0.996 |
| 500 | 0.998 | 0.994 |
| 460 | 0.997 | 0.993 |
| 436 | 0.997 | 0.992 |
| 420 | 0.997 | 0.993 |
| 405 | 0.997 | 0.993 |
| 400 | 0.997 | 0.992 |
| 390 | 0.996 | 0.989 |
| 380 | 0.993 | 0.983 |
| 370 | 0.991 | 0.977 |
| 365 | 0.988 | 0.971 |
| 350 | 0.967 | 0.920 |
| 334 | 0.910 | 0.78 |
| 320 | 0.77 | 0.52 |
| 310 | 0.57 | 0.25 |
| 300 | 0.29 | 0.05 |
| 290 | 0.06 | |
| 280 | | |
| 270 | | |
| 260 | | |
| 250 | | |
| | | |

| Color code | |
|---|---|
| $\lambda_{80}/\lambda_5$ | 33/29 |

| Remarks | |
|---|---|
| | |
| | |
| | |

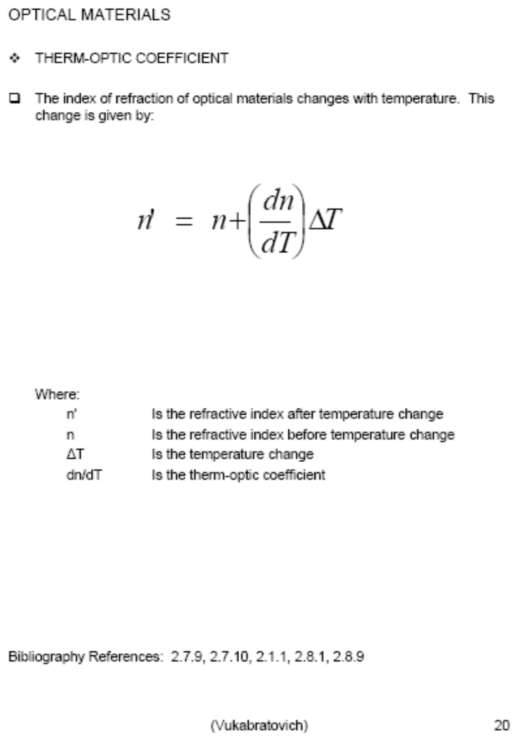
| Relative partial dispersion | |
|---|---|
| $P_{s,t}$ | 0.3098 |
| $P_{C,s}$ | 0.5612 |
| $P_{d,C}$ | 0.3076 |
| $P_{e,d}$ | 0.2386 |
| $P_{g,F}$ | 0.5349 |
| $P_{i,h}$ | 0.7483 |
| | |
| $P'_{s,t}$ | 0.3076 |
| $P'_{C',s}$ | 0.6062 |
| $P'_{d,C'}$ | 0.2566 |
| $P'_{e,d}$ | 0.2370 |
| $P'_{g,F'}$ | 0.4754 |
| $P'_{i,h}$ | 0.7432 |
| | |

| Deviation of rel. partial dispersion $\Delta P$ from "Normal line" | |
|---|---|
| $\Delta P_{C,t}$ | 0.0216 |
| $\Delta P_{C,s}$ | 0.0087 |
| $\Delta P_{F,e}$ | −0.0009 |
| $\Delta P_{g,F}$ | −0.0009 |
| $\Delta P_{i,g}$ | 0.0035 |
| | |

| Other properties | |
|---|---|
| $\alpha_{-30/+70°C}$ [$10^{-6}$/K] | 7.1 |
| $\alpha_{+20/+300°C}$ [$10^{-6}$/K] | 8.3 |
| Tg [°C] | 557 |
| $T10^{13.0}$ [°C] | 557 |
| $T10^{7.6}$ [°C] | 719 |
| $c_p$ [J/(g·K)] | 0.858 |
| $\lambda$ [W/(m·K)] | 1.114 |
| | |
| $\rho$ [g/(cm$^3$)] | 2.51 |
| E [$10^3$(N/mm$^2$)] | 82 |
| $\mu$ | 0.206 |
| K [$10^{-6}$mm$^2$/N] | 2.77 |
| $HK_{0.1/20}$ | 610 |
| HG | 3 |
| | |
| B | 0 |
| | |
| CR | 2 |
| FR | 0 |
| SR | 1 |
| AR | 2 |
| PR | 2.3 |

