The CRYSTRAN HANDBOOK

of Infra-Red and Ultra-Violet OPTICAL MATERIALS

CRYSTRAN
ALWAYS ON YOUR WAVELENGTH

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A COMPREHENSIVE SOURCE ACROSS THE SPECTRUM

This handbook is published by Crystran Ltd as a service to optics professionals. It is designed to help you determine the best material for your application. The materials that we work with are mainly crystal or innovative glasses used for their particular transmission properties. We also have a great deal of experience within the company of the crystal growth techniques used in making the raw materials. If your requirement is for prototypes or for production quantities our technical team are happy to help.

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Crystran Ltd are primarily a custom manufacturer of optics to drawing or specification. For those who require a component fast we do hold an enormous range of stock. Access our shop from our website.
Website: www.crystran.co.uk

Join our Company Linked in for news and updates
https://www.linkedin.com/company/crystran-limited/

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Material Data

INTRODUCTION TO THE HANDBOOK

This Handbook, as well as being a catalogue of the range of materials and production capabilities available to you at Crystran Ltd, is hoped to be a useful reference source for optical, physical and chemical data.

The data in this Handbook is provided in good faith and reviews have been made to verify the sources of information where possible; however Crystran Ltd can accept no responsibility for accuracy. It is not always possible to verify data where there are conflicting figures in different publications, revisions are a continuing process and we have applied our best judgement where appropriate. References are stated where possible. Transmission scans are original Crystran company data.

Formulae and notes included within the Handbook are not intended to be comprehensive. We have found them a useful reference and consult them continually.

Values quoted in the Handbook are, as standard, SI units except where alternative units are in common usage – an Appendix is included containing unit conversion tables.

Crystran Ltd would like to acknowledge the help of our associates.

INTRODUCING THE CRYSTRAN APP.

Since the last print edition we have published a free App for both Android and Apple Formats. This contains much of the data in this Handbook as well as some routines for making optical and pressure calculations. You are welcome to download it.

ANDROID APP ON Google play

Available on the App Store

INTRODUCTION TO CRYSTRAN LTD

Crystran Ltd is a manufacturer and supplier of high quality optical components. We manufacture windows, lenses, prisms and specialist optics as both standard products and to the designs of our customers. For over 30 years we have specialised in crystal materials and exotic glasses and used them to manufacture highly precise optical components for the Infrared, Ultraviolet and Visible regions of the spectrum.

In 2018 we launched our web shop. We know many of our customers prefer to speak to us or to email, but we were very pleased with its immediate popularity both with existing customers and new ones.

You can see a full list of the materials we work with in this book and on our website.

Crystran Ltd no longer grow crystal in-house, however we still retain the experience and understanding that is invaluable when talking to suppliers and customers alike. Crystran holds extensive stocks of crystal as ingots to offer a comprehensive range of crystals and crystal products for UV, IR and visible applications.

Crystal materials can be supplied in a number of different forms – raw boule, cut and shaped blanks, and polished optics. Our production facilities include cutting and several polishing shops for the production of components to customer specifications.

Our dedication to investment in both staff and equipment enables us to work to increasingly higher standards. Surface qualities of up to $\lambda/20$ at 633nm and parallelism of better than 2 arc seconds can be achieved (dependent on material and method required). Double sided and conventional polishing techniques, coupled with computerised interferometry and other test equipment, ensure that specifications can be met.

REFERENCE SECTION

Our extensive range of test equipment includes

NAME	INSTRUMENT	MEASUREMENT
Trioptics Prism Master	Auto Collimator	Parallelism and angular tolerance <2 arc secs
Trioptics Optiangle	Auto Collimator	Parallelism and angular tolerance <2 arc secs
12" vertical interferometer Bespoke	Fizeau Interferometer	Surface flatness accuracy < λ/20 (λ = 632.8 nm)
Interoptics Intervue (Interferometer)	Twyman Green Interferometer (Low Coherence)	Surface flatness accuracy < λ/20 (λ = 632.8 nm) Enables the ability to measure surface flatness on parallel parts without rear surface Interference
6" Rail interferometer	Fizeau Interferometer	Surface flatness accuracy < λ/20 (λ = 632.8 nm) Lens RoC between -900 mm (con-cave) and +650 mm (convex)
Perkin-Elmer Frontier FTIR	Spectrophotometer	Spectral transmission between 2 µm and 22 µm
Perkin-Elmer Lambda 750	Spectrophotometer	Spectral transmission between 190 nm and 2.0 µm
Lyman Alpha Instrument	Spectrometer	Transmission at 121.6 nm
Optilux SD / RedLux	Scratch/Dig Evaluation System	Automated assessment of surface imperfections according to: MIL-PRF-13830B & ISO10110_7
Taylor Hobson CCI 6000 Talysurf	Roughness Interferometer	Surface roughness (Ra/Rq) with resolution < 0.1 Å (0.01 nm).
Taylor Hobson PGI 840 Talysurf	Form Talysurf	Aspheric form error to an accuracy < 50 nm (Pt)
Bristol instrument	Optical Thickness Gauge	Thickness range between 0.1 mm to 8 mm (CaF2), accuracy < 2 µm
Mitutoyo Coordinate Measuring Machine	CMM	Measurement envelope of 400 x 400 x 400 mm, accuracy < 3 µm
Baty Venture Vision System	Optical CMM	Dimensional accuracy < 2 µm
Trioptics Spherocompact	Contact Radius Instrument	Convex / concave RoC, accuracy < 5 µm (mainly used for in-process checks)

REFERENCE SECTION

Polishing Specifications

Specifying a polishing standard must be approached with caution. Costs can escalate rapidly for more exacting specifications, particularly if combinations of requirements are needed. For instance, ultra-flatness can be achieved at the expense of a good cosmetic finish and vice versa. Good flatness and parallelism in thin windows is possible with a double-sided polishing technique.

Typical Polishing Specifications used at Crystran
It is not possible to give examples of a typical specification as that will depend on several factors such as material, size and method of manufacture. We do have certain specifications that we always apply to windows as standard (some traded materials may have different specifications).

Diameter (up to 50mm)	+0/-0.1mm
Length of sides (up to 50mm)	+0/-0.1mm
Thickness	+/-0.1mm
Surface quality (IR grade)	60/40 or better
Surface quality (UV grade)	40/20
Edge chips	Up to 0.5mm
Clear aperture	80% of diameter

Our technical sales team will be happy to discuss and advise on these matters.

Lens Tooling

Crystran have an extensive list of tooling and NPL qualified test plates for the manufacture of lenses with close tolerances. Please contact us for more information.

Hot Forging

This is a quick and cost effective method for manufacture of silver chloride and silver bromide optics. The quality achieved by this technique, although inferior to conventional polishing, is more than adequate for a wide range of infra-red applications.

The technique is particularly appropriate for spectroscopic mini-cell windows where the surface has a small depression for liquid films.

In the course of our hot-forging operations we have acquired a stock of tooling which it is economical to design around. Please contact us about sizes available.

REFERENCE SECTION

Bubbles & Flaws (ISO/BS/MIL Specification 1/)

These are normally associated with glasses and rarely with crystal, however present in soft crystals such as CsI, KRS5 etc.
Example: 1/5 x 0.06 is 5 flaws less than 0.06mm (square root of the area)

Stria (ISO/BS/MIL Specification 2/)

Stria are vitreous inclusions mainly in glass and rarely with crystal. There are 6 grades of decreasing severity.
Example: 2/0 is the greatest amount of stria, 2/5 is the lowest amount

Max. variation of the refractive index within a part of 10^{-6}	
0	+/- 50
1	+/- 20
2	+/- 5
3	+/- 2
4	+/- 1
5	+/- 0.5

Inhomogeneity classes in optical materials as per ISO 10110 Part 4

Flatness (ISO/BS/MIL Specification 3/)

Flatness is specified in terms of the wavelength of light which represents the degree of power, with the addition of form error which defines the allowed irregularity of the fringe pattern.
Example: 3/2(0.5) is 2 fringes power/0.5 fringes irregularity

Parallelism

The parallelism of a window can be specified in terms of angle, usually as minutes of arc. Sometimes it is in terms of thickness variation or 'run-out'. Conventional polishing will typically produce <3-10 arc minutes. Double-sided polishing can produce <5 arc seconds. To prevent multiple reflections between faces (an etalon effect) it may be prudent to have a small wedge angle specified.

Lens Centration (ISO/BS/MIL Specification 4/)

Lenses involve variations on other specifications. 'Flatness' is the radius of curvature as measured against a reference standard test plate, whilst 'parallel' is more accurately specified as centration error.
Example: 4/3' is 3 minutes centration.

REFERENCE SECTION

Cosmetic Finish (ISO/BS/MIL Specification 5/)

Visual appearance is often a subjective matter and is still commonly specified by scratch/dig. This classifies the surface in terms of the maximum length of small scratches after polishing.

Under this classification, S/D 80/50 would be regarded as quite poor and appropriate for simple spectroscopic windows and S/D 20/10 is an exacting standard suitable for low scattering laser applications. S/D 60/40 is a reasonably routine finish.

SCRATCH		
MIL-PRF-13830B *	MIL-F-48616 MIL-C-48497A	Width (µm)
5	A	5
10	B	10
20	C	20
40	D	40
60	E	60
80	F	80
120	G	120

DIG		
MIL-PRF-13830B	MIL-F-48616 MIL-C-48497A	Width (mm)
5	A	0.05
10	B	0.1
20	C	0.3
30	D	0.4
40	E	0.5
50	F	0.6
70	G	0.7
100	H	1

* This parameter is a measure of the brightness of scatter rather than the physical width of the scratch.

REFERENCE SECTION

Working Equivalents Applied at Crystran

These are not absolute measures but used as a guide based upon our experience.

S/D	< 30mm Ø optics	30 to 40mm Ø optics
80/50	5/3 x 0.25 ; K5 x 0.016	5/4 x 0.4 ; K5 x 0.016
80/40	5/2 x 0.25 ; K5 x 0.016	5/3 x 0.4 ; K5 x 0.016
60/40	5/2 x 0.25 ; K3 x 0.016	5/3 x 0.4 ; K3 x 0.016
60/30	5/3 x 0.16 ; K3 x 0.016	5/3 x 0.25 ; K3 x 0.016
40/20	5/2 x 0.16 ; K4 x 0.01	5/3 x 0.25 ; K4 x 0.01
40/10	5/3 x 0.063 ; K4 x 0.01	5/3 x 0.1 ; K4 x 0.01
20/10	5/3 x 0.063 ; K2 x 0.01	5/3 x 0.1 ; K2 x 0.01
15/5	5/4 x 0.025 ; K2 x 0.0063	5/4 x 0.04 ; K2 x 0.0063
10/5	5/4 x 0.025 ; K2 x 0.004	5/4 x 0.04 ; K2 x 0.004

S/D	40 to 50mm Ø optics	> 50mm Ø optics
80/50	5/8 x 0.4 ; K5 x 0.016	5/20 x 4 x 0.4 ; K5 x 0.016
80/40	5/6 x 0.4 ; K5 x 0.016	5/20 x 3 x 0.4 ; K5 x 0.016
60/40	5/2 x 0.4 ; K3 x 0.016	5/20 x 3 x 0.4 ; K3 x 0.016
60/30	5/8 x 0.25 ; K3 x 0.016	5/20 x 4 x 0.25 ; K3 x 0.016
40/20	5/6 x 0.25 ; K4 x 0.01	5/20 x 3 x 0.25 ; K4 x 0.01
40/10	5/6 x 0.1 ; K4 x 0.01	5/20 x 3 x 0.1 ; K4 x 0.01
20/10	5/6 x 0.1 ; K2 x 0.01	5/20 x 3 x 0.1 ; K2 x 0.01
15/5	5/8 x 0.04 ; K2 x 0.0063	5/20 x 4 x 0.04 ; K2 x 0.063
10/5	5/8 x 0.04 ; K2 x 0.004	5/20 x 4 x 0.04 ; K2 x 0.004

Surface finish can also be specified in terms of surface roughness (Roughness Average, Ra) and can be measured by interferometric profiling

Stresses (ISO/BS/MIL Specifications 6/)

Stresses, known as strain birefringence, are variations in refractive index generally caused during the annealing of the glass or crystal. It is defined as the optical path difference caused by the stressed region in terms of nm path difference per cm reference path. Generally, CaF_2 and similar crystal is controlled better than 5nm/cm.

Example: 6/10 defines strain birefringence of 10nm/cm.

REFERENCE SECTION

Chamfers

Chamfers are usually required both to protect the work from chipping during polishing and also in use. Protective chamfers are referred to as 'break edge' and may be removed by the polishing process. For operational reasons Crystran may choose not to apply chamfers to some, especially small windows. Some polishing operations may require slightly larger chamfers.

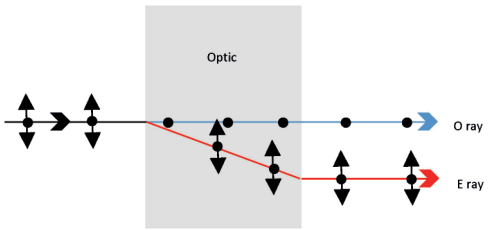
Chamfers are usually 45° (nominally) and measured down the edge of the optic unless otherwise specified. The size of chamfers is considered uncritical unless specifically requested.

Optic Axis (Birefringence)

Birefringence is a phenomenon that occurs in non-cubic crystals. Most materials are isotropic and the speed of light is the same in all directions as it passes through. Birefringent materials are anisotropic and the speed of light depends on the plane of polarisation and direction of propagation of the light.

When light is incident on a birefringent material, it is split into 2 rays – the ordinary (o ray) and the extraordinary (e ray). As illustrated below, the rays become polarised in perpendicular directions. These rays travel at different speeds and may travel in different directions.

There is one direction in a birefringent material where the 2 rays travel aligned – this is known as the optic axis. The light will behave as it would in an isotropic material. When light is incident at any angle to the optic axis, the e and o rays are split and are separated in space. The e ray will rotate around the o ray if the material is rotated.



For windows in Sapphire, Quartz, Calcite or MgF_2 the optic axis is usually specified as perpendicular to the surface, known as z-cut or Zero degree.

REFERENCE SECTION

Reflection Loss, Brewster Angle & Critical Angle

When light is incident on a boundary between two media, some of the light is lost in reflection; this loss is calculated as a percentage of the intensity of the original beam and is dependent on the reflective indices of the material, the angle of incidence and state of polarisation of the light. The reflection loss of unpolarised light normally incident on a surface from one surface is:

$$\text{Reflection Loss} = \frac{(n - 1)^2}{(n + 1)^2}$$

For transparent materials, the second surface must be accounted for. Thus, the internal transmittance of a parallel plate is:

$$\text{Transmittance} = \frac{2n}{(n^2 + 1)}$$

Unpolarised light reflected from a plane surface boundary of two transparent media is partially polarised. At the polarising angle (Brewster's angle θ_b) the reflected light is completely polarised and perpendicular to the refracted ray.

$$\text{Brewsters Angle: } \tan \theta_b = \frac{n_1}{n_2}$$

Total internal reflection occurs when the angle of incidence of a beam of light incident upon an interface is increased until the angle of refraction is 90°. This critical angle θ_c can be found in terms of the index of refraction for the two media by solving Snell's Law when $\theta_r = 90°$.

$$\text{Snell's Law: } n = n_1 \sin \theta_i = n_2 \sin \theta_r$$

$$\sin \theta_c = \frac{n_1}{n_2} \quad \sin 90°$$

This phenomenon only occurs when the light is emerging from a denser medium, i.e. when n_1 is greater than n_2.

REFERENCE SECTION

Reststrahlen

For many inorganic materials used in optical applications, the refractive index remains constant and the absorption coefficient is zero or very small over the majority of its transmission range. When Reststrahlen materials are illuminated at wavelengths that excite the atomic, or crystal lattice structure, a number of resonance effects are noticed. As the Reststrahlen maximum frequency is approached, the refractive index (*n*) undergoes a rapid change, the extinction coefficient (*k*) rises rapidly and the Fresnel reflection coefficient (*R*) may become high. Therefore, at the Reststrahlen maximum frequency for a particular material, the reflectance of that material rises sharply:

$$R = \frac{(n - 1)^2 + k^2}{(n + 1)^2 + k^2}$$

The Reststrahlen effect occurs notably in the 6µm to 300µm range. There are not many satisfactory filters in this region; hence the effect is often used for the extraction of a narrow spectral region from a spectral continuum.

In practical applications, some properties of Reststrahlen materials are significant; particularly the fact that the maximum reflectance increases as the temperature is reduced. When used as thin films (for coatings on mirrors and lenses) they exhibit interference maxima and minima on the short wavelength side of the reflectance peaks.

REFERENCE SECTION

Metrological Wavelengths

λ (nm)	Code	Spectral Line	λ (nm)	Code	Spectral Line
10640.0		CO2 laser	546.0740	e	Green mercury
2325.42		IR mercury	486.1327	F	Blue hydrogen
1970.09		IR mercury	479.9914	F’	Blue cadmium
1529.582		IR mercury	435.8343	g	Blue mercury
1064.0		Nd:YAG laser	404.6561	h	Violet mercury
1013.98	t	IR mercury	365.0146	i	UV mercury
852.11	s	IR caesium	334.1478		UV mercury
706.5188	r	Red helium	312.5663		UV mercury
656.2725	C	Red hydrogen	296.7278		UV mercury
643.8469	C’	Red cadmium	280.4		UV mercury
632.8		He:Ne laser	248.3		UV mercury
589.2938	D	Yellow sodium	121.567		Lyman α
587.5618	d	Yellow helium			

Kodak™ IRTRAN™ Numbers

IRTRAN-1 = MgF_2 IRTRAN-4 = ZnSe
IRTRAN-2 = ZnS IRTRAN-5 = MgO
IRTRAN-3 = CaF_2 IRTRAN-6 = CdTe

UV Bands

UV-A = 400 - 320nm
UV-B = 320 - 290nm
UV-C = 290 - 100nm

Neutral Density Filters

Transmission % = $100 / 10^{ND}$
Where ND is the optical density

REFERENCE SECTION

Hardness Scales

The Knoop scale (HK) is the most commonly used, the others being; Moh, Vickers, Rockwell and Brinell.

The experimental procedure for the derivation of a value on the Knoop scale is to use a pyramidal diamond point which is pressed into the material in question with a known force. The indentation made by the point is then measured and the Knoop number calculated from this measurement. The test has been designed for use on a surface that has not been work-hardened in the lattice direction in which the hardness value is being measured. The hardness is usually stated as a Knoop figure but the units are actually kgf mm^{-2}

The values on the Moh scale are arrived at by measuring the relative hardness of materials by observing which materials are able to scratch other materials. The Moh scale, which is not linear, is limited by the softest material Talc (Moh=1) and the hardest material Diamond (Moh=10).

1. Talc	2. Gypsum	3. Calcite	4. Fluorite	5. Apatite
6. Feldspar	7. Quartz	8. Topaz	9. Sapphire	10. Diamond

Elastic Coefficients

Elastic coefficients, otherwise known as Elastic Stiffness Constants are the constants of proportionality between the components of stress and strain. They are therefore related to the elastic moduli.

For cubic crystals the coefficients are three: C_{11}, C_{12}, C_{44}
For tetragonal crystals, five: $C_{11}, C_{12}, C_{13}, C_{33}, C_{44}$
For hexagonal crystals, six: $C_{11}, C_{12}, C_{13}, C_{14}, C_{33}, C_{44}$

For a cubic crystal he three moduli relate to these coefficients as follows:

Youngs modulus = $E = (C_{11} + 2C_{12})(C_{11} - C_{12}) / (C_{11} + C_{12})$
Bulk modulus = $K = (C_{11} + 2C_{12}) / 3$
Shear modulus = $G = C_{44} = (C_{11} - C_{12})/2$

Note that the subscripts are compressions of notation. $C_{1111} \rightarrow C_{11}$ $C_{2323} \rightarrow C_{44}$

In general $11 \rightarrow 1$ $22 \rightarrow 2$ $33 \rightarrow 3$ $23=32 \rightarrow 4$

The three modulii are also related:

$E=9KG / (3K+G)$ $K=EG / (3(3G-E))$ $G=3KE / (9K-E)$

REFERENCE SECTION

Some Useful Definitions

Transmittance = $\frac{I_E}{I_o}$ $\frac{\text{Intensity of exit beam}}{\text{Intensity of Incident beam}}$

Transmittance is usually expressed as a percentage.

Transmissivity = Internal Transmittance per unit thickness

Absorptance = $\frac{I_o - I_E}{I_o}$ $\frac{\text{Intensity of absorbed beam}}{\text{Intensity of Incident beam}}$

The complement of transmittance

Absorbance = $\log_{10}\left(\frac{I_o}{I_e}\right)$

Example: 20% transmittance is $\log_{10}\left(\frac{100}{20}\right)$ *= 0.7 absorbance.*

Wave Number = $\frac{1}{\text{wavelength}}$ (cm) = $\frac{10000}{\text{wavelength}}$ (μm)

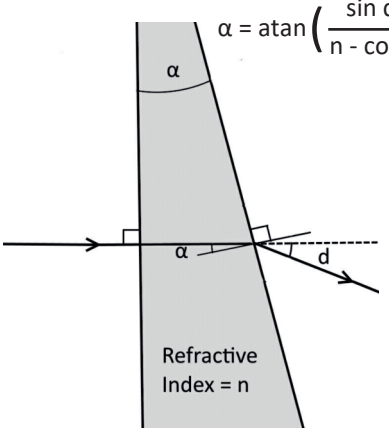
Focal length (mm) = $\frac{1000}{\text{dioptre}}$

Example: 20 dioptre = 50mm F.L.

Beam Deviation through Wedge

Angle (α) to provide a given deviation.

$\alpha = \text{atan}\left(\frac{\sin d}{n - \cos d}\right)$



Transmission Absorption Coefficient

$T_i = \exp(-\mu \cdot L)$

$\mu = -(\ln T) / L$

μ = Absorption Coefficient (cm^{-1})
L = Path Length (cm)
T_i = Internal Transmission (%/100)
$T_e = T_i$ + Reflection losses
n = Refractive Index

Example: n = 1.5492 ; Path length 10cm
External Transmission = 76.8% = 0.768
Reflection loss is 0.0887 (page 14)
Ti = 0.768 + 0.0887 = 0.8567
μ = - (ln 0.8567) / 10 = 0.0155 cm^{-1}

REFERENCE SECTION

S.I. Prefixes

Y	Yotta	10^{24}	d	deci	10^{-1}
Z	Zetta	10^{21}	c	centi	10^{-2}
E	Exa	10^{18}	m	milli	10^{-3}
P	Peta	10^{15}	µ	micro	10^{-6}
T	Tera	10^{12}	n	nano	10^{-9}
G	Giga	10^{9}	p	pico	10^{-12}
M	Mega	10^{6}	f	femto	10^{-15}
K	Kilo	10^{3}	a	atto	10^{-18}
h	hecto	10^{2}	z	zepto	10^{-21}
da	deka	10	y	yocto	10^{-24}

Units Conversions

1 Å	= 10^{-4} µm	= 10^{-7} mm	= 10^{-8} cm	= 10^{-10} m
λ (µm)	1.234 /ev			
1 µm	10^{3} nm	10^{-3} mm	10^{-4} cm	10^{-6} m
1 mm	0.04" (40 thou)			
1 microinch	254 Å	25.4 nm	0.0254 µm	10^{-6} inch
1 thou	0.001"	25.4 µm		
1 inch	25.5mm	2.54 cm		
1 radian	57.30°			
1 mile	1.609344 km			
1°	17.45 x 10^{-3} rad			
π rad	180°			
Degrees °C =	5 . (°F - 32) / 9	Degrees °F =	32 + (9 x °C) / 5	
1 lb	0.4535 kg	1 kg	2.205 lb	
1 imp gallon	4.5454 litre	1 litre	0.22 imp gallon	1.76 imp pint
Frequency MHz	300 / λ metres			
Frequency GHz	300 / λ mm			
Frequency THz	300 / λ µm			

Pressure

	GPa	N mm^{-2}	Kgf cm^{-2}	Kgf mm^{-2}	Mbar	lbf in^{-2}	Dyne cm^{-2}	Torr
Gpa	1	$1x10^{3}$	$1.02x10^{4}$	$1.02x10^{2}$	0.01	$1.45x10^{5}$	$1x10^{10}$	$7.5x10^{6}$
N mm^{-2}	$1x10^{-3}$	1	10.2	0.102	$1x10^{-5}$	145.0	$1x10^{7}$	$7.5x10^{3}$
Kgf cm^{-2}	$9.81x10^{-5}$	$9.81x10^{-2}$	1	0.01	$9.81x10^{-7}$	14.223	$9.81x10^{5}$	735.6
Kgf mm^{-2}	$9.81x10^{-3}$	9.81	100	1	$9.81x10^{-5}$	$1.42x10^{3}$	$9.81x10^{7}$	$7.36x10^{4}$
Mbar	100	$1x10^{5}$	$1.02x10^{6}$	$1.02x10^{4}$	1	$1.45x10^{7}$	$1x10^{12}$	$7.5x10^{8}$
lbf in^{-2}	$6.89x10^{-6}$	$6.89x10^{-3}$	$7.03x10^{-2}$	$7.03x10^{-4}$	$6.89x10^{-8}$	1	$6.89x10^{4}$	51.71
Dyne cm^{-2}	$1x10^{-10}$	$1x10^{-7}$	$1.02x10^{-6}$	$1.02x10^{-8}$	$1x10^{-12}$	$1.45x10^{-5}$	1	$7.5x10^{-4}$
Torr	$1.33x10^{-7}$	$1.33x10^{-4}$	$1.36x10^{-3}$	$1.36x10^{-5}$	$1.33x10^{-9}$	0.019	1333.2	1

REFERENCE SECTION

Normal Atmospheric Pressure (1 atm)

(1) pounds/sq inch	14.7 psi
(2) inches of mercury	29.9213"
(3) mm of mercury (torr)	760 mm (760 torr)
(4) millibar	1013.240 mBar
(5) Pascals	101.324 kPa

(2) and (3) are measures of a column of mercury supported by 1 atmosphere.
(4) and (5) are actual measures of force/area and take account of the density of mercury (13.595 gm/cc at 0°C) and the acc of gravity (980.665 cm/sec²) when converting from a mercury barometer reference.

Medium vacuum 20 to 10^{-2} torr	High vacuum 10^{-2} to 10^{-6} torr
Very high vacuum 10^{-6} to 10^{-9} torr	Ultra high vacuum $>10^{-9}$ torr
Low Earth Orbit = 10^{-10} torr	Interplanetary Space = 10^{-16} torr

Specific Heat

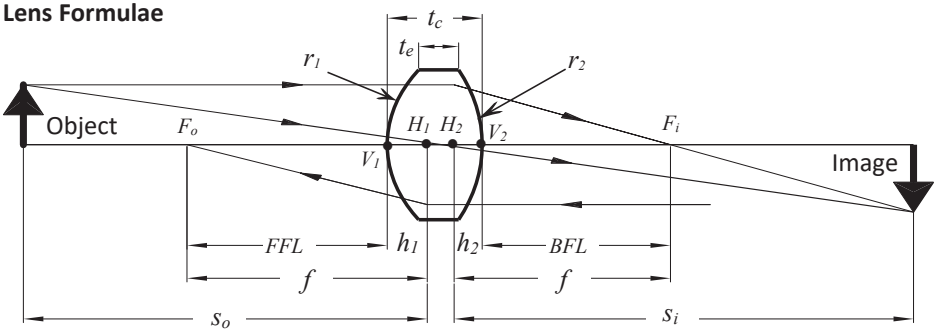
	$J\ g^{-1}\ K^{-1}$	$J\ Kg^{-1}\ K^{-1}$	$cal\ g^{-1}\ K^{-1}$
$1\ J\ g^{-1}\ K^{-1}$ =	1	1000	0.2388
$1\ J\ Kg^{-1}\ K^{-1}$ =	0.001	1	238.8×10^{-6}
$1\ cal\ g^{-1}\ K^{-1}$ =	4.1868	4186.8	1

Thermal Conductivity

	$W.\ cm^{-1}.\ K^{-1}$	$W.\ m^{-1}.\ K^{-1}$	$cal.\ cm^{-1}.\ s.\ K^{-1}$	$Btu\ ft^{-1}.\ hr.\ F^{-1}$
$1\ W.\ cm^{-1}.\ K^{-1}$ =	1	100	0.2388	694
$1\ W.\ m^{-1}.\ K^{-1}$ =	0.01	1	2.388×10^{-3}	6.94
$1\ cal.\ cm^{-1}.\ s.\ K^{-1}$ =	4.1868	418.68	1	2903
$1\ Btu\ ft^{-1}.\ hr.\ F^{-1}$ =	1.44 x 10-3	0.144	34.5×10^{-4}	1

FORMULAE

Lens Formulae



Thin Lens Equation :

$$\frac{1}{f} = \frac{1}{s_o} + \frac{1}{s_i}$$

Lens Makers Equation :

$$\frac{1}{f} = (n-1)\left(\frac{1}{r_1} - \frac{1}{r_2} + \frac{(n-1)\,t_c}{n\,r_1\,r_2}\right)$$

For a thin lens, it reduces to :

$$\frac{1}{f} = (n-1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$

For a plano-vex or plano-cave lens the equation reduces to :

$$\frac{1}{f} = \frac{(n-1)}{r}$$

Principal point distances are given :

$$h_1 = \frac{f\,(n-1)\,t_c}{n\,r_2} \qquad h_2 = \frac{f\,(n-1)\,t_c}{n\,r_1}$$

Thus :

$$BFL = f - h_2$$

Sag is the distance from the lens vertex to the lens edge

$$sag_1 = r_1 \pm \sqrt{r_1^2 - \frac{D^2}{4}} \qquad c_t = e_t + sag_1 + sag_2$$

Magnification of a lens = $\frac{s_i}{s_o} = \frac{f}{(f - s_o)}$ Conventionally taken as ≡ 0.25 P

Sign convention of +ve and -ve radii and linear measurements must be applied consistently.

s_o = Object distance
F_1 = Front focal point
V_1 = Front vertex
H_1 = First principal point
r_1 = Front radius of curvature
f = Effective focal length
FFL = Front focal length
n = Lens Refractive Index in air

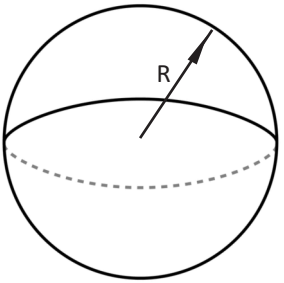
s_i = Image distance
F_2 = Back focal point
V_2 = Back vertex
H_2 = Second principal point
r_2 = Back radius of curvature
D = Diameter of lens
BFL = Back focal length
P = Power in dioptre

FORMULAE

Spheres

Area of surface = $4\pi R^2$

Volume = $\frac{4\pi R^3}{3}$



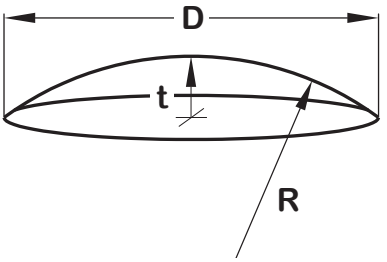
Segment of a Sphere (Lens)

The segment is a volume cut off from a sphere by a chord plane.

Spherical Area = $2\pi R T$

Total Area = $\frac{\pi (D^2 + 8R t)}{4}$

Volume = $\frac{\pi t (3D^2 + 4 t^2)}{24}$

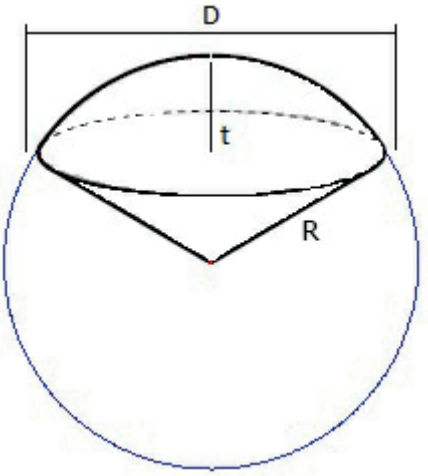


Sector of a Sphere

The circular sector is a three dimensional portion of a sphere enclosed by the curved surface and the cone to the centre.

Total area = $\pi R (2t + \frac{D}{2})$

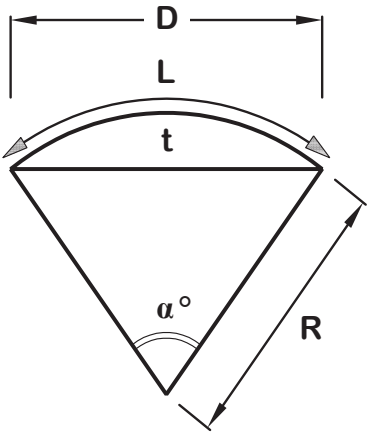
Total volume = $\frac{2}{3} \pi R^2 t$



FORMULAE

Segment of a Circle

The segment is a portion of a circle informally defined as a area cut off from the rest of the circle by a chord.



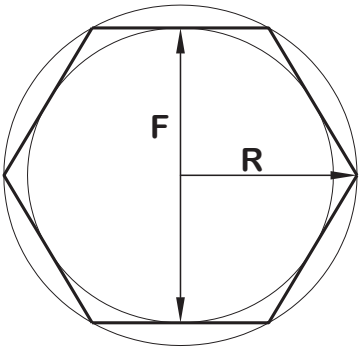
$$\text{Area} = \frac{(RL - RD - Dt)}{2} = \frac{(\pi R^2 \alpha°)}{360°} - \frac{(RD - Dt)}{2}$$

Sector of a Circle

The circular sector is a wedge of a circle enclosed by the curved edge and the angle to the centre.

$$\text{Area} = \frac{(\pi R^2 \alpha°)}{360°} = \frac{(R L)}{2}$$

Hexagon

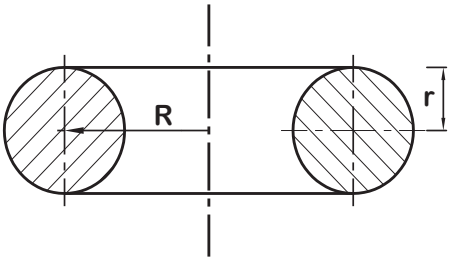


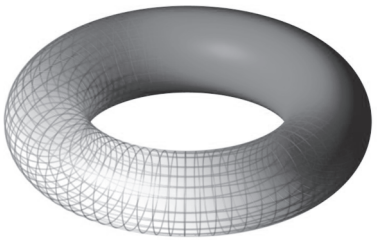
$$\text{Area} = 3 R^2 \cos 30^\circ = 2.6 R^2$$
$$= F^2 \cos 30^\circ = 0.866 F^2$$

$$\text{Area External Circle} = \pi R^2 = 1.05 F^2$$

$$\text{Area Internal Circle} = \pi \frac{F^2}{4} = 2.35 R^2$$

Torus





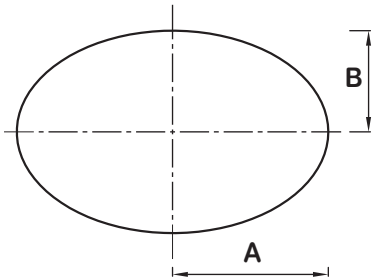
$$\text{Area of Surface} = 4\pi^2 . R. r$$

$$\text{Volume} = 2\pi^2 . R. r^2$$

FORMULAE

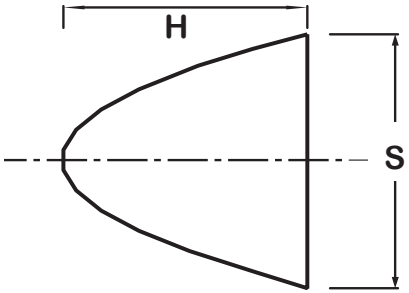
Ellipse

Area $= \pi\ A\ B$



Parabola

$$\text{Area} = \frac{S\ H}{3}$$



Frustum of a Pyramid

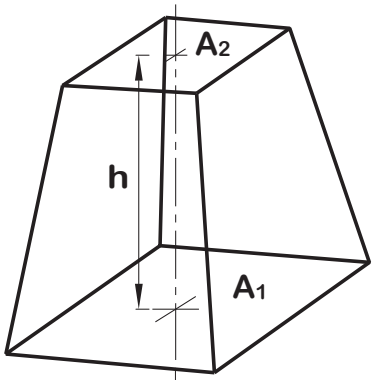
$$\text{Volume} = \frac{A_1 + A_2 + h\sqrt{(A_1\ A_2)}}{3}$$

A_1 = area of base A_2 = area of top

H = height

For a pyramid $A_2 = 0$

For a prism $A_1 = A_2$



Frustum of a Cone

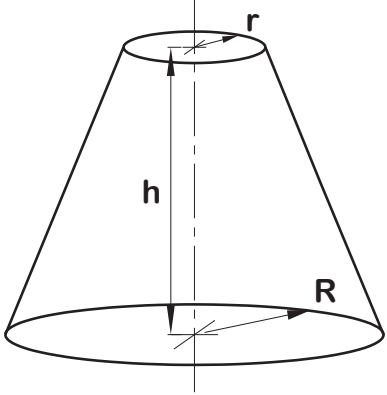
$$\text{Volume} = \frac{\pi\ h\ (R^2 + r^2 + R\ r)}{3}$$

R = radius of base r = radius of top

H = height

For a cone r = 0

For a cylinder R = r



GUIDES - Design of Pressure Windows

Calculation of thickness of optical windows used in vacuum or pressure application

DEFINITIONS			
S_{max}	= Maximum Stress	R	= L/W
SF	= Safety Factor	T	= Thickness
F_a	= Apparent Elastic Limit	P	= Load per Unit Area
K	= Empirical Constant	L, W	= Length and Width
D	= Unsupported Diameter for an unsupported window		

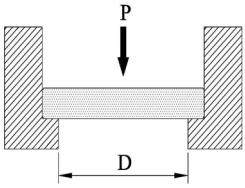
The maximum stress S_{max} on a uniformly loaded window is given by:

$S_{max} = (K \cdot D^2 \cdot P) / (4 \cdot T^2)$ *and also* $S_{max} = F_a / SF$ *(See Safety Factor Box)*

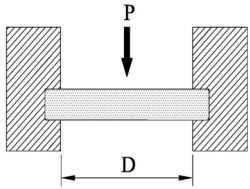
And then solving for thickness, T

$T = D \cdot \sqrt{(SF \cdot K / 4)} \cdot \sqrt{(P / F_a)}$ *(CIRCULAR WINDOWS)*

$T = L \cdot \sqrt{(SF\ K / 2)} \cdot \sqrt{(P / (F_a (1 + R^2)))}$ *(RECTANGULAR WINDOWS)*



Unclamped, S_{max} at centre



Clamped, S_{max} at edge

CLAMPED

Circular Window (Safety Factor of 4 & $K_c = 0.75$) $T = 0.866\ D \sqrt{(P / F_a)}$

Rectangular Window (Safety Factor of 4 & $K_c = 0.75$) $T = 1.23\ L \sqrt{(P / (F_a (1 + R^2)))}$

UNCLAMPED

Circular Window (Safety Factor of 4 & $K_u = 1.125$) $T = 1.06\ D \sqrt{(P / F_a)}$

Rectangular Window (Safety Factor of 4 & $K_u = 1.125$) $T = 1.50\ L \sqrt{(P / (F_a (1 + R^2)))}$

CONSTANT K

The value of **K** depends on the method of support, upon the force introduced in clamping and upon the brittle / ductile character of the window material involved.