| Temperature coefficents of refractive index | | | | | | |
|---|---|---|---|---|---|---|
| | $\Delta n_{rel}/\Delta T$ [$10^{-6}$/K] | | | $\Delta n_{abs}/\Delta T$ [$10^{-6}$/K] | | |
| [°C] | 1060.0 | e | g | 1060.0 | e | g |
| −40/−20 | 2.4 | 2.9 | 3.3 | 0.3 | 0.8 | 1.2 |
| +20/+40 | 2.4 | 3.0 | 3.5 | 1.1 | 1.6 | 2.1 |
| +60/+80 | 2.5 | 3.1 | 3.7 | 1.5 | 2.1 | 2.7 |

# Focal length change due to temperature change:



OPTICAL MATERIALS

❖ THERM-OPTIC COEFFICIENT

❑ The index of refraction of optical materials changes with temperature. This change is given by:

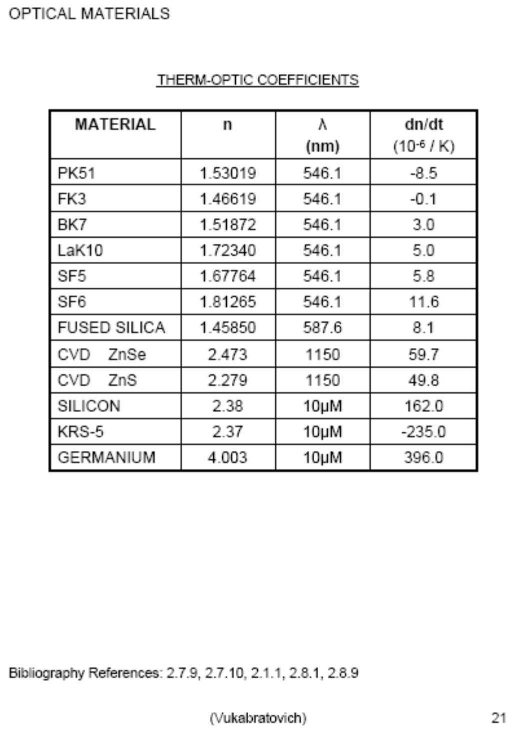
$$n' = n + \left(\frac{dn}{dT}\right)\Delta T$$

Where:

| | |
|---|---|
| n' | Is the refractive index after temperature change |
| n | Is the refractive index before temperature change |
| ΔT | Is the temperature change |
| dn/dT | Is the therm-optic coefficient |