Empirically, a **K** value of 0.75 is found suitable for most optical crystals when the perimeter is clamped, and a value 50% greater when unclamped.

$$K_c = 0.75 \qquad K_u = 1.125$$

SAFETY FACTOR

To avoid plastic deformation, the maximum stress (S_{max}) should be less than the Apparent Elastic Limit (F_a) by an appropriate Safety Factor (SF)

$$S_{max} = F_a / SF$$

A modest safety factor of 4 (i.e., maximum stress equals one quarter of the elastic limit) seems to suffice for many laboratory applications where the operating conditions are reasonably under control. Severe conditions such as thermal shock require special consideration and may even result in a decision to use a *reduced* thickness. The published Apparent Elastic Limit of some materials may not be completely reliable. Crystals vary and cleavage may occur according to grain boundaries or the particular cut of the ingot. Ultimately, the final design thickness must be a carefully considered decision and may need to be empirically tested. Crystran Ltd can accept no responsibility for the adoption of these calculations and recommendations.

NOTES:

- A carefully designed window may still break before any significant loading if the mounting introduces any localised stress.
- Mismatch of expansion coefficients generally dictates the use of resilient material between window and mounting.
- Thermal outgassing used in UHV systems should be undertaken with caution with crystal windows as thermal shock may initial cleavage in some crystals
- The constant for clamped mounting allows for no flexure at the wall. The use of soft gaskets may allow flexure so the formula for the "unclamped" condition should be used.

GUIDES - Aspheric Lens Design

The standard aspheric formula is:

$$Z = \frac{cr^2}{1+\sqrt{1-(1+K)c^2r^2}} + A_4r^4 + A_6r^6 + A_8r^8 + A_{10}r^{10} \ldots$$

Where:

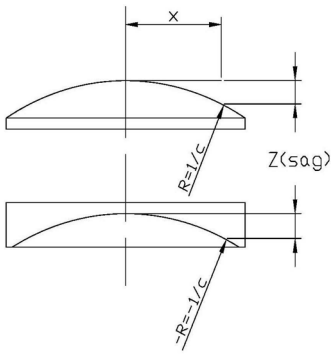
Z = Depth or "Sag" of the curve

r = Distance from the centre

C = Curvature (= 1 / Radius)

K = Conic Constant

A_x = Higher order terms



Be aware that for some reason many designers show c as the Radius (R) and forget to show the reciprocal. This of course renders the equation obviously unworkable in most cases but it can catch you out. The Radius (R) does not represent the closest spherical surface, but the spherical surface from which the aspheric terms cause the curve to diverge from it, either shallower or deeper than the spherical curve. The closest or "best fit" spherical surface is the Radius which matches the aspheric sag at the largest useful diameter.

Taking care to obey the sign conventions, the sag figure must be added to the lens centre thickness to derive the actual lens thickness at any point. Do not simply present sag data to the machinist, they are likely to generate to that figure and produce a lens with zero edge thickness.

Most optical designers use only the even-order terms from A_2 to A_{20}, but should they be required the odd-order terms are available, for the profile only, from A_1 to A_{19}

The conic constant K has traditionally been used to design the first aspheres; simple parabolas and hyperbolas. It is now largely redundant in the above equation as the A_x terms can define any surface. A spherical surface is defined by the above equation when K=0 and all A_x terms are zero.

GUIDES - Cleaning Optics

Crystal optics are delicate and should be treated carefully if they are to be cleaned. Described is a method, but the technique comes with practice. Handle optics by the edge using lint-free nylon gloves or plastic protective gloves when cleaning with solvent, checking that the solvent does not attack the glove. Handle optics as little as possible. Cleaning may create fine scratches which you cannot see easily but which may contribute to scattering, particularly in the UV. If the optic is mounted, try never to let solvent creep into the mounting ring. Use an air jet only for removal of dust.

Very Delicate Materials: CsI, KRS5, Germanium, Zinc Selenide, Zinc Sulfide.

Soft materials are inclined to take marks (sleeks) or show up marks easily. Wash in a solvent such as methanol or propanol for light marking. Use an environment friendly solvent such as NuSol Rapide (a replacement for trichloroethylene which is available in the UK) or otherwise acetone, for greasy or waxy contaminants. Soak the optic and wipe whilst wet with cotton wool (absorbent cotton in the USA) dipped in the solvent and let the optic dry by evaporation or assist it with airflow as it is wiped.

Delicate Materials: Fluorides, Silicon.

These should be treated as above where practical, but it is often preferable to clean them carefully with a damp tissue. We use Kimtech Science 100 professional wipes. Do not rub the optic, but wipe gently and allow the thinnest film of solvent to dry by evaporation.

Harder Materials: Glasses, Sapphire.

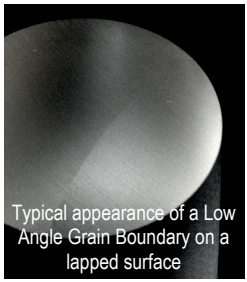
We treat these materials in the same manner as delicate materials.

Coated Materials: Coatings should be treated as delicate even though they can be more rugged than the crystal base material. DLC on germanium is an example of a very tough coating.

Aqueous Cleaning: Calcium Fluoride, Magnesium Fluoride, Lithium Fluoride

We have become aware that very small absorptions (< 1%) can occur due to closely bonded organic surface contamination. Notably, this is found at 3.4µm and probably due to waxes used in the polishing process. Aqueous cleaning using demineralized water with a surfactant detergent such as Alconox can be effective. Use a bath of the fresh warm solution in place of, or additionally to, the solvent methods. Soak the optic for 10 minutes and wipe while wet with cotton wool dipped in the solvent. Rinse in clean warm demineralized water dry by evaporation or assist it with airflow.

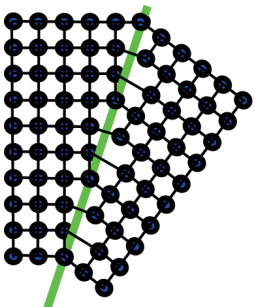
GUIDES - Low Angle Grain Boundaries


Typical appearance of a Low Angle Grain Boundary on a lapped surface

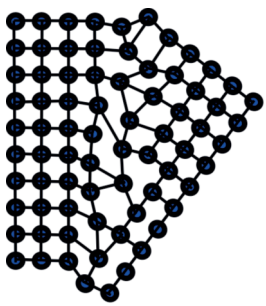
Large cubic crystals of fluorides are not seeded on any particular crystal orientation. This is not a difficulty in normal use. The bulk crystals often contain one or two grain boundaries and so it is sometimes difficult to select larger pieces strictly as single crystal. The supplied blank may include a low-angle grain boundary. This is not a weak point and will become invisible on polishing not even detectable in the interferogram of the finished optic. It will not cleave. Crystran will guarantee its integrity during normal working.

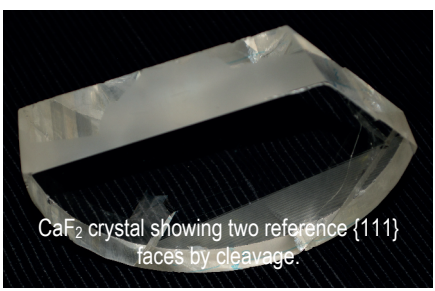
The definition of 'low angle' boundaries is not simply a matter of angle, but more about the dislocation of the lattice at the boundary. Typically though there is a maximum value of about 4° tilting between adjacent crystal grains where the two grains share common lattice points before lattice strain dominates. The grain boundary can be thought of as a row of dislocations. Consider also that a perfect single crystal is an impossibility, even within a 'single' grain, there will be a huge number of dislocations and lattice defects.

At higher angles, the lattice cannot compensate and deformation rather than dislocation makes for a weaker join; a high angle grain boundary. It is then more common that the crystal cracks along this line or the boundary opens up because of higher built-in strain.


Low Angle Grain Boundary Structure.
Note the shared atoms along the division line.

Diagrams are illustrative only and not intended to show any actual situation.


'High' Angle Grain Boundary Structure.
Note the distorted lattice at the division.


CaF_2 crystal showing two reference {111} faces by cleavage.

CaF_2, BaF_2 and SrF_2 are cubic crystals and with some skill can be cleaved on the {111}. The CaF_2 here has been cleaved to show two of the planes which form part of a tetrahedron. Note that they are randomly aligned with the grown crystal diameter. If it is an absolute requirement, these planes can be used as reference to supply oriented single crystal pieces. This is only important where lattice effects are inherent to the final product.

LiF which cleaves more easily on the {100} is more often required as oriented single crystal.

MgF_2 is not cubic and exhibits bifrefringence. It does not cleave on any recognised planes and must be seeded in growth and thus is always aligned optically. It is always supplied without grain boundaries and with reference to the optical axis.

GUIDES - Thermal Shock

Crystal optical materials vary widely in how they may be treated thermally and particularly in regard to rates of heating and cooling to avoid thermal shock. There are no definite answers. Apart from the material, the size and shape of the component has a large factor in the assessment. These suggestions are based on moderate circular windows up to approximately 50mm diameter and 6mm thick. Always err on the safe side. If the component is to be of a high specification, try to arrange to test an unpolished blank before proceeding.

For very large pieces >1kg of CaF2 (Grade 2) we would use a rate of 10ºC/hour

Smaller pieces may be heated and cooled at higher rates.

We cannot find any firm correlation between Thermal Expansion and Conductivity and our practical knowledge of how different materials behave in actual handling.

Maximum working temperatures are Crystran recommendations only and not related to melting points.

Grade 1. Natural cooling rate on removal from oven, ~ 5ºC/min No particular precautions.
Grade 2. Slightly Sensitive to thermal shock. ~ 2ºC/min (Cool over 1 to 2 hours from 150ºC)
Grade 3. Sensitive to thermal shock. ~ 0.75ºC/min (Cool over 3 to 4 hours from 150ºC)
Grade 4. Very sensitive to thermal shock. ~ 0.3ºC/min (Cool overnight. 7 to 8 hours from 150ºC)

MATERIAL	Symbol	Thermal Cond. $W\ m^{-1}\ K^{-1}$	Thermal Expansion $x\ 10^{-6}\ K^{-1}$	Max Temp ºC	Crystran Shock Grade
Barium fluoride	BaF_2	11.7	18	300	IV
Calcium fluoride	CaF_2	9.71	19	500	III
Lithium fluoride	LiF	11.3	37	400	IV
Magnesium fluoride	MgF_2	21 / 33	13.7 / 8.9	500	II
Strontium fluoride	SrF_2	8.3	18	500	III
Sodium chloride	NaCl	6.49	44	400	II
Sodium fluoride	NaF	3.75	36	400	III
Potassium bromide	KBr	4.82	43	300	III
Potassium chloride	KCl	6.53	36	400	II
Cesium bromide	CsBr	0.94	48	400	I
Cesium iodide	CsI	1.1	48	200	I
Silver bromide	AgBr	1.21	30	200	I
Silver chloride	AgCl	1.15	31	200	I
Thallium bromo-iodide	KRS-5	0.54	58	200	I
Magnesium oxide	MgO	42	10.8	2000	I
Sapphire	Al_2O_3	27	5.6	1700	I
Crystal quartz	SiO_2	10.7 / 6.2	7.1 / 13.2	1000	I
Zinc sulfide (MS)	ZnS	27.2	6.5	250	I
Zinc selenide	ZnSe	18	7.1	250	I
Diamond	C	2600	1	700	I
Silicon	Si	163	2.6	150	I
Germanium	Ge	58	6.1	80	I
Gallium arsenide	GaAs	48	5.7	200	II

GUIDES - Materials

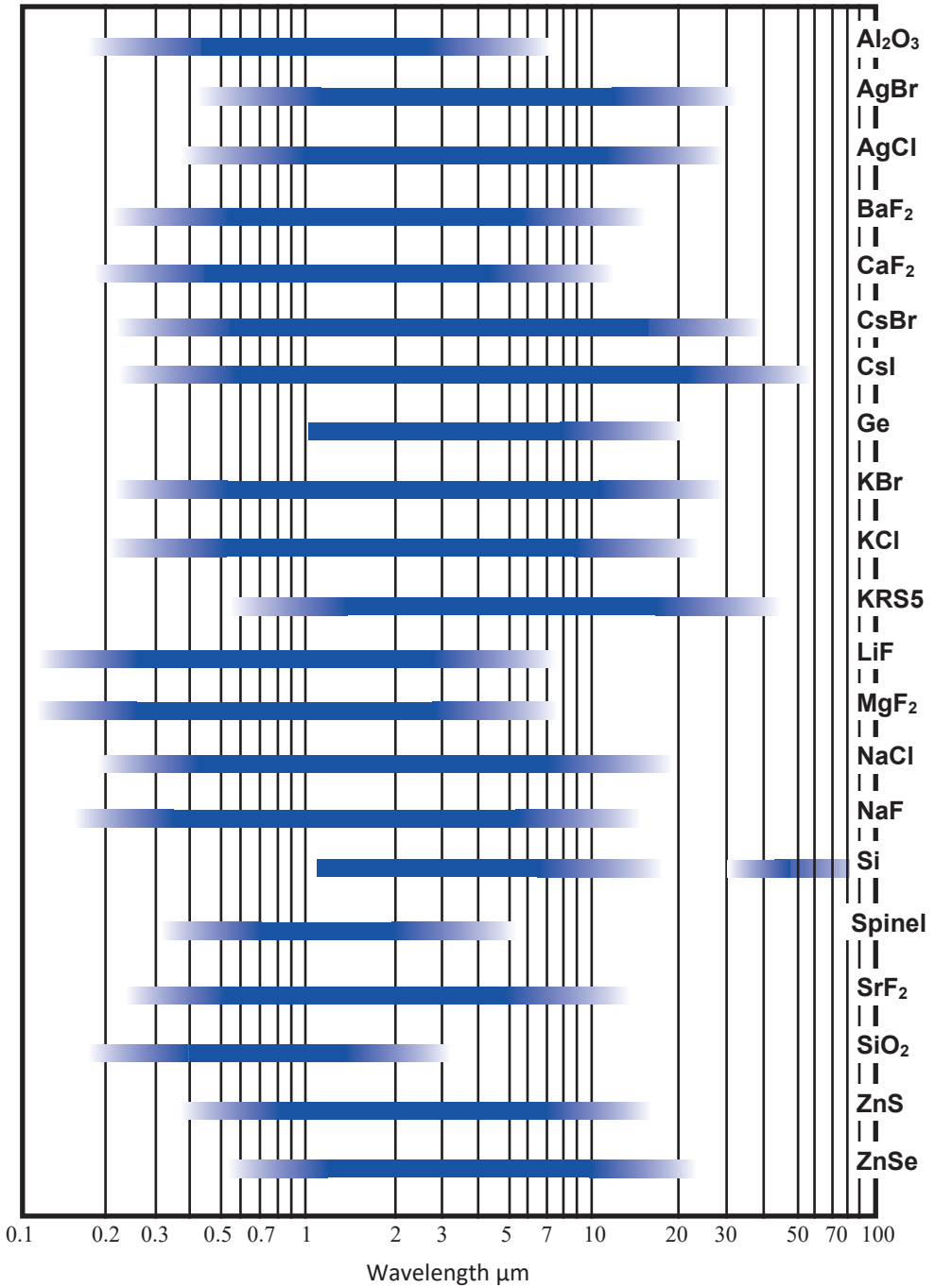
Crystran publish a number of guides with practical details relating to the grades and uses of the materials that we supply. Because these guides are reviewed on a regular basis as old grades and trade designations disappear or new ones become available, we reference the guides here with a link to our website repository where the latest versions will be available.