Bibliography References: 2.7.9, 2.7.10, 2.1.1, 2.8.1, 2.8.9

(Vukabratovich) 20



OPTICAL MATERIALS

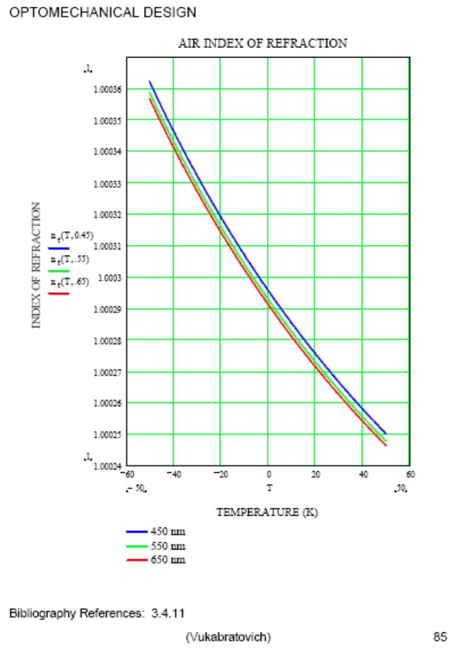
THERM-OPTIC COEFFICIENTS

| MATERIAL | n | λ (nm) | dn/dt ($10^{-6}$ / K) |
|---|---|---|---|
| PK51 | 1.53019 | 546.1 | -8.5 |
| FK3 | 1.46619 | 546.1 | -0.1 |
| BK7 | 1.51872 | 546.1 | 3.0 |
| LaK10 | 1.72340 | 546.1 | 5.0 |
| SF5 | 1.67764 | 546.1 | 5.8 |
| SF6 | 1.81265 | 546.1 | 11.6 |
| FUSED SILICA | 1.45850 | 587.6 | 8.1 |
| CVD ZnSe | 2.473 | 1150 | 59.7 |
| CVD ZnS | 2.279 | 1150 | 49.8 |
| SILICON | 2.38 | 10µM | 162.0 |
| KRS-5 | 2.37 | 10µM | -235.0 |
| GERMANIUM | 4.003 | 10µM | 396.0 |

Bibliography References: 2.7.9, 2.7.10, 2.1.1, 2.8.1, 2.8.9

(Vukabratovich) 21

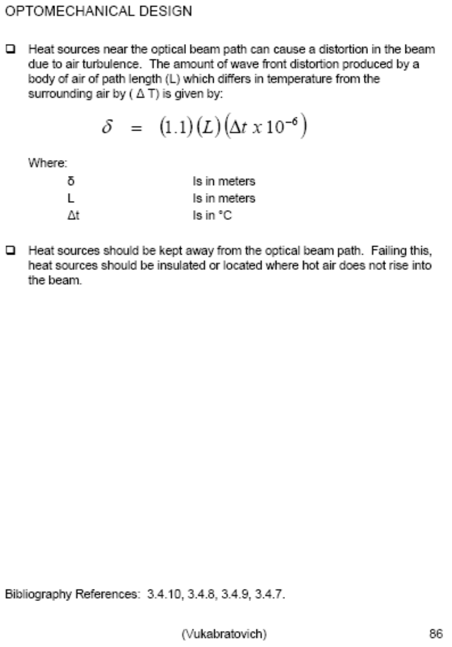
For lenses in air, we need to consider the effect of the changing refractive index of the air!



OPTOMECHANICAL DESIGN

Bibliography References: 3.4.11

(Vukabratovich) 85



OPTOMECHANICAL DESIGN

❑ Heat sources near the optical beam path can cause a distortion in the beam due to air turbulence. The amount of wave front distortion produced by a body of air of path length (L) which differs in temperature from the surrounding air by ( Δ T) is given by:

$$\delta = (1.1)(L)(\Delta t \; x \; 10^{-6})$$

Where:

| | |
|---|---|
| δ | Is in meters |
| L | Is in meters |
| Δt | Is in °C |

❑ Heat sources should be kept away from the optical beam path. Failing this, heat sources should be insulated or located where hot air does not rise into the beam.

Bibliography References: 3.4.10, 3.4.8, 3.4.9, 3.4.7.

(Vukabratovich) 86

# Change in lens focal length due to temperature

The refractive index of most materials, including air, varies with temperature. This causes the power in a lens to vary with temperature, which may cause a system focus to change.

The power $\phi$ in an optical surface is $\phi = \dfrac{\left(n_{glass} - n_{air}\right)}{R} = \dfrac{\left(n_r - 1\right)}{R}$

With $n_r$ defined as effective $n$ relative to air so $(n_{glass} - n_{air}) = (n_r - 1)$:

Taking derivative with temperature

$$\frac{d\phi}{dT} = \frac{dn_r}{dT}\frac{1}{R} - \frac{(n_r - 1)}{R^2}\frac{dR}{dT}$$

dividing through by $\phi$,

$$\frac{1}{\phi}\frac{d\phi}{dT} = \frac{1}{(n_r - 1)}\frac{dn_r}{dT} - \frac{1}{R}\frac{dR}{dT}$$

Change in focal length goes as

$f = \dfrac{1}{\phi}$ so $\dfrac{1}{\phi}\dfrac{d\phi}{dT} = -\dfrac{1}{f}\dfrac{df}{dT}$

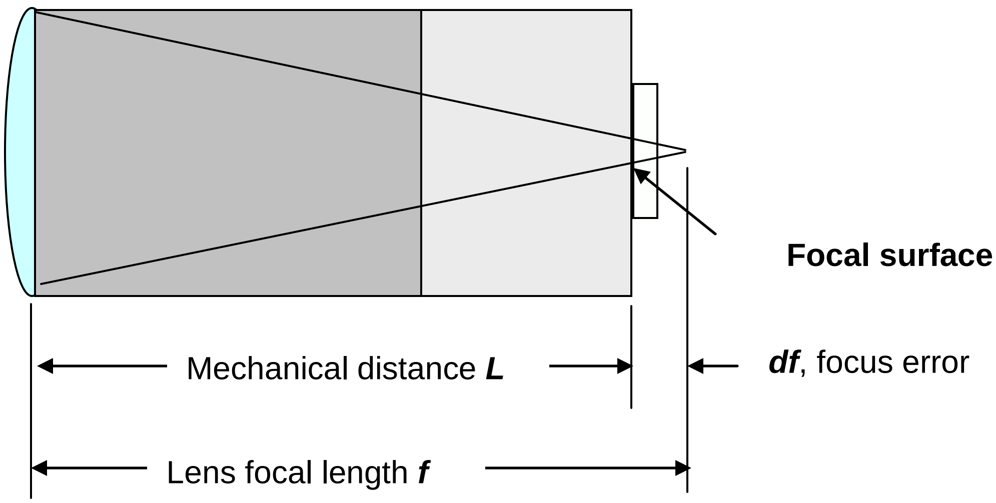
Define $\beta$ so $\Delta f = \beta f \Delta T$