Please go to our website at www.crystran.co.uk/documents

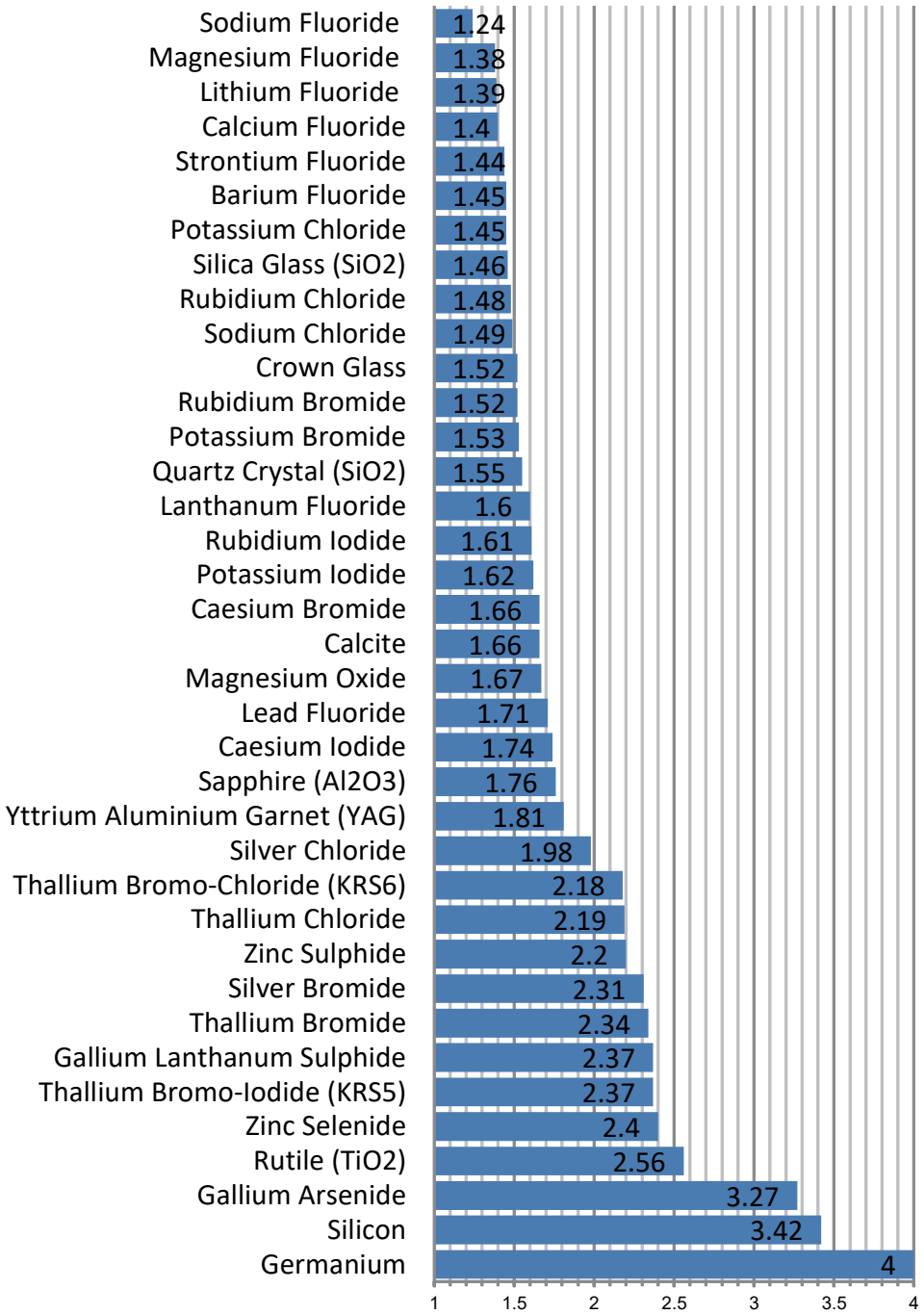
Guide to Calcium Fluoride Grades
Guide to Raman Quality Material
Guide to Silica Glass
Guide to Quartz Crystal
Guide to Sapphire
Guide to Lanthanum Fluoride
Guide to Crystal Quality

All Safety Data Sheets (SDS)

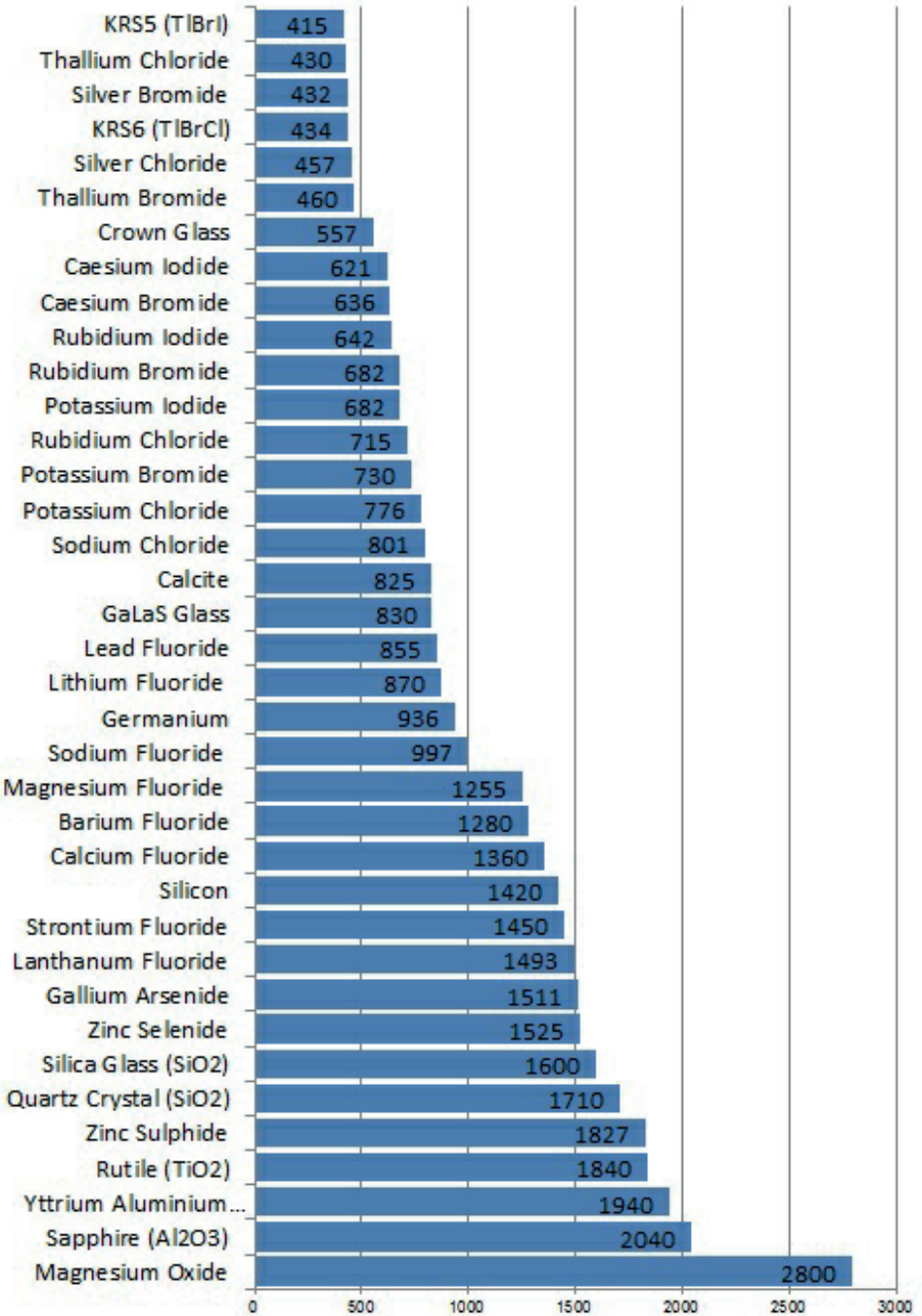
COMPARISON OF DATA - Transmission



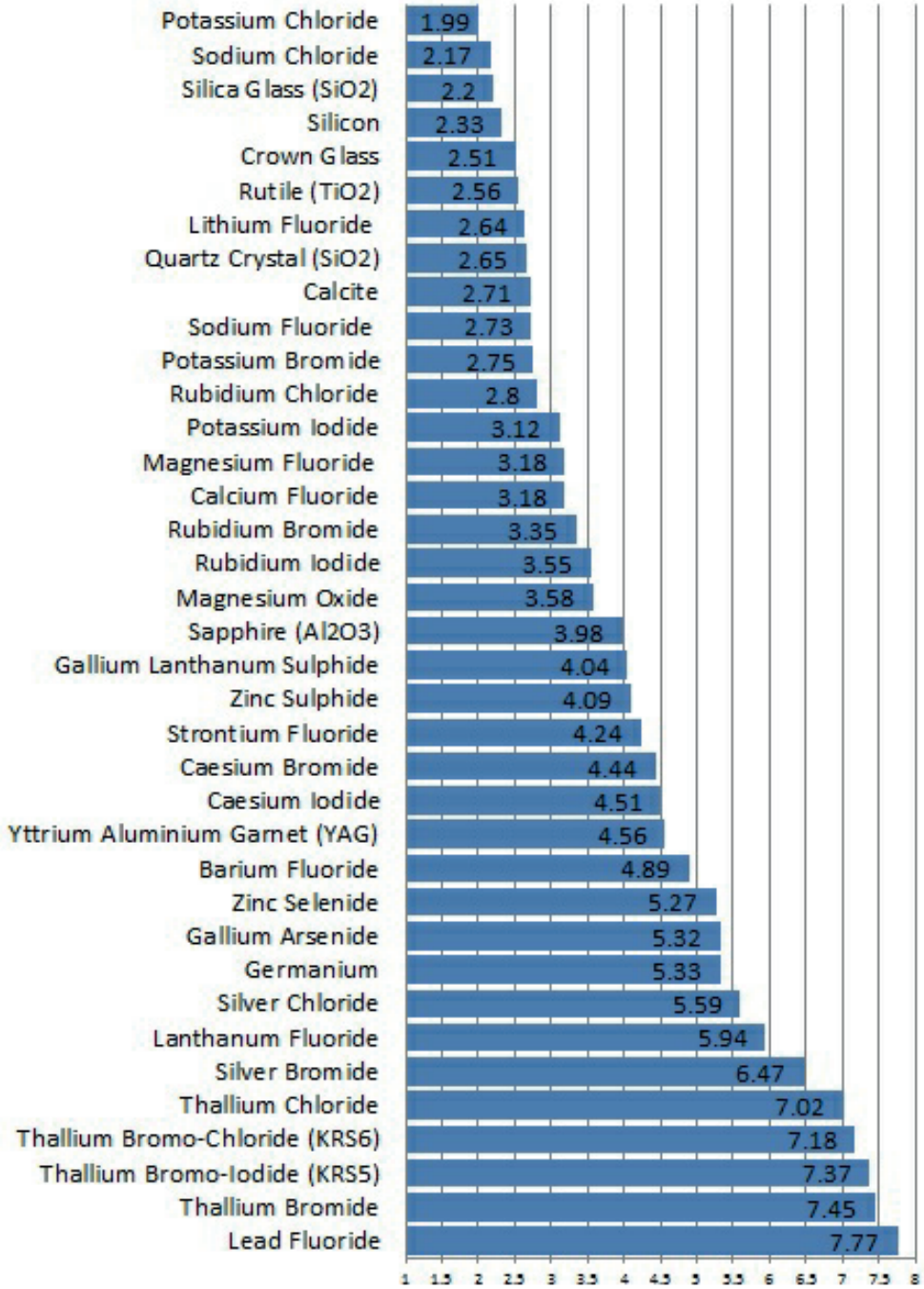
COMPARISON OF DATA - Refractive Index



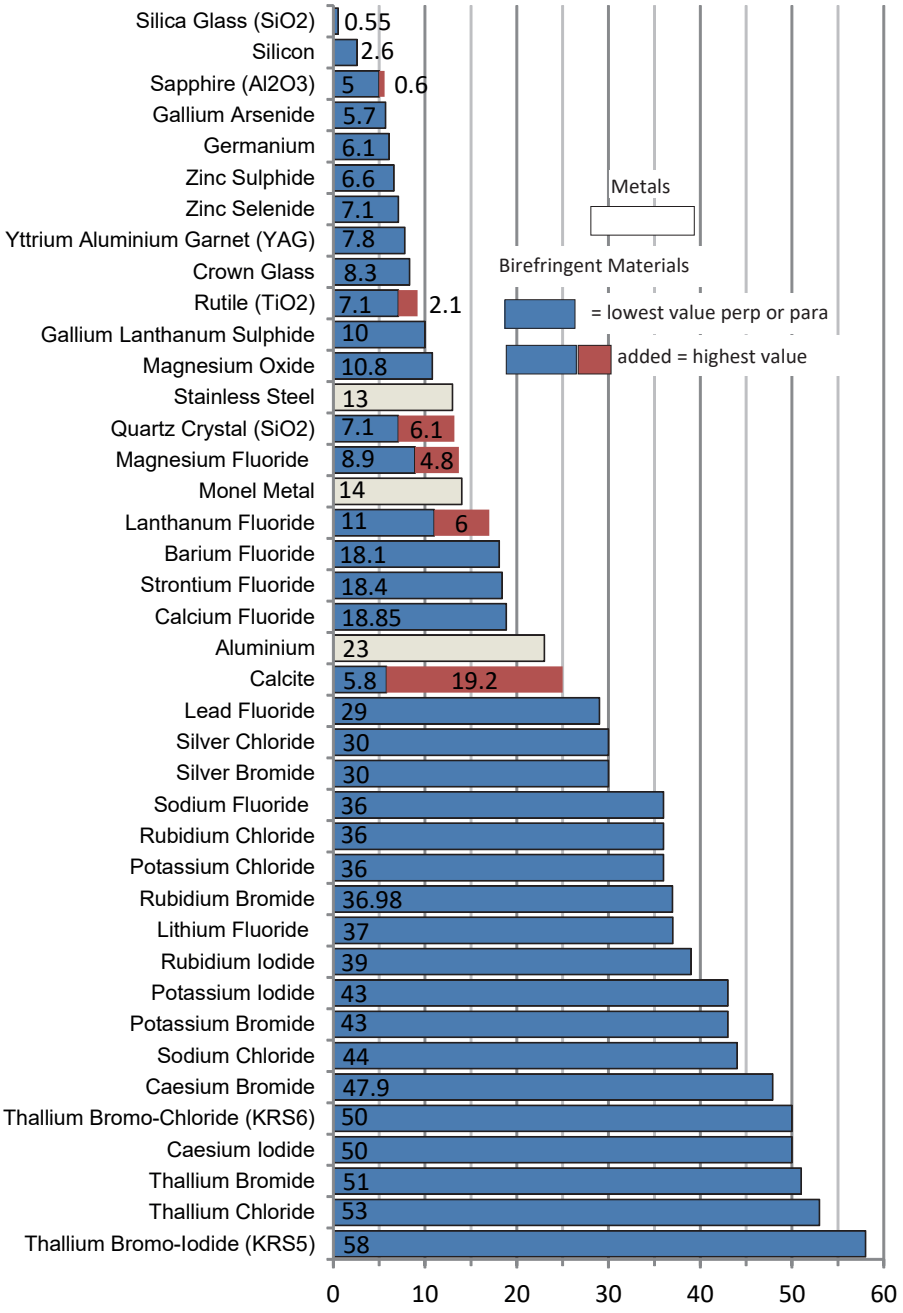
COMPARISON OF DATA - Melting Point °C



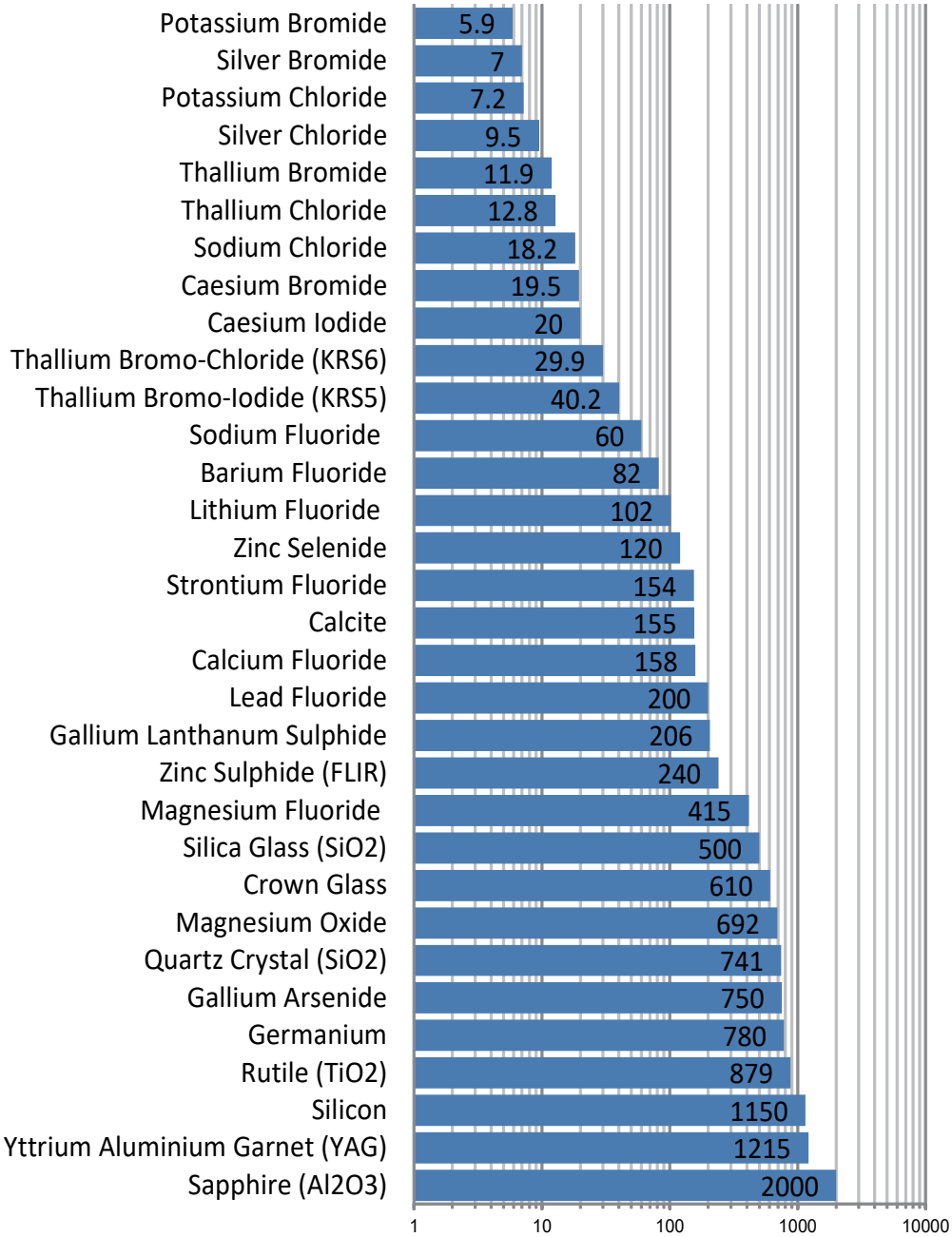
COMPARISON OF DATA - Density g/cc



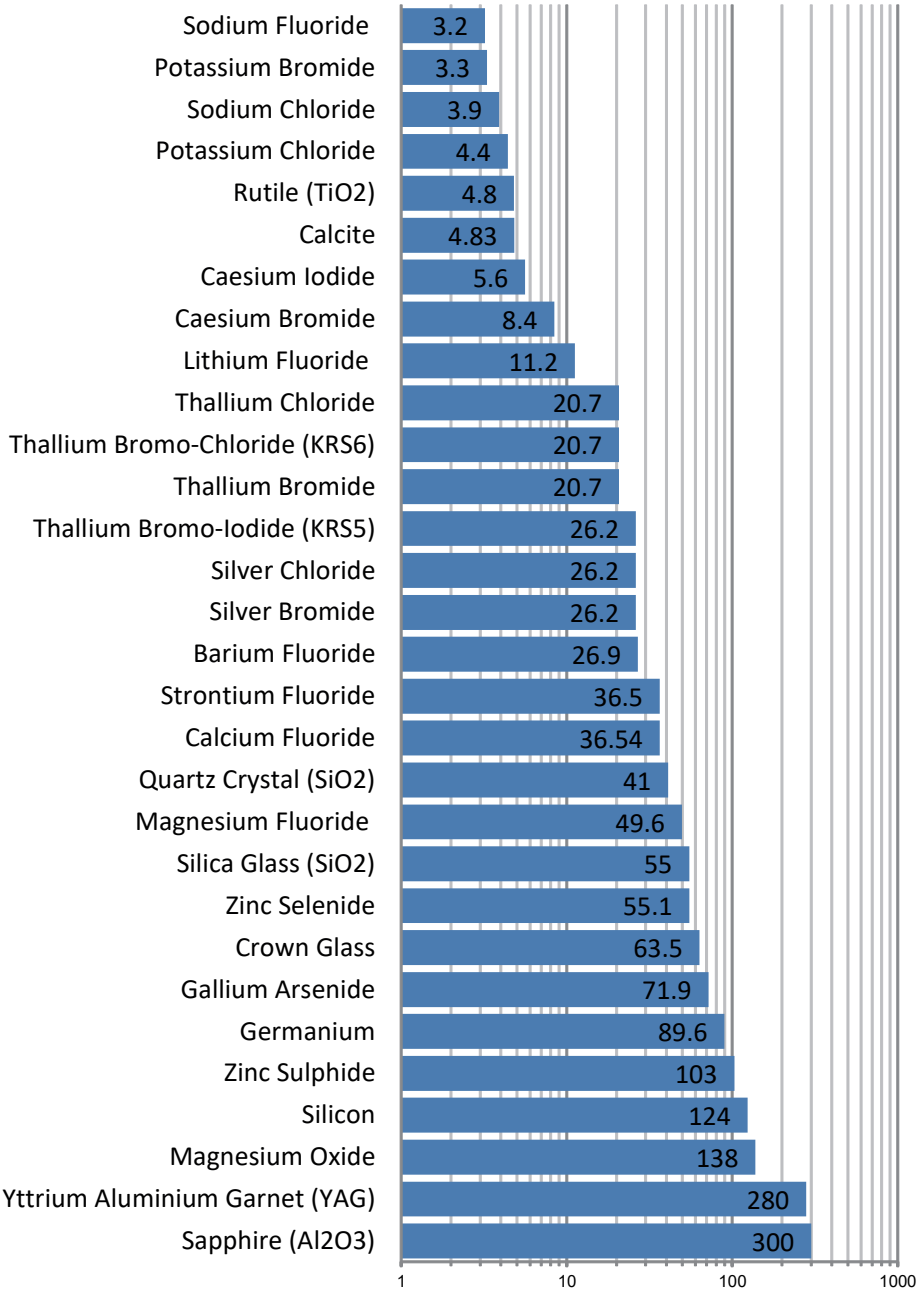
COMPARISON OF DATA - Expansion Coefficient x 10^{-6}