$$\beta = \frac{1}{R}\frac{dR}{dT} - \frac{1}{(n_r - 1)}\frac{dn_r}{dT}$$

$$= \alpha - \frac{1}{(n_r - 1)}\frac{dn_r}{dT}$$

Where $\alpha$ is the glass CTE

Athermalize by making change in focal length = change in spacing

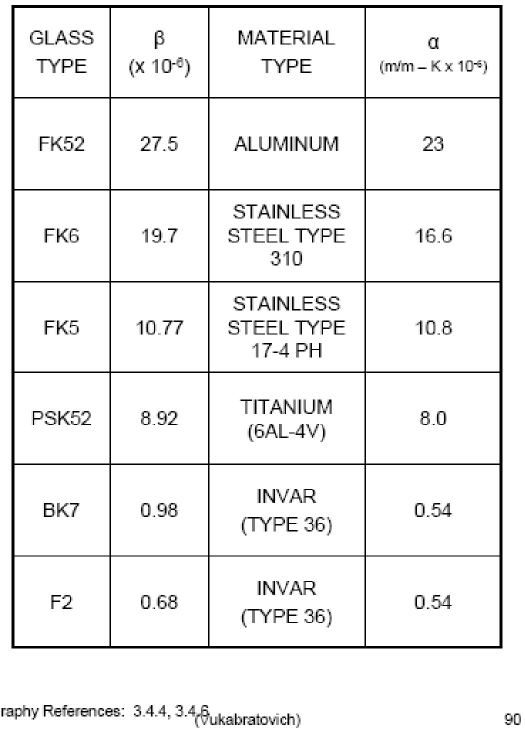


System stays in focus if

$$\frac{df}{dT} = \frac{dL}{dT}$$

$$\beta \cdot f = \sum \alpha_i L_i$$

One material defining the spacing L



| GLASS TYPE | β (x $10^{-6}$) | MATERIAL TYPE | α (m/m – K x $10^{-6}$) |
|---|---|---|---|
| FK52 | 27.5 | ALUMINUM | 23 |
| FK6 | 19.7 | STAINLESS STEEL TYPE 310 | 16.6 |
| FK5 | 10.77 | STAINLESS STEEL TYPE 17-4 PH | 10.8 |
| PSK52 | 8.92 | TITANIUM (6AL-4V) | 8.0 |
| BK7 | 0.98 | INVAR (TYPE 36) | 0.54 |
| F2 | 0.68 | INVAR (TYPE 36) | 0.54 |

ibliography References: 3.4.4, 3.4.6 (Vukabratovich) 90

For the case where more materials define the spacing can be easily calculated as a sum of the expansion from the individual sections.

Multiple lenses, multiple materials, easily calculated, optimized in CodeV, Zemax

# Hardness (from Schott TIE-31)

## 3. Knoop Hardness

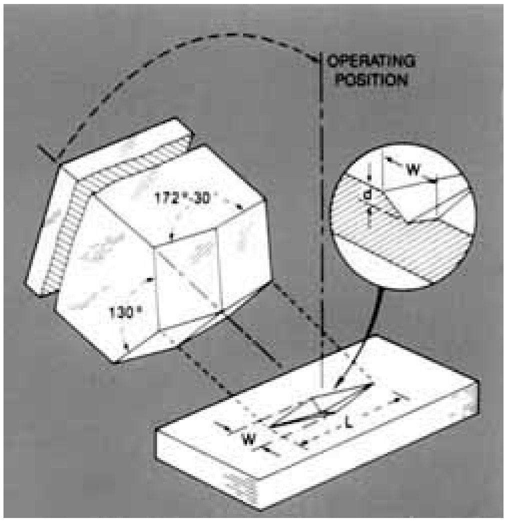
The resistance of a material to indentation is characterized by the indentation hardness. Several testing methods can be used: scratching, abrasion or penetration; however, the results are not exactly comparable.

In the Knoop hardness test the indentation depth of a rhombus-shaped diamond pressed with a defined force a time on the material is measured. The diamond surfaces have defined intersection angles of 172.5° and 130.0°. During pressing of the diamond into the glass plate an elastic and plastic deformation occurs. The size of the permanent indentation depends on the hardness of the material, which is given by the chemical composition. The Knoop hardness can be calculated from the diagonal size d of the indentation using the following formula:

$$HK = 1.4233 \cdot \frac{F}{d^2}$$

The standard ISO 9385 [1] describes the measurement procedure for glasses. In accordance with this standard, the values for Knoop hardness HK are listed in the data sheets for a test force of 0.9807 N (corresponds to 0.1 kp) and an effective test period of 20 s. The test was performed on polished glass surfaces at room temperature. The data for hardness values are rounded to 10 HK 0.1/20. The microhardness is a function of the magnitude of the test force and decreases with increasing test force.

In general glasses with a high content of network formers (silica or boron oxide) have high hardness values. Barium-lanthanum-borate glasses (LaK and LaSF glasses) have the highest hardness. An increasing alkaline and/or lead content decreases the indentation hardness.



## 8. Fracture toughness of glass

So far the strength of optical glass was considered from a statistical point of view by measuring the bending strength of samples and subsequently estimating the failure probabilities. Looking at a single flaw in a material the maximum bending strength depends on the size of the flaw and geometry in the material. For example in case of a flaw with a short depth in a thick plate with tensile forces acting normal to the crack plane one can define a stress intensity factor $K_I$ by:

$$K_I \approx 2\sigma_0\sqrt{a} \qquad (8\text{-}1)$$

with $\sigma_0$ being the nominal stress perpendicular to the stress plane and a the depth of the flaw. A flaw will result in a fracture if :

$$K_I \geq K_{IC} \qquad (8\text{-}2)$$

$K_{IC}$ is the critical stress intensity factor for crack mode I (tensile forces normal to the crack plane, crack propagation perpendicular to the forces). $K_{IC}$ is a material constant. For glasses without additional strengthening the value is typically $\leq 1$. Table 3 gives fracture toughness values of some glasses:

| **Glass** | **$K_{IC}$ [ MPa $m^{1/2}$]** |
|---|---|
| N-BK7 | 1.1 |
| F5 | 0.9 |
| ZERODUR® | 0.9 |
| SF6 | 0.7 |

**Table 3:** Fracture toughness values of some glasses [7,9]

For a given nominal stress the plate will break for a critical depth $a_c$ of

$$a_c \approx \left(\frac{K_{IC}}{2\sigma_0}\right)^2 \qquad (8\text{-}3)$$

Numerical example: For the characteristic strength of ZERODUR® of samples with D64 surface condition $\sigma_0 \approx 64$ MPa (table 1) and ZERODUR® $K_{IC} \approx 0.9$ MPa $m^{1/2}$ the critical flaw size $a_c$ is approx. 49 µm. This flaw size compares to the grain sizes for D64 bonded diamond grains (table 4).

Most glasses exhibit slow crack growth for a stress intensity factor well below the critical value. As mentioned above the most important sub-critical crack growth occurs in the presence of water (amounts less then 10 mg per $m^2$). The velocity of the crack can be described by [8]:

$$\frac{da}{dt} = A * \left(\frac{K_I(a)}{K_{IC}}\right)^n \qquad (8\text{-}4)$$

a denotes the depth of the crack, A is a constant and n is the stress corrosion constant.

# Estimation of strength of glass using statistical methods

**Rule of thumb:** Glass can withstand long term tensile stresses of 1,000 psi (6.9 MPa), momentary stress of 4000 psi, and compressive stresses of 50,000 psi (345 MPa) before problems or failures occur [1].

**Explanation and Usefulness:** When designing a mount for a given optical system, it is critical to consider the stresses that will occur at any glass interface. Knowing the force that will be exerted on a metal-glass interface can drive the type of edge contact, the thermal operating range, and the overall tolerances of the system. Considering that failure in glass is typically catastrophic, a conservative approach should be taken to ensure a given glass can withstand the expected load in a system. This rule of thumb is considered very conservative. Looking at the examples given below, using this estimation for most glasses gives a very small or zero probability of failure.

**Limitations:** Unfortunately, there is no characteristic strength value for a given glass, so this estimation should be used with caution. The actual tensile and compressive strength of any given optic depends on a large variety of factors. The area of the surface under stress, surface finish, size of internal flaws, glass composition, surrounding environment, and the amount and duration of the load all are important factors in determining the strength of glass. In general, glass is weaker with increasing moisture in the air and is able to withstand rapid, short loads better than slow lengthy loads [2].

**Complete Analysis:** Weibull statistics are commonly used to predict the probability of failure and strength of a glass. This approach allows for the characterization of the inert strength of glass but does not take time factors into account [3]. It assumes that flaws and loads remain constant over time. The mathematical distribution is given by:

$$P_f = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right]$$

$P_f =$ Probability of failure
$\sigma =$ Applied stress
$\sigma_0 =$ Characteristic strength (stress at which 63.2% of samples fail)
$m =$ Weibull modulus (indicator of the scatter of the distribution of the data)

A list of Weibull parameters are shown below for some common glasses. The probability of failure is also displayed for an applied stress of 6.9MPa (1,000psi).

Note that the parameters depend on the type of finish as well as the material. Optically polished or flame polished surfaces are much stronger than cut or ground surfaces.