COMPARISON OF DATA - Knoop Hardness Kgf/mm



COMPARISON OF DATA - Rupture Modulus MPa



Barium Fluoride (BaF_2)

Barium Fluoride is grown by vacuum Stockbarger technique. Unlike CaF2, BaF2 is not found in the native state and all material must be synthesised chemically making BaF2 relatively expensive to produce. Barium Fluoride cleaves easily and is highly susceptible to thermal shock. It polishes well and can be etched (5). The highest purity VUV material can be qualified as fast scintillator grade.

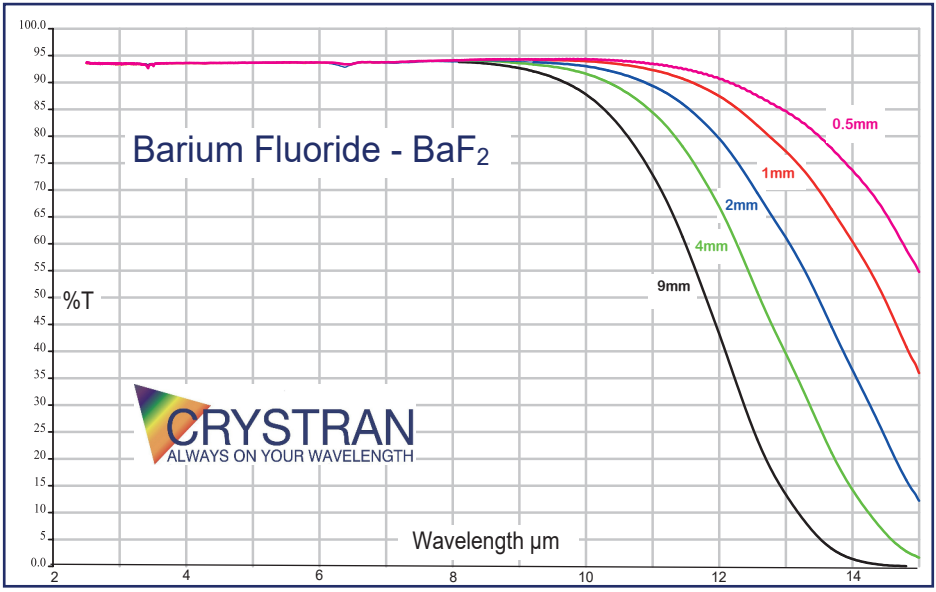
APPLICATIONS: Barium Fluoride is used in spectroscopic components. It is often suitable for applications in the passive IR band (8 to 14µm) and is often used as a view-port window for thermography. For an equivalent thickness the transmission extends approximately 1µm further into the IR than CaF2. The highest quality BaF_2 also has application as the fastest known scintillator material and is used in High Energy Physics Experiments.

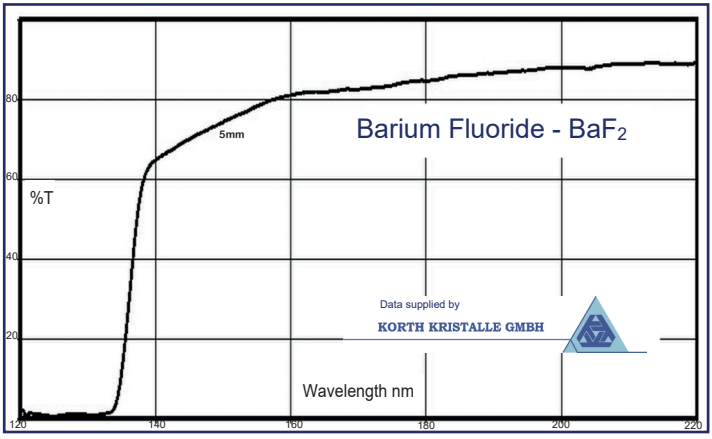
Transmission Range	0.15 to 12µm
Refractive Index	1.45 at 5µm (1)
Reflection Loss	6.5% at 5µm (2 surfaces)
Absorption Coefficient	3.2×10^{-4} cm^{-1} @ 6µm
Reststrahlen Peak	47 µm
dn/dT	-15.2×10^{-6}/°C (2)
dn/dµ = 0	1.95µm
Density	4.89 g/cc
Melting Point	1386°C
Thermal Conductivity	11.72 W m^{-1} K^{-1} @ 286 K
Thermal Expansion	18.1×10^{-6} K^{-1} @ 273 K
Hardness	Knoop 82 with 500g indenter (4)
Specific Heat Capacity	410 J Kg^{-1} K^{-1} (3)
Dielectric Constant	7.33 at 1 MHz
Youngs Modulus (E)	53.07 GPa (3)
Shear Modulus (G)	25.4 GPa (3)
Bulk Modulus (K)	56.4 GPa
Elastic Coefficients	C_{11} = 89.2 C_{12} = 40.0 C_{44} = 25.4 (2)
Apparent Elastic Limit	26.9 MPa (3900psi) (4)
Poisson Ratio	0.343
Solubility	0.17g/100g water at 23°C
Molecular Weight	175.36
Class/Structure	Cubic $Fm\bar{3}m$ (#225) Fluorite structure Cleaves on (111)

(1) Handbook Optical Constants, ed Palik, V3, ISBN 0-12-544423-0
(2) I.H.Malitson; J.Opt.Soc.Am. Vol52, p1377, 1962
(3) D.Girlich; Elastic Constants of BaF2; Phys.Rev. Vol135, p1826, 1964
(4) S.Ballard et al; J.Opt.Soc.Am. Vol42, p684, 1952
(5) US patent. Chemical polish. 4,040,896 1977
(6) M.Laval et al; Nu. Insts.Meth, V206 p169, 1983

Barium Fluoride (BaF_2)

µm	No	µm	No	µm	No	µm	No	µm	No
0.1408	1.815	0.3021	1.500	0.5893	1.4744	1.5295	1.4661	5.5490	1.4473
0.1452	1.7820	0.3130	1.4978	0.6438	1.4730	1.6810	1.4656	6.2380	1.4422
0.1477	1.7670	0.3254	1.4952	0.6563	1.4727	1.7012	1.4655	6.6331	1.4390
0.1500	1.6780	0.3403	1.4925	0.7065	1.4718	1.9701	1.4647	7.0442	1.4353
0.2000	1.557	0.3466	1.4915	0.8521	1.4699	2.3254	1.4636	7.2680	1.4331
0.2652	1.5122	0.3610	1.4894	0.8944	1.4694	2.6738	1.4623	9.7240	1.4051
0.2803	1.5066	0.3663	1.4887	1.0140	1.4685	3.2434	1.4602	10.346	1.3936
0.2893	1.5039	0.4046	1.4844	1.1287	1.4678	3.4220	1.4594		
0.2967	1.5019	0.5461	1.4759	1.3673	1.4667	5.1380	1.4501		





Cadmium Telluride (CdTe)

CAUTION: Cadmium salts are considered TOXIC and should be handled with care.

CdTe is rarely used because of its toxicity. The finished optics are not particularly hazardous but should be handled with care. However, difficulties with processing cadmium compounds means that very few optical companies will cut and polish the material. Crystran Ltd does not supply CdTe. This data is provided for reference only. A form of CdTe was originally utilised as the obsolete Kodak designation of IRTRAN-6

APPLICATIONS: Cadmium Telluride can be used for spectroscopy and where deep IR transmission is required. It is relatively workable and offers transmission to >20µm. CdTe has some application for solar cells.

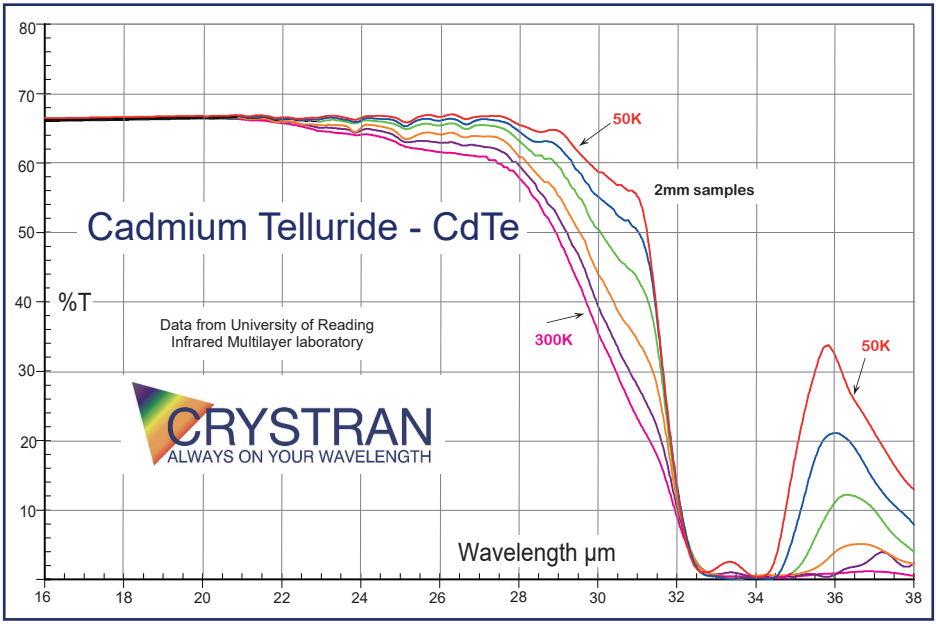
Transmission Range	0.85 to 28µm (1)(3)
Refractive Index	2.653 @ 10µm (1)
Reflection Loss	32% @ 10µm
Absorption Coefficient	n/a
Reststrahlen Peak	n/a
dn/dT	50×10^{-6} K^{-1}
dn/dµ = 0	n/a
Density	6.2 g cm^{-3} (2)
Melting Point	1092°C (4)
Thermal Conductivity	6.2 W m^{-1} K^{-1} at 293 K
Thermal Expansion	5.9×10^{-6} K^{-1} at 293 K
Hardness	Knoop 54 (3)
Specific Heat Capacity	210 J Kg^{-1} K^{-1} at 293 K
Dielectric Constant	11 @ 1MHz
Youngs Modulus (E)	36.52 GPa
Shear Modulus (G)	n/a
Bulk Modulus (K)	25 GPa
Elastic Coefficients	C_{11}=53.51; C_{12}=36.81; C_{44}=19.94
Apparent Elastic Limit	5.9 MPa (3)
Poisson Ratio	0.41
Solubility	Insoluble in water
Molecular Weight	240.02
Class/Structure	Cubic ZnS (110) cleavage

Crystran does not hold stock of this material. This is for information only purposes

(1) Handbook Optical Constants, ed. Palik, V1, ISBN 0-12-544420-6
(2) Capper; Properties of Narrow Gap Cadmium-Based Compounds, IET, ISBN 978-0-85296-880-2
(3) Hawkins, Sherwood, Djotni; Mid IR Filters for astronomical and remote sensing instrumentation, invited paper SPIE Conference, Glasgow (2008)
(4) David R Lide; CRC Handbook of Chemistry and Physics, 78th ed (1997)

Cadmium Telluride (CdTe)

µm	No	µm	No	µm	No	µm	No	µm	No
0.8	2.876	3.0	2.695	6.0	2.681	12.5	2.646	24.8	2.5801
1.0	2.840	3.5	2.691	7.0	2.679	15.5	2.6407	26.32	2.570
2.0	2.713	4.0	2.6807	8.0	2.677	20.0	2.614	27.03	2.564
2.5	2.702	5.0	2.684	10.0	2.653	22.2	2.601		



Caesium Bromide (Cesium Bromide) (CsBr)

CsBr is grown by sealed ampoule Stockbarger technique. It is a soft pliable material.

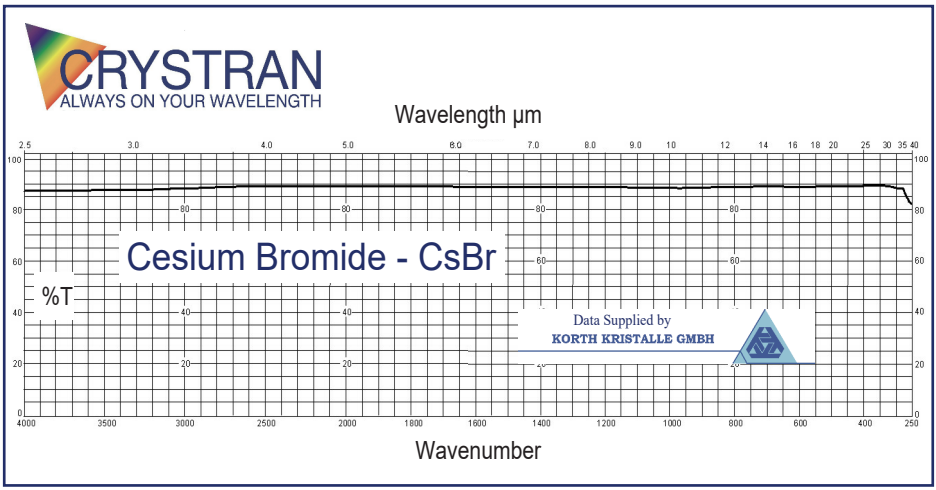
APPLICATIONS: Cesium Bromide has limited application in the deep IR. It is slightly more amenable to optical working than CsI and is sometimes used as a beamsplitter component in wide-band spectrophotometers

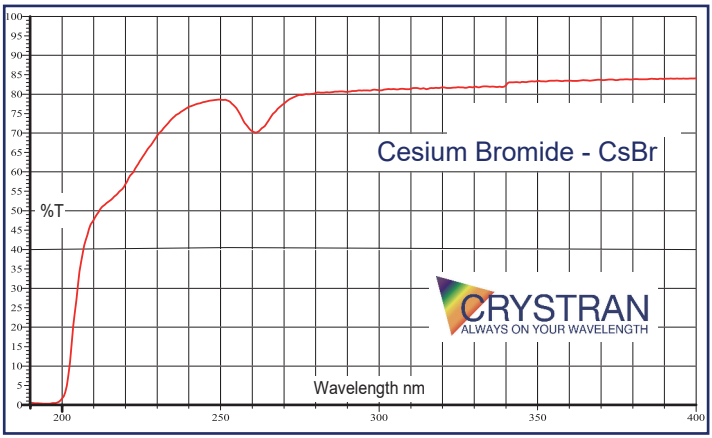
Transmission Range	0.25 to 40µm (1)
Refractive Index	1.6612 at 11µm (1)
Reflection Loss	11.6% at 11µm (2 surfaces)
Absorption Coefficient	n/a
Reststrahlen Peak	121.2µm (2)
dn/dT	-84×10^{-6}/°C at 0.6µm (5)
dn/dµ = 0	5.3µm
Density	4.44 g/cc
Melting Point	636 °C
Thermal Conductivity	0.94 W m^{-1} K^{-1} at 273K
Thermal Expansion	47.9×10^{-6} K^{-1} at 273K
Hardness	Knoop 19.5 with 200g indenter
Specific Heat Capacity	263.8 J Kg^{-1} K^{-1} (3)
Dielectric Constant	6.51 at 2 MHz
Youngs Modulus (E)	15.85 GPa (4)
Shear Modulus (G)	7.5 GPa
Bulk Modulus (K)	13.01 GPa
Elastic Coefficients	C_{11}=30.97; C_{12}=4.03; C_{44}=7.5
Apparent Elastic Limit	8.4 MPa (1220 psi) (4)
Poisson Ratio	0.279
Solubility	90g/100g water at 25°C (6)
Molecular Weight	212.83
Class/Structure	Cubic CsCl, Pm3m, no cleavage planes

(1) Handbook Optical Constants, ed Palik, V3, ISBN 0-12-544423-0
(2) Mitsuishi et al., J Opt Soc. Am. V52, p14, 1962
(3) Kelly, Bureau of Mines Bulletin, No371, p51, 1934
(4) S.Ballard et al; J.Opt.Soc.Am. Vol42, p684, 1952
(5) H.H.Li; J.Phys. Chem. Ref. Data. Vol 5, No 2. 1976
(6) K Matthews. Crystran Ltd. Test Data 2021

Caesium Bromide (Cesium Bromide) (CsBr)

µm	No	µm	No	µm	No	µm	No
0.5	1.70896	10.0	1.66251	20.0	1.64348	31.0	1.6051
1.0	1.67793	11.0	1.6612	21.0	1.6408	32.0	1.60053
2.0	1.67061	12.0	1.65976	22.0	1.63798	33.0	1.59576
3.0	1.66901	13.0	1.6582	23.0	1.635	34.0	1.59078
4.0	1.66813	14.0	1.6561	25.0	1.62856	35.0	1.58558
5.0	1.66737	15.0	1.65468	26.0	1.62509	36.0	1.58016
6.0	1.66659	16.0	1.65272	27.0	1.62146	37.0	1.5745
7.0	1.66573	17.0	1.65062	28.0	1.61764	38.0	1.5686
8.0	1.6477	18.0	1.64838	29.0	1.61365	39.0	1.56245
9.0	1.6637	19.0	1.646	30.0	1.60947		





Caesium Iodide (Cesium Iodide) (CsI)

Cesium Iodide is grown by sealed ampoule Stockbarger techniques with ingots of approximately 70mm diameter. CsI is very soft and pliable.

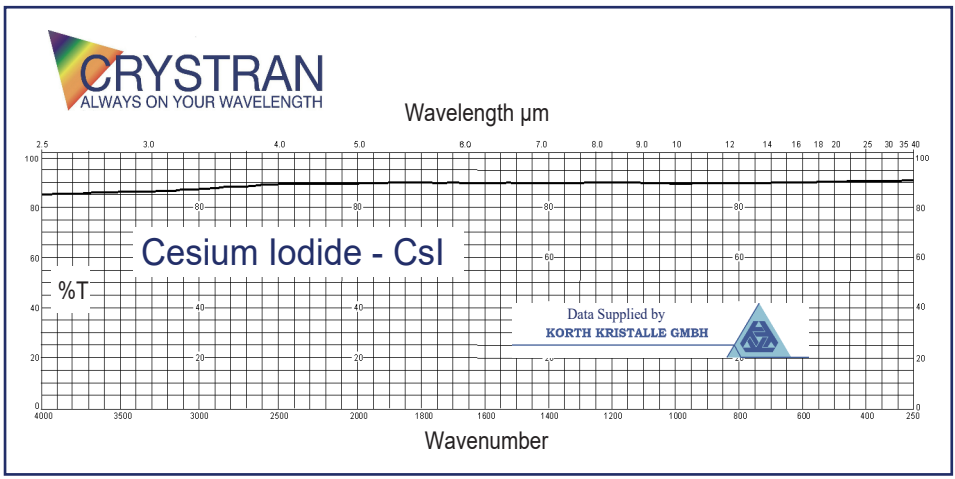
APPLICATIONS: Cesium Iodide is the material with the deepest known IR transmission, and is sometimes used for components in the widest range spectrophotometers. An extremely soft material, Cesium Iodide is extremely difficult to polish, and so performance is compromised for range. Doped with Thallium, CsI(Tl) is a useful scintillator which emits at a wavelength that is a good match for Silicon photodiodes. Arrays of Cesium Iodide(Tl) are used in security imaging systems.

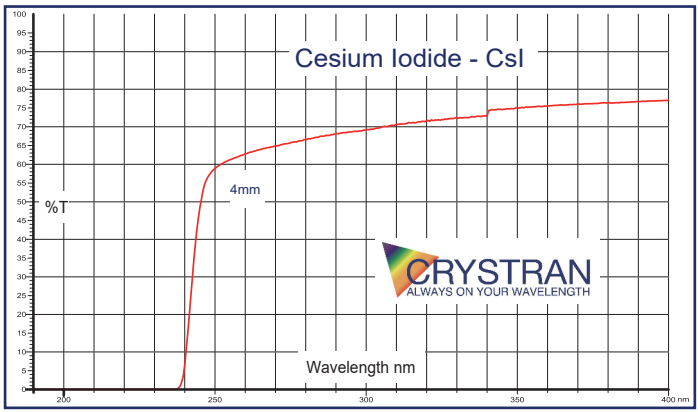
Transmission Range	0.25 to 55µm (1)
Refractive Index	1.73916 at 10µm (1)(2)
Reflection Loss	13.6% at 10µm
Absorption Coefficient	n/a
Reststrahlen Peak	145.8µm
dn/dT	-99.3×10^{-6} /°C (2)
dn/dµ = 0	6µm
Density	4.51 g/cc
Melting Point	621 °C
Thermal Conductivity	1.1 W m^{-1} K^{-1} at 298 K (3)
Thermal Expansion	48.3×10^{-6} K^{-1} at 293 K (3)
Hardness	Knoop 20 with 200g indenter
Specific Heat Capacity	201 J Kg^{-1} K^{-1} (4)
Dielectric Constant	5.65 at 1 MHz
Youngs Modulus (E)	5.3 GPa
Shear Modulus (G)	6.24 GPa
Bulk Modulus (K)	12.67 GPa
Elastic Coefficients	C_{11}=24.6 C_{12}=6.7 C_{44}=6.24
Apparent Elastic Limit	5.6 MPa (810psi)
Poisson Ratio	0.214
Solubility	44 g/100 g water at 0 °C
Molecular Weight	259.83
Class/Structure	Cubic CsCl, Pm3m, no cleavage, deforms

(1) Handbook Optical Constants, ed Palik, V2, ISBN 0-12-544422-2
(2) Rodney, J.Opt.Soc.Am. V45, p987, 1955
(3) Combes et al, J.Opt.Soc.Am. V41, p215, 1951
(4) Kelly, Bureau of Mines Bulletin, No371, p51, 1934

Caesium Iodide (Cesium Iodide) (CsI)

µm	No	µm	No	µm	No	µm	No
0.5	1.8064	13.0	1.7365	26.0	1.7168	39.0	1.6816
1.0	1.7572	14.0	1.7355	27.0	1.7147	40.0	1.6781
2.0	1.7466	15.0	1.7344	28.0	1.7125	41.0	1.6746
3.0	1.7440	16.0	1.7332	29.0	1.7101	42.0	1.6709
4.0	1.7431	17.0	1.7319	30.0	1.7077	43.0	1.6671
5.0	1.7424	18.0	1.7306	31.0	1.7052	44.0	1.6631
6.0	1.7418	19.0	1.7291	32.0	1.7027	45.0	1.6591
7.0	1.7412	20.0	1.7276	33.0	1.7000	46.0	1.6549
8.0	1.7406	21.0	1.7260	34.0	1.6972	47.0	1.6505
9.0	1.7399	22.0	1.7244	35.0	1.6943	48.0	1.6460
10.0	1.7392	23.0	1.7226	36.0	1.6913	49.0	1.6414
11.0	1.7384	24.0	1.7207	37.0	1.6882	50.0	1.6366
12.0	1.7375	25.0	1.7188	38.0	1.6849		





Calcite ($CaCO_3$)

Calcite is mined naturally, not manufactured synthetically. Crystran Ltd has a stock of small calcite "rhombs" of good clear optical quality. Calcite cuts and polishes well.

APPLICATIONS: Calcite, or Iceland Spar, is a strongly birefringent material and is used for polarisers and retardation plates.

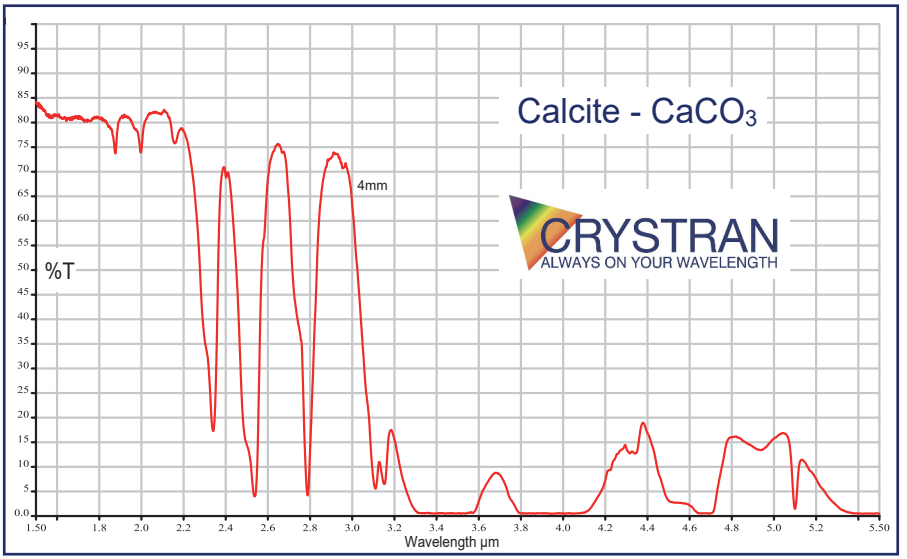
Transmission Range	0.3 to 2.3µm
Refractive Index	No 1.6654 at 0.51µm
Reflection Loss	11.7% at 0.51µm (2 surfaces)
Absorption Coefficient	n/a
Reststrahlen Peak	n/a
dn/dT	3 (para) 13 (perp) x 10^{-6} K^{-1} at 0.5µm
dn/dµ = 0	n/a
Density	2.71 g/cc
Melting Point	825°C (Decomposes)
Thermal Conductivity	5.526 (para) 4.646 (perp) W m^{-1} K^{-1} at 273K
Thermal Expansion	25.6 (para) -5.8 (perp) x 10^{-6} K^{-1} at 273K (2) (3)
Hardness	Knoop 155 Moh 3
Specific Heat Capacity	852 J Kg^{-1} K^{-1}
Dielectric Constant	8 (para) 8.5 (perp) at 10kHz at 293K
Youngs Modulus (E)	72.35 (perp) 88.19 (para) GPa
Shear Modulus (G)	35 GPa
Bulk Modulus (K)	129.53 GPa
Elastic Coefficients	C_{11}=137; C_{12}=45; C_{13}=45; C_{14}=21; C_{33}=79
Apparent Elastic Limit	4.83 MPa (700 psi)
Poisson Ratio	n/a
Solubility	0.0014g/100g water at 25°C
Molecular Weight	100.09
Class/Structure	Trigonal (hex), R3c, (1014) cleavage (1)

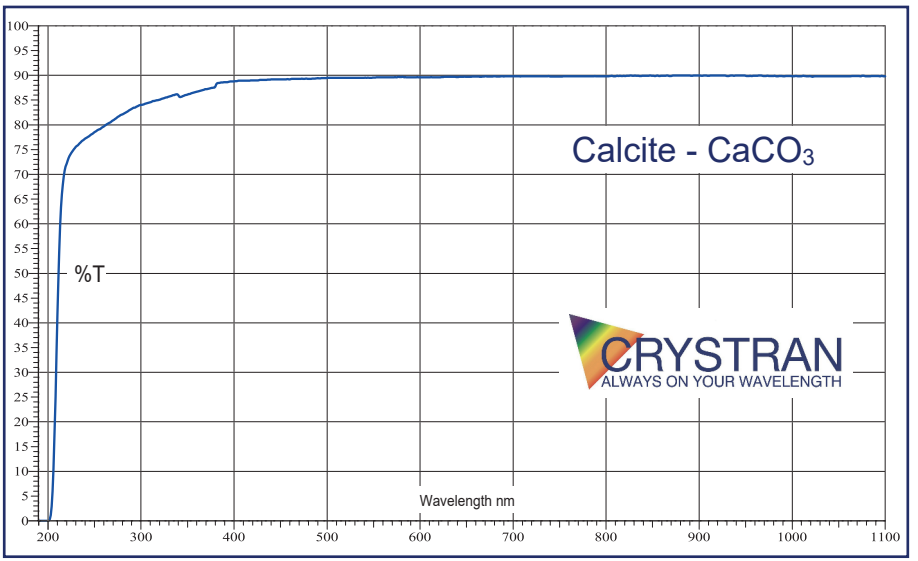
CLEAVAGE PLANE : *There can be confusion in the definition of the cleavage plane in calcite. Conventionally this has always been referred to as {1011} but recent papers on AFM studies use {1014}. Calcite cleaves between the bonds of the CO_3 groups (in the CO_3 layer). The CO_3 group are offset relative to each other and inclined to the c-axis giving 3 cleavage directions defining a rhomb. Following the {1011} nomenclature the unit cell requires ¼ the length of the c axis as measured from XRD (on a dimension 4 times longer). The correct Miller indices are {1014} but the conventional {1011} is often used in order not to confuse and for easier comparison.*

(1) Private Communication. J.A.Elliott. Material Science, University of Cambridge. 2011
(2) Practical Crystal Measurement. A.E.H.Tutton, Vol2, page 1329.
(3) Mineral Society of America "Linear Thermal Expansion of Calcite" See Crystran Website

Calcite ($CaCO_3$)

µm	No	Ne	µm	No	Ne	µm	No	Ne
0.20	1.9028	1.5765	0.64	1.6550	1.4849	1.04	1.6428	1.4799
0.30	1.7196	1.5137	0.71	1.6521	1.4835	1.50	1.6346	1.4774
0.41	1.6801	1.4954	0.80	1.6487	1.4822	1.91	1.627	1.4757
0.51	1.6653	1.4896	0.91	1.6458	1.4810	2.10	1.622	1.4749





Calcium Fluoride (CaF_2)

Calcium fluoride is grown by vacuum Stockbarger technique in diameters of up to about 250mm. Material for IR use is grown using naturally mined fluorite, in large quantities at a relatively low cost. For UV applications chemically prepared raw material is generally used. For Excimer applications, we use only the highest grade of specially selected material and crystal.

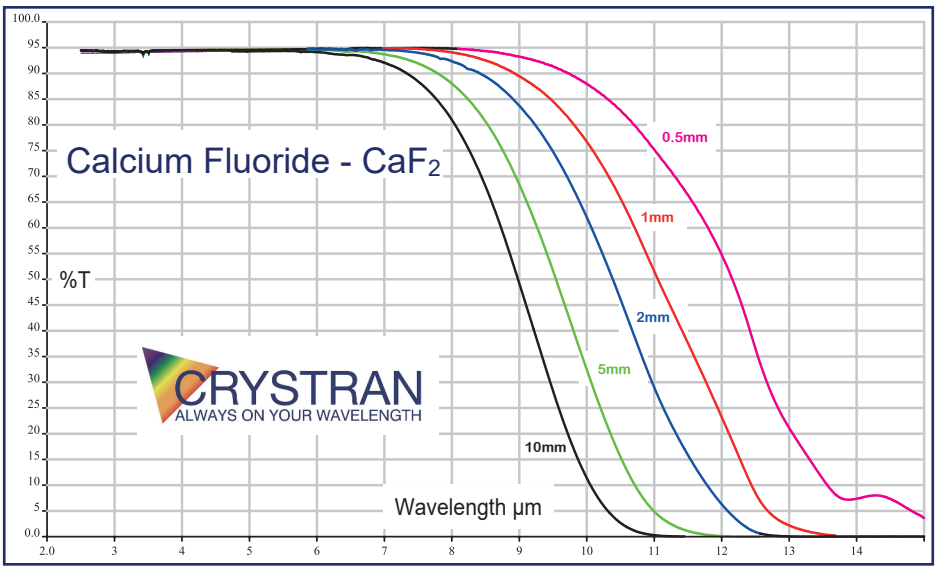
APPLICATIONS: Calcium Fluoride has widespread IR application as spectroscopic windows, prisms and lenses. Especially pure grades of Calcium Fluoride find useful application in the UV and as UV Excimer laser windows. Specially selected material is used for Raman work as it has no interfering fluorescence peaks. Use the links on page 32 for more data on Raman Grade and Crystal Quality.

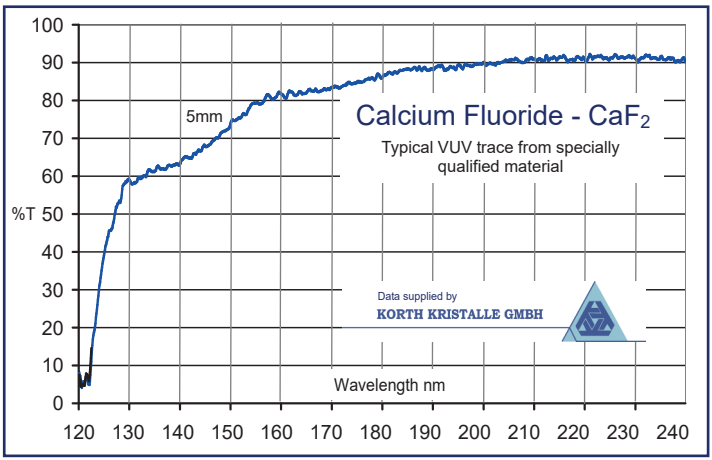
Transmission Range	0.13 to 10µm	
Refractive Index	1.39908 at 5µm (1) (2)	
Reflection Loss	5.4% at 5µm	
Absorption Coefficient	0.00002cm^{-1} @ 1.06µm	0.000078cm^{-1} @ 2.7µm
0.0002cm^{-1} @ 3.8µm	0.0005cm^{-1} @ 5.25µm	0.0035cm^{-1} @ 6.25
0.11cm^{-1} @ 7.69µm	0.48cm^{-1} @ 8.69µm	0.65cm^{-1} @ 9.09µm
	3.5cm^{-1} @ 10.6µm (8)	
Reststrahlen Peak	35µm	
dn/dT	-10.6 x 10^{-6} K^{-1} (3)	
dn/dµ = 0	1.7µm	
Density	3.18 g/cc	
Melting Point	1360°C	
Thermal Conductivity	9.71 W m^{-1} K^{-1} (4)	
Thermal Expansion	18.85 x 10^{-6} K^{-1} (5)(6)	
Hardness	Knoop 158.3 (100) with 500g indenter	
Specific Heat Capacity	854 J Kg^{-1} K^{-1}	
Dielectric Constant	6.76 at 1MHz (7)	
Youngs Modulus (E)	75.8 GPa (7)	
Shear Modulus (G)	33.77 GPa (7)	
Bulk Modulus (K)	82.71 GPa (7)	
Elastic Coefficients	C_{11} = 164 C_{12} = 53 C_{44} = 33.7 (7)	
Apparent Elastic Limit	36.54 MPa	
Poisson Ratio	0.26	
Solubility	0.0017g/100g water at 20°C	
Molecular Weight	78.08	
Class/Structure	Cubic Fm3m (#225) Fluorite. Cleaves on (111)	

(1) Handbook Optical Constants, ed Palik, V2, ISBN 0-12-544422-2
(2) Dressler et al., Cryst.Res.Technol. V27, p413, 1992
(3) I.H.Malitson; J.Opt.Soc.Am. Vol52, p1377, 1962
(4) Ballard et al; Rev. Sci. Instr., V21, p905, 1950
(5) Batchelder & Simmons, J.Chem. Phys. V41, p2324 N8 1964
(6) Schumann & Neumann, Crys. Res. Tech V19, 1984
(7) Dickinson, IR laser windows, AFCRL-TR-0318, Air Force, Cambridge 1975
(8) Manufacturers Published Data.