**Probability of Failure at 6.9MPa (1,000 psi) for common glasses**

| Material | Weibull Modulus (m) | Characteristic Strength (MPa) | Probability of failure |
|---|---|---|---|
| N-BK7 | 30.4 | 70.6 | 0 |
| F2 | 25.0 | 57.1 | 0 |
| SF6 | 21.9 | 57.3 | 0 |
| Silicon | 4.5 | 346.5 | $2.2 \times 10^{-8}$ |
| Germanium | 3.4 | 119.8 | $6.1 \times 10^{-5}$ |
| ZnSe | 6.0 | 54.9 | $3.9 \times 10^{-6}$ |
| Sapphire | 4.0 | 485 | $4.1 \times 10^{-8}$ |
| Calcium Fluoride | 3.0 | 5.0 | 0.93 |
| Zerodur | 5.3 | 293.8 | $2.5 \times 10^{-9}$ |
| Corning ULE | 4.5 | 40.4 | $3.75 \times 10^{-4}$ |

Another approach is to determine the fracture toughness of a glass based on the critical flaw size [4]. Fracture toughness, the resistance of a material to crack propagation, is one of the many ways to characterize a material. Once an applied stress exceeds the material's fracture toughness, a failure would most likely occur. Schott's technical paper TIE-33 [4] presents a simple approximation for determining if a material will fail. For a given stress, a material will fail if a flaw exceeds the critical length, $a_c$ :

$$a_c = \left(\frac{K_c}{2\sigma_0}\right)^2$$

$a_c =$ critical depth of flaw
$K_c =$ fracture toughness of glass
$\sigma_0 =$ applied stress

The maximum flaw depth can be estimated from the size of the grinding particle used to finish the optic. Doyle and Kahan [3] state that the maximum flaw depth can be estimated to be three times the diameter of the average grinding particle used. The fracture toughness of glass can typically be found in the material's data sheet, and values for some common glasses can be found in Yoder [1]. The units of fracture toughness are $Pa\sqrt{m} \times 10^5$.

**References:**

[1] Yoder, Paul R. *Opto-mechanical Systems Design*. Bellingham, Wash.: SPIE, 2006, Pgs. 738, 745-746.
[2] Schott –Technical Note. *TIE-31: Mechanical and Thermal Properties of Optical Glass*. 2004.
[3] K.B. Doyle, M.A. Kahan, "Design strength of optical glass," Optomechanics 2003, Proc. SPIE 5176 (2003).
[4] Schott – Technical Note. *TIE-33: Design strength of optical glass and Zerodur*. 2004.
[5] Ashby, M. F. *Materials Selection in Mechanical Design*. Oxford: Pergamon, 1992. Pg 273.
[6] Vukobratovich, D. and S. *Introduction to Opto-mechanical Design.* Short course notes.