Calcium Fluoride (CaF_2)

µm	No	µm	No	µm	No	µm	No	µm	No
0.149	1.5800	0.337	1.4481	1.100	1.4283	3.400	1.4149	7.661	1.357
0.161	1.5490	0.400	1.4419	1.250	1.4275	4.000	1.4096	8.251	1.3444
0.195	1.5000	0.486	1.4370	1.650	1.4256	4.400	1.4057	8.840	1.3308
0.200	1.4950	0.588	1.4339	1.900	1.4244	4.800	1.4014	9.429	1.3161
0.222	1.4800	0.656	1.4325	2.058	1.4236	5.000	1.3991		
0.248	1.4680	0.687	1.4320	2.450	1.4214	5.304	1.3952		
0.266	1.4621	0.728	1.4314	2.700	1.4199	5.893	1.3871		
0.280	1.4584	0.884	1.4298	2.800	1.4192	6.483	1.3782		
0.300	1.454	1.014	1.4288	3.050	1.4175	7.072	1.3681		





Diamond (C) - Cubic Carbon

Diamond is available as single crystal (Type IIa) natural or synthetic or as CVD film. Single crystal is available economically up to about 4mm diameter. CVD diamond of 75mm diameter is available. The IR transmission has a range of absorptions in the mid-IR between 2.5 and 7µm due to inherent lattice resonance. The UV transmission may be limited to 350nm in poorer quality samples. Single crystal diamond is selected into four forms: Ia ~98% of natural yield (>100ppm Nitrogen - yellow)
Ib ~0.1% of natural yield (~100ppm Nitrogen)
IIa ~2% of natural yield (1ppm Nitrogen)
IIb - Synthetic only (100ppm boron for electronic applications)

Only Type IIa is used for optical applications. CVD diamond transmission and characteristics are very similar to Type IIa.

APPLICATIONS: Diamond is used for transmission windows and domes.

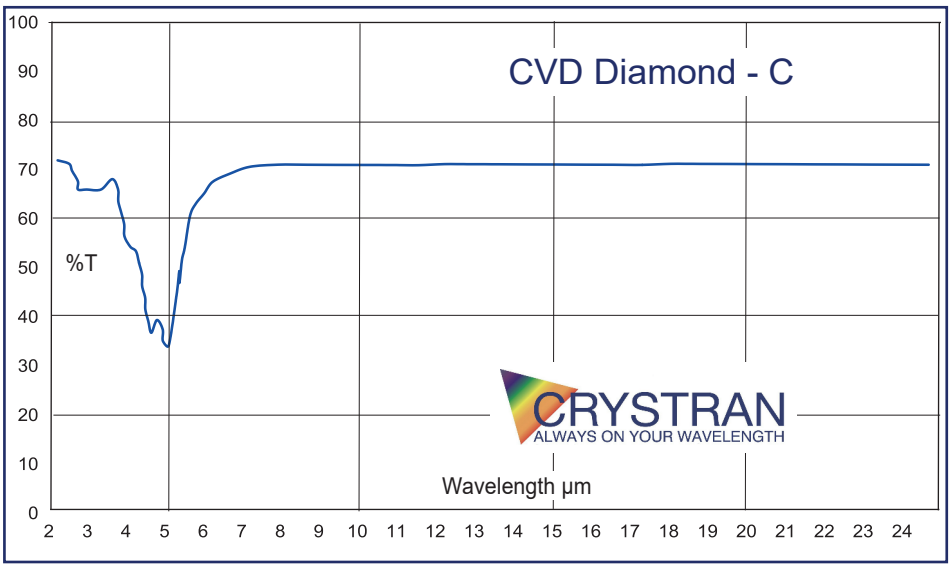
Transmission Range	300nm to 2.5µm and 7µm to >100µm (1)
Refractive Index	2.4175 @ 0.589µm (1)
Reflection Loss	30% @ 0.589µm
Absorption Coefficient	~0.09 cm^{-1} @ 10.6µm
Reststrahlen Peak	n/a
dn/dT	30 x 10^{-6} K^{-1} @ 300K (3)
dn/dµ = 0	n/a
Density	3.51
Melting Point	3497°C (Oxidises in air at 700°C - see note)
Thermal Conductivity	2600 W m^{-1} K^{-1} @ 273K (2)
Thermal Expansion	1 x 10^{-6} K^{-1} at 293K
Hardness	Knoop 5700 to 10400
Specific Heat Capacity	502 J Kg^{-1} K^{-1} @ 300K (4)
Dielectric Constant	5.68 @ 1.68Mhz at 300K (2)
Youngs Modulus (E)	1050 GPa
Shear Modulus (G)	n/a
Bulk Modulus (K)	442 GPa
Elastic Coefficients	C_{11}=1076; C_{12}=125; C_{44}=577
Apparent Elastic Limit	276 MPa
Poisson Ratio	0.16 to 0.29
Solubility	Insoluble in water
Molecular Weight	12.01
Class/Structure	Cubic Diamond, Fd3m

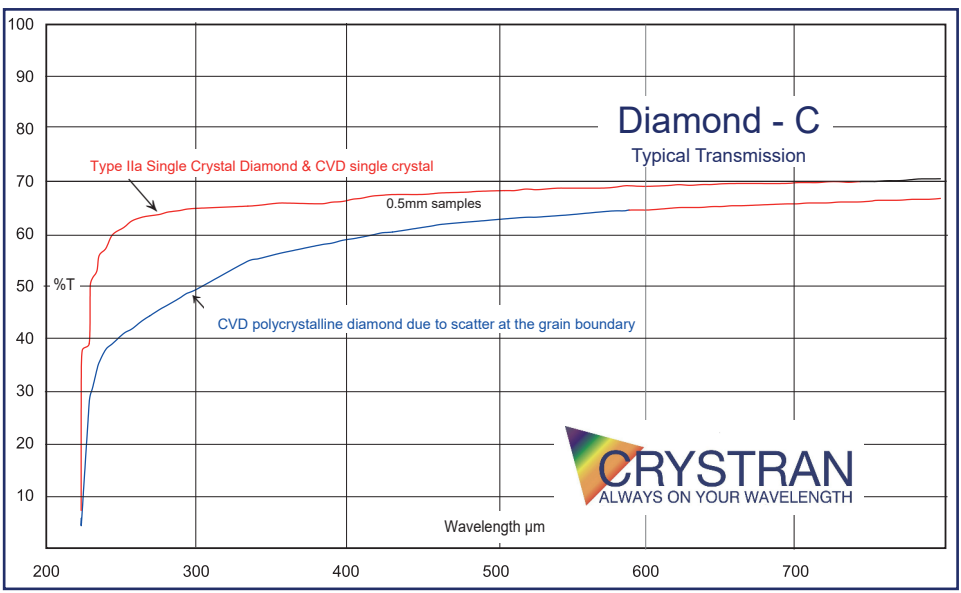
Note:Being a form of carbon, diamond oxidises in air over 700°C. In the absence of oxygen such as in a flow of argon gas, diamond can be heated to 1700°C. The surface blackens but can be recovered by polishing.

(1) Handbook Optical Constants, ed Palik, V1, ISBN 0-12-544420-6
(2) Properties of Polycrystalline Diamond, Sussmann et. al. Diamond & Rel. Mat. 3(1994) 303-312
(3) Fontenella et. al. App. Optics **16**, 2949 (1977)
(4) Slack & Bartram J.Appl. Phys. **46**, 89 (1975)

Diamond (C) - Cubic Carbon

µm	No	µm	No	µm	No	µm	No	µm	No
0.232	2.6917	0.589	2.4175	2.0	2.3813	5.0	2.3783	20.0	2.3741
0.298	2.5429	0.656	2.4104	3.0	2.3795	6.0	2.3779		
0.405	2.4626	1.00	2.3905	4.0	2.3787	10.0	2.3765		





Gallium Arsenide (GaAs)

Gallium Arsenide is produced by Czochralski or horizontal Bridgeman crystal growth techniques. As it is arsenic bearing, precautions in handling and working should be observed.

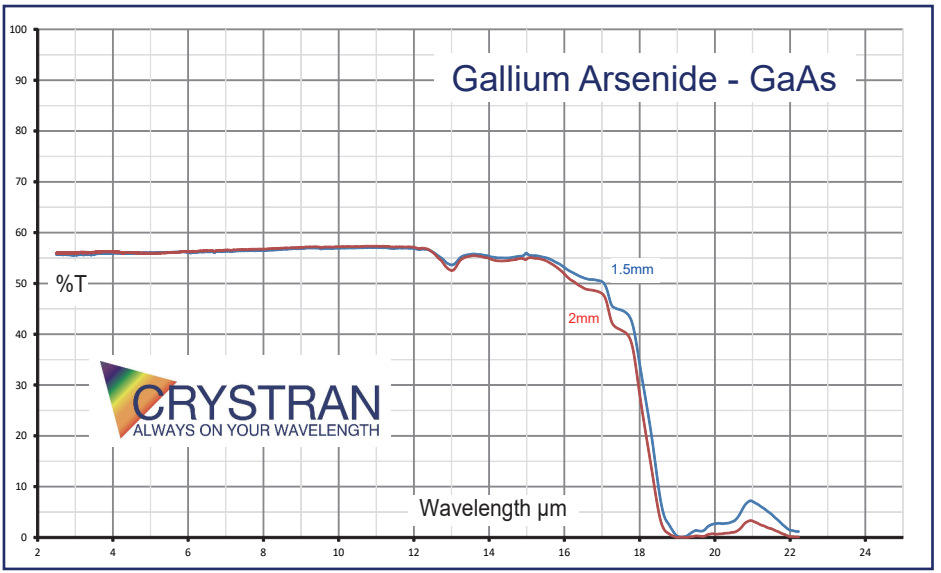
APPLICATIONS: Gallium Arsenide has specialist applications in far IR optics and lens systems.

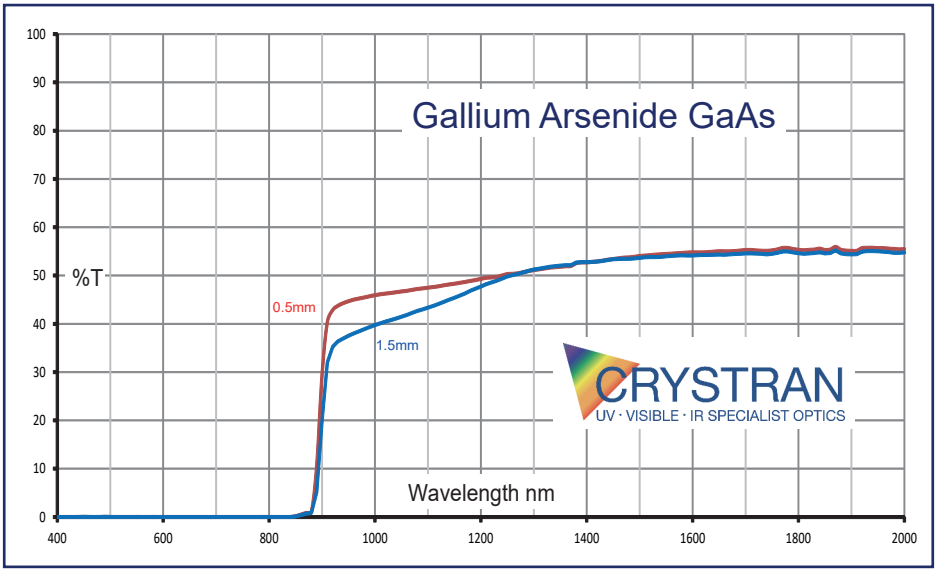
Transmission Range	0.9 to 16µm (1)
Refractive Index	3.2727 @ 10.33µm (1)
Reflection Loss	44% @ 10.33 µm
Absorption Coefficient	0.01 cm^{-1}
Reststrahlen Peak	n/a
dn/dT	147 x 10^{-6} K^{-1} @ 10µm (4)
dn/dµ = 0	6.3µm
Density	5.315 g/cc
Melting Point	1511°C
Thermal Conductivity	48 W m^{-1} K^{-1} @ 273K (2)
Thermal Expansion	5.7 x 10^{-6} /°C at 300K (3)
Hardness	Knoop 750
Specific Heat Capacity	360 J Kg^{-1} K^{-1}
Dielectric Constant	12.91 at low frequencies
Youngs Modulus (E)	84.8 GPa
Shear Modulus (G)	n/a
Bulk Modulus (K)	75.5 GPa
Elastic Coefficients	n/a
Apparent Elastic Limit	71.9 MPa
Poisson Ratio	0.31
Solubility	Insoluble in water
Molecular Weight	144.64
Class/Structure	Cubic ZnS, F43m, (100) cleavage

(1) Handbook Optical Constants, ed Palik, V1, ISBN 0-12-544420-6
(2) Deutch, J.Electron. Mater. V4 p679
(3) Sze, Physics of Semiconductor Devices, Wiley 1981
(4) M.Cardona, Proc. Int. Conf. Semicond. Phys., Prague 1960 p.388.

Gallium Arsenide (GaAs)

µm	No	µm	No	µm	No	µm	No	µm	No
1.033	3.492	3.100	3.3125	7.293	3.2874	11.27	3.2671	17.71	3.2081
1.550	3.3737	4.133	3.3027	8.266	3.2831	12.40	3.2597	19.07	3.1866
2.066	3.338	4.959	3.2978	9.537	3.2769	13.78	3.2493		
2.480	3.324	6.199	3.2921	10.33	3.2727	15.50	3.2336		





Gallium Lanthanum Sulphide (GLS)

Gallium Lanthanum Sulphide (GLS) glass is produced by proprietary processes under conditions of the highest purity. Particular effort is made in removing transition metal impurities to a level of better than 1 ppm total metallic impurities with SH^- and OH^- less than 1 ppm. GLS is routinely processed from ingots of 500 grams. Other glass compositions are available including rare earth doped (Ce, Pr, Nd, Tb, Dy, Ho, Er, Tm, Yb), halide (F, Cl), and Ag doped samples.

APPLICATIONS: Gallium Lanthanum Sulphide is a chalcogenide glass, an alternative to toxic arsenic-based glasses. Developed at Southampton University, GLS has found use in a wide range of optoelectronic applications and is available as polished optical components, thin and thick films and in optical fibre form.

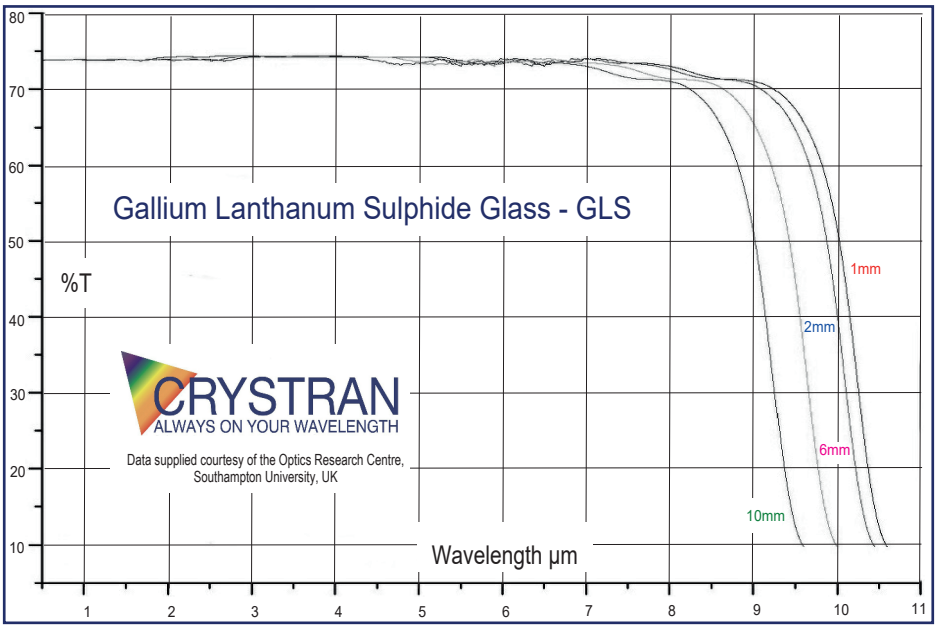
Transmission Range	0.5 to 10µm
Refractive Index	2.398 at 1.014µm
Reflection Loss	29% at 1.014µm
Absorption Coefficient	<0.005 cm^{-1}
Reststrahlen Peak	n/a
dn/dT	+75 x 10^{-6} /°C
dn/dµ = 0	4µm
Density	4.04 g/cc
Melting Point	830°C
Thermal Conductivity	0.43 W m^{-1} K^{-1} at 273K
Thermal Expansion	10 x 10^{-6} K^{-1} at 273K
Hardness	Knoop 206 with 200g indenter
Specific Heat Capacity	0.54 J g^{-1} K^{-1}
Dielectric Constant	8.1 at 1KHz
Youngs Modulus (E)	59 GPa
Shear Modulus (G)	23 GPa
Bulk Modulus (K)	24.5 GPa
Elastic Coefficients	n/a
Apparent Elastic Limit	n/a
Poisson Ratio	0.24
Solubility	Negligible in water
Molecular Weight	276.9
Class/Structure	Amorphous glass

Damage Threshold >200MW cm^{-2} at 1550nm
Acousto-optic Figure of Merit: M2 = 6 x 10^{-15}
Verdet Constant = 0.205 min/Oe/cm

Petrovich, Hewak et al Journal of Non-Crystalline Solids 326&327 (2003) 93–97

Gallium Lanthanum Sulphide (GLS)

µm	No	µm	No	µm	No	µm	No
0.5461	2.522	0.6678	2.458	1.3673	2.379		
0.5790	2.500	0.7065	2.466	1.7101	2.371		
0.6439	2.467	1.0140	2.398				



Germanium (Ge)

Germanium is grown using the Czochralski technique by a small number of manufacturers in Belgium, USA, China and Russia. The refractive index of Germanium changes rapidly with temperature and the material becomes opaque at all wavelengths a little above 350°K as the band gap floods with thermal electrons.

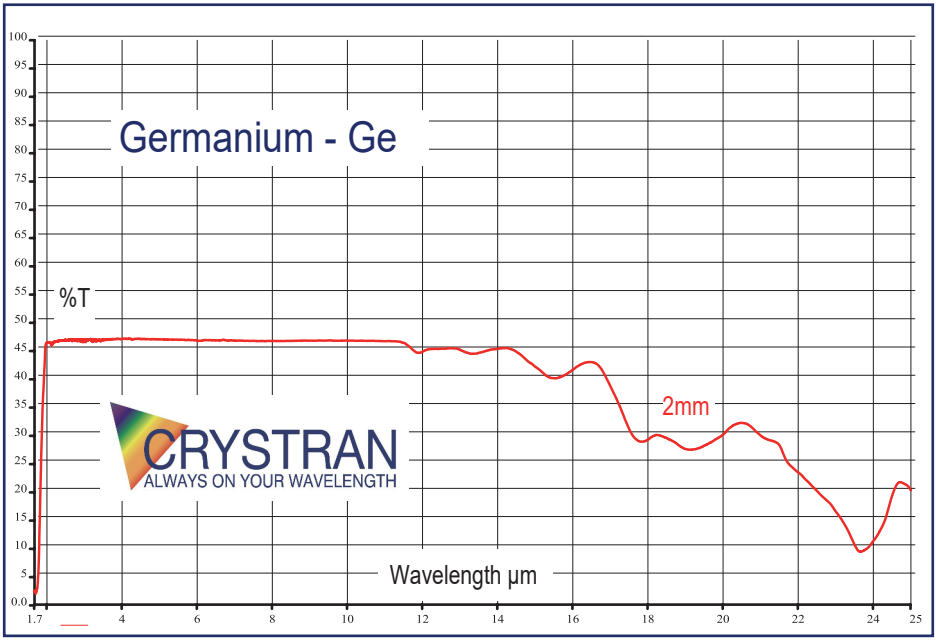
APPLICATIONS: Germanium is a high index material that is used to manufacture Attenuated Total Reflection (ATR) prisms for spectroscopy. Its refractive index is such that Germanium makes an effective natural 50% beamsplitter without the need for coatings. Germanium is also used extensively as a substrate for production of optical filters. Germanium covers the whole of the 8-14µm thermal band and is used in lens systems for thermal imaging. Germanium can be AR coated with Diamond producing an extremely tough front optic.