| **Material** | **Index of Refraction - $n_d$** | **Transmission Range (μm)** | **Young's Modulus –E (GPa)** | **CTE – α (x10$^{-6}$/°C)** | **Density – ρ (g/cm$^3$)** | **dn/dT (absolute) (x10$^{-6}$/°C)** | **Poisson Ratio – ν** | **Thermal Conductivity – λ (W/mK)** | **Stress Optic Coefficient – $K_s$ (10$^{-12}$/Pa)** |
|---|---|---|---|---|---|---|---|---|---|
| N-BK7 | 1.5168 | 0.35 – 2.5 | 82 | 7.1 | 2.51 | 1.1 | 0.206 | 1.11 | 2.77 |
| Borofloat 33 Borosilicate | 1.4714 | 0.35 – 2.7 | 64 | 3.25 | 2.2 | | 0.20 | 1.2 | 4 |
| Calcium Fluoride | 1.4338 | 0.35 – 7 | 75.8 | 18.85 | 3.18 | -10.6 | 0.26 | 9.71 | 2.15 |
| Fused Silica | 1.4584 | 0.18 – 2.5 | 72 | 0.5 | 2.2 | 8.1 | 0.17 | 1.31 | 3.4 |
| Germanium | 4.0026 (at 11μm) | 2 – 14 | 102.7 | 6.1 | 5.33 | 396 | 0.28 | 58.61 | -1.56 |
| Magnesium Fluoride | 1.413 $N_{ord}$ (at 0.22 | 0.12 – 7 | 138 | 13.7<br>8.9 | 3.18 | 2.3 (//)<br>1.7 (_\|_) | 0.276 | 11.6? | |
| Sapphire | 1.7545 $N_{ord}$ (at 1.06 | 0.17 – 5.5 | 335 | 5.3 | 3.97 | 13.1 | 0.25 | 27.21 | |
| SF57 | 1.8467 | 0.4 – 2.3 | 54 | 8.3 | 5.51 | 6.0 | 0.248 | 0.620 | 0.02 |
| N-SF57 | 1.8467 | 0.4 – 2.3 | 96 | 8.5 | 3.53 | -2.1 | 0.26 | 0.990 | 2.78 |
| Silicon | 3.4223 (at 5 μm) | 1.2 – 15 | 131 | 2.6 | 2.33 | 160 | 0.266 | 163.3 | |
| ULE (Corning | 1.4828 | 0.3 – 2.3 | 67.6 | 0.03 | 2.21 | 10.68 | 0.17 | 1.31 | 4.15 |
| Zerodur | 1.5424 | 0.5 – 2.5 | 90.3 | 0.05 | 2.53 | 14.3 | 0.243 | 1.46 | 3.0 |
| Zinc Selenide | 2.403 (at 10.6 | 0.6 – 16 | 67.2 | 7.1 | 5.27 | 61 | 0.28 | 18 | -1.60 |
| Zinc Sulfide | 2.2008 (at 10μm) | 0.4 – 12 | 74.5 | 6.5 | 4.09 | 38.7 | 0.28 | 27.2 | 0.804 |

| Material | Advantages/Outstanding Properties | Disadvantages/Difficult Properties | Common Application Areas |
|---|---|---|---|
| N-BK7 | Easy to make high quality<br>Readily available, inexpensive | Tranmission limited to visible/near IR | Versatile for everyday optical applications |
| Fused Silica | Wide transmission range<br>Low CTE | Higher dn/dT than BK7 | Standard optics, high power laser applications |
| Silicon | Wide IR transmission range<br>Lower CTE | High dn/dT | Filter substrates, IR windows |
| SF57 | Low stress-optic coefficient | Softer material | Special polarization optics |
| Sapphire | Very hard, very scratch resistant<br>Wide transmission range | Difficult to machine<br>Expensive | Windows/domes for UV, IR, and visible |
| Calcium Fluoride | Wide transmission range<br>Very low dispersion | Soft material<br>High CTE | IR and UV applications – windows, filters, and prisms |
| Magnesium Fluoride | Wide transmission range<br>Birefringent | Birefringent, larger anisotropic CTE | Common anti-reflection coating, UV optics |
| Borofloat Borosilicate | Low CTE, CTE matches Silicon, can be made very flat | Poor optical properties | Applications needed thermal stability |
| Zinc Selenide | Transmits in IR and Visible | Soft, High dn/dT | IR windows and lenses, $CO_2$ laser optics for 10.6μm |
| Zinc Sulfide | Transmits in IR and Visible |  | IR windows and lenses, combined visible/IR systems |
| Germanium | Low dispersion | High density (heavy), high dn/dT | IR applications |
| ULE (Corning 7972) | Very low CTE | Poor optical properties<br>Expensive | Telescope mirror substrates, space applications |
| Zerodur | Very low CTE | Poor optical properties<br>Expensive | Telescope mirror substrates, space applications |

(K. Schwertz, *Useful Estimations and Rules of Thumb in Optomechanics*, MS Report, University of Arizona, 2010)