Transmission Range	1.8 to 23µm (1)
Refractive Index	4.0026 at 11µm (1)(2)
Reflection Loss	53% at 11µm (Two surfaces)
Absorption Coefficient	<0.027 cm^{-1} @ 10.6µm (typical) (7) 0.006 cm^{-1} @ 5.6µm (typical) (7) <0.005 cm^{-1} @ 2.7µm (7)
Reststrahlen Peak	n/a
dn/dT	396 x 10^{-6} K^{-1} (2)(6)
dn/dµ = 0	Almost constant
Density	5.33 g/cc
Melting Point	936 °C (3)
Thermal Conductivity	58.61 W m^{-1} K^{-1} at 293K (6)
Thermal Expansion	6.1 x 10^{-6} K^{-1} at 298K (3)(4)(6)
Hardness	Knoop 780
Specific Heat Capacity	310 J Kg^{-1} K^{-1} (3)
Dielectric Constant	16.6 at 9.37 GHz at 300K
Youngs Modulus (E)	102.7 GPa (4) (5)
Shear Modulus (G)	67 GPa (4) (5)
Bulk Modulus (K)	77.2 GPa (4)
Elastic Coefficients	C_{11}=129; C_{12}=48.3; C_{44}=67.1 (5)
Apparent Elastic Limit	89.6 MPa (13000 psi)
Poisson Ratio	0.28 (4) (5)
Solubility	Insoluble in water
Molecular Weight	72.59
Class/Structure	FCC Cubic, Fm3m (#225) Diamond structure

(1) Handbook Optical Constants, ed Palik, V1, ISBN 0-12-544420-6
(2) Li, Refractive Index of Germanium etc, J.Phys Chem, V9, p561, 1980
(3) Pearson & Brattain, Proc. Inst. Radio Eng. V43, p1794, 1955
(4) Fine, J.App.Phys, V24, p338, 1953
(5) Wortman & Evans, V36, (1), P153 (1965)
(6) Hawkins, Sherwood, Djotni: Mid IR Filters for astronomical and remote sensing instrumentation. Invited Paper SPIE Conference Glasgow 2008
(7) Manufacturers Published Data

Germanium (Ge)

µm	No	µm	No	µm	No	µm	No
2.058	4.102	2.577	4.0609	4.258	4.0216	9.720	4.0034
2.153	4.0919	2.714	4.0562	4.866	4.017	11.04	4.0026
2.313	4.0786	2.998	4.0452	6.238	4.0094	12.00	4.0023
2.437	4.0708	3.303	4.0369	8.660	4.0043	13.02	4.0021



KRS5 Thallium Bromo-Iodide (TlBr-TlI)

CAUTION: Thallium salts are considered TOXIC and should be handled with care.

KRS5 crystallises by the sealed-ampoule Stockbarger technique. Starting materials of the highest purity are selected to ensure that there are no anionic absorption bands between 2µm and 16µm and all crystals are checked for quality by using a pathlength of 120mm.

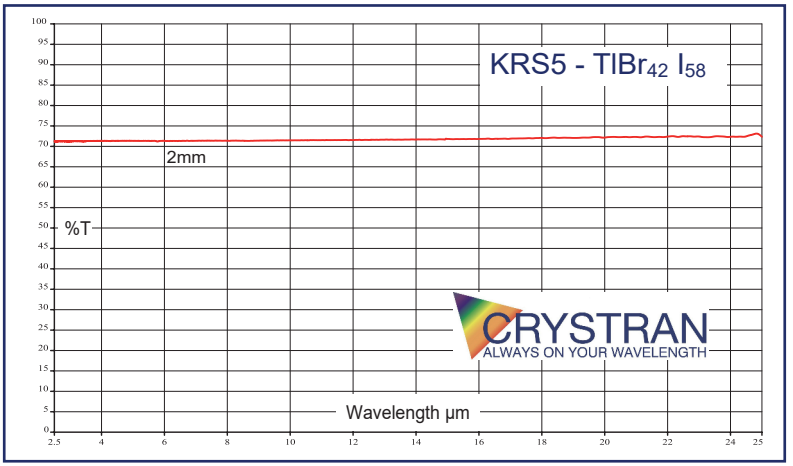
APPLICATIONS: KRS5 is a deep IR material with a high refractive index, KRS5 is used extensively in spectroscopy for ATR prisms, windows and lenses. In conjunction with Germanium, KRS5 can also be used in thermally compensated IR imaging systems.

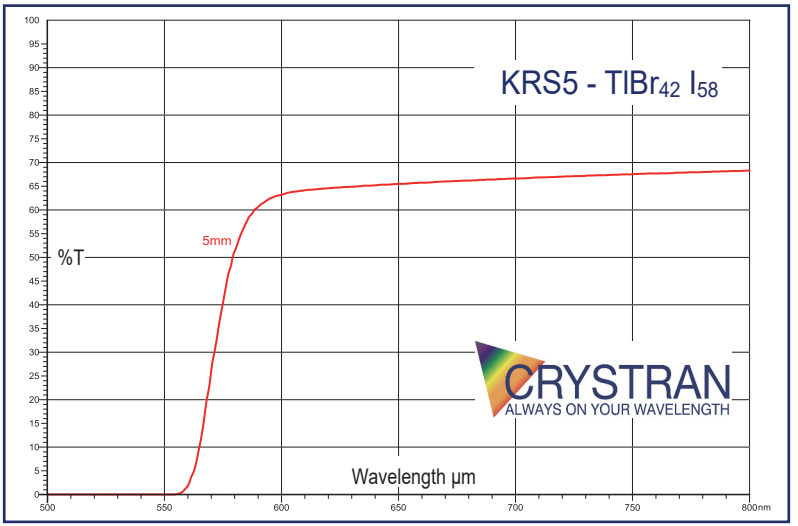
Transmission Range	0.6 to 40µm
Refractive Index	2.371 at 10µm (1) (3)
Reflection Loss	28.4% at 10µm (2 surfaces)
Absorption Coefficient	n/a
Reststrahlen Peak	n/a
dn/dT	$-235 \times 10^{-6}\ K^{-1}$
dn/dµ = 0	7µm
Density	7.371 g/cc (3)
Melting Point	414.5°C (3)
Thermal Conductivity	$0.544\ W\ m^{-1}\ K^{-1}$ at 293K
Thermal Expansion	$58 \times 10^{-6}\ K^{-1}$ (2)
Hardness	Knoop 40.2 (2)
Specific Heat Capacity	$200\ J\ Kg^{-1}\ K^{-1}$ at 273K
Dielectric Constant	32.5
Youngs Modulus (E)	15.85 GPa (2)
Shear Modulus (G)	5.79 GPa (2)
Bulk Modulus (K)	19.78 GPa (2)
Elastic Coefficients	C_{11}=331; C_{12}=13.2; C_{44}=5.79
Apparent Elastic Limit	26.2 MPa (2)
Poisson Ratio	0.369
Solubility	0.05g/100g water at 293K
Molecular Weight	42 mole% TlBr; 58 mole% TlI
Class/Structure	Cubic, CsCl structure, Pm3m, No cleavage (3)

(1) Rodney and Malitson J.Opt Soc.Am. V46, p 956, 1953
(2) Combes, Ballard, McCarthy: J.Opt Soc.Am. V41, p 215, 1951
(3) Handbook of Optical Constants, ed Palik, V3, ISBN 0-12-544423-0

KRS5 Thallium Bromo-Iodide (TlBr-TlI)

µm	No	µm	No	µm	No	µm	No
0.54	2.68059	10.0	2.37069	21.0	2.33643	32.0	2.27531
1.00	2.44620	11.0	2.36854	22.0	2.33206	33.0	2.26823
1.50	2.40774	12.0	2.36622	23.0	2.32746	34.0	2.26087
2.00	2.39498	13.0	2.36371	24.0	2.32264	35.0	2.25322
3.00	2.38574	14.0	2.36101	25.0	2.31758	36.0	2.24528
4.00	2.38204	15.0	2.3581	26.0	2.31229	37.0	2.23705
5.00	2.37979	16.0	2.35502	27.0	2.30676	38.0	2.22850
6.00	2.37797	17.0	2.35173	28.0	2.30098	39.0	2.21965
7.0	2.37627	18.0	2.34822	29.0	2.29495	40.0	2.21047
8.0	2.37452	19.0	2.34451	30.0	2.28867		
9.0	2.37267	20.0	2.34058	31.0	2.28212		





KRS6 Thallium Bromo-Chloride (TlBr-TlCl)

CAUTION: Thallium salts are considered TOXIC and should be handled with care.

KRS6 crystals are grown by the sealed-ampoule Stockbarger technique. Starting materials of the highest purity are selected to ensure that there are no anionic absorption bands between 2 and 16µms and all crystals are checked for quality by using a pathlength of 120mm. Thallium salts are toxic, and KRS6 has enough solubility to require extreme caution. Careful handling with plastic gloves covered with soft cotton gloves as appropriate to delicate optics is required.

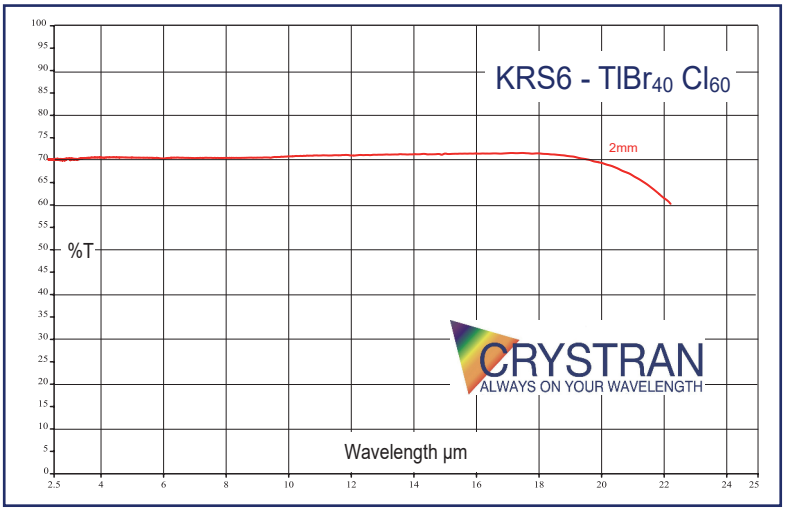
APPLICATIONS: KRS6 has only a few applications. Occasionally, it is required for research.

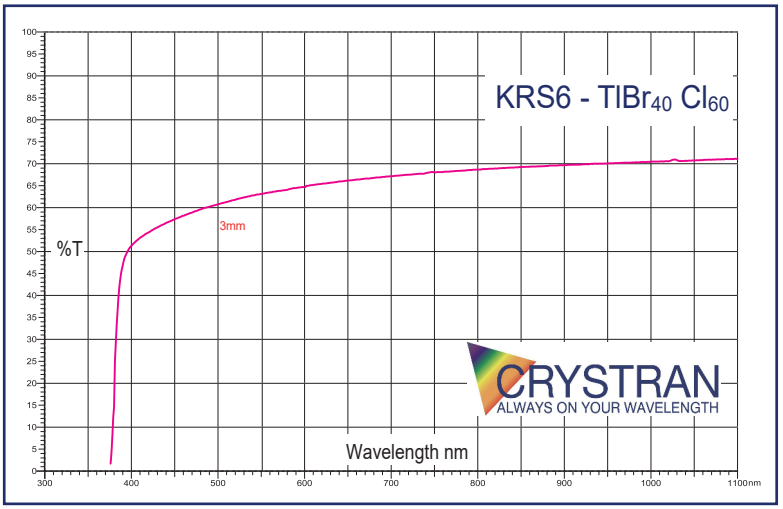
Transmission Range	0.4 to 25µm
Refractive Index	2.1723 at 11µm (1)
Reflection Loss	24.0% at 11µm (2 surfaces)
Absorption Coefficient	n/a
Reststrahlen Peak	91.5µm
dn/dT	n/a
dn/dµ = 0	5µm
Density	7.18 g/cc (3)
Melting Point	423°C (3)
Thermal Conductivity	0.7 W m^{-1} K^{-1} at 329°K
Thermal Expansion	50 x 10^{-6} K^{-1} (2)
Hardness	Knoop 29.9 with 500g indenter (2)
Specific Heat Capacity	188 J Kg^{-1} K^{-1}
Dielectric Constant	32 at 1 MHz
Youngs Modulus (E)	20.68 GPa (2)
Shear Modulus (G)	8.48 GPa (2)
Bulk Modulus (K)	22.81 GPa (2)
Elastic Coefficients	C_{11}=38.5; C_{12}=14.9; C_{44}=7.37
Apparent Elastic Limit	20.7 MPa (3000 psi)
Poisson Ratio	0.219
Solubility	0.3g/100g water at 20°C
Molecular Weight	40 mole% TlBr; 60 mole% TlCl
Class/Structure	Cubic, CsCl structure, Pm3m, no cleavage planes

(1) Hettner and Leisegang; Optik, V3, p305, 1948
(2) Combes, Ballard, McCarthy: J.Opt Soc.Am. V41, p 215, 1951
(3) Handbook of Optical Constants, ed Palik, V3, ISBN 0-12-544423-0

KRS6 Thallium Bromo-Chloride (TlBr-TlCl)

µm	No	µm	No	µm	No	µm	No
0.6	2.3294	4.0	2.1956	12.0	2.1674	20.0	2.1154
0.7	2.2982	5.0	2.1928	13.0	2.162	21.0	2.1067
0.8	2.2660	6.0	2.190	14.0	2.1563	22.0	2.0976
0.9	2.251	7.0	2.187	15.0	2.1504	23.0	2.0869
1.0	2.2404	8.0	2.1839	16.0	2.1442	24.0	2.0752
1.5	2.2148	9.0	2.1805	17.0	2.1377		
2.0	2.2059	10.0	2.1767	18.0	2.1309		
3.0	2.199	11.0	2.1723	19.0	2.1236		





Lanthanum Fluoride (LaF_3)

Lanthanum Fluoride is grown as small ingots of about 10mm diameter as it is difficult to anneal. Doped with Europium, it is a pale yellow colour.

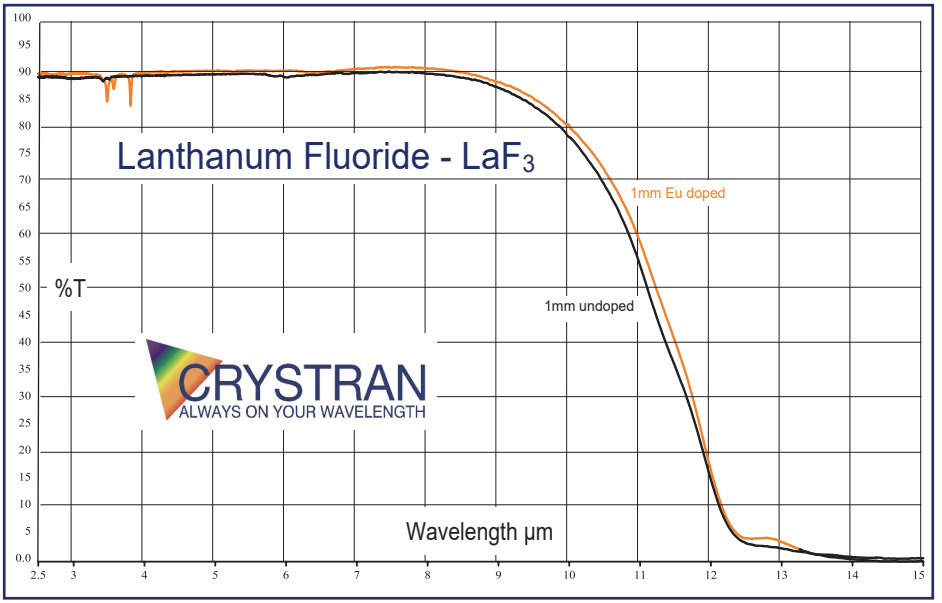
APPLICATIONS: Lanthanum Fluoride is not often used as an optical material. Lanthanum Fluoride is usually doped with Europium at a nominal level of 0.3% mole. In this form, the usual application is as the active element in an ion-selective electrode for the detection and measurement of Fluoride ions in solution. Use the QR link on page 30 for application notes on ion-selective electrodes.

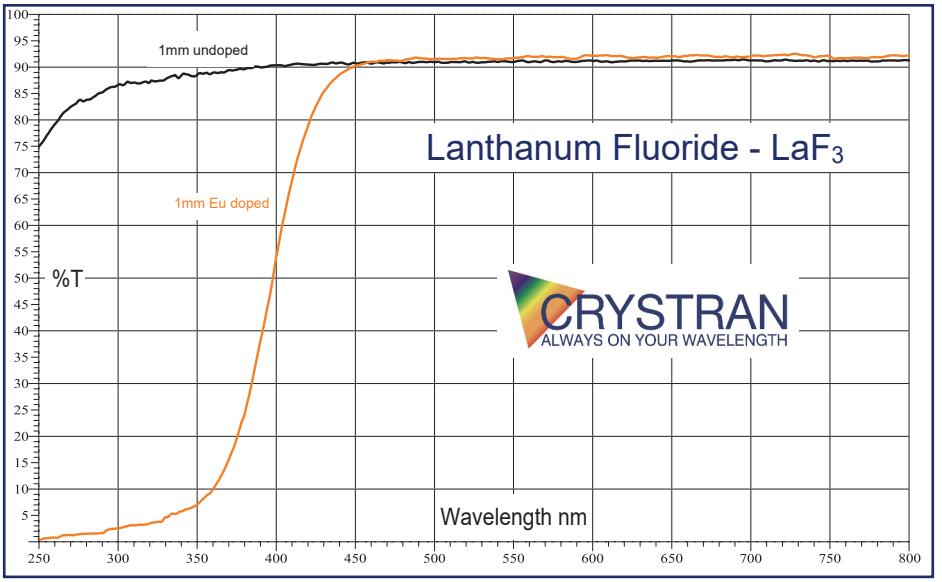
Transmission Range	0.2 to 11µm
Refractive Index	No 1.506 at 0.55µm
Reflection Loss	10.3% at 0.55µm
Absorption Coefficient	n/a
Reststrahlen Peak	n/a
dn/dT	n/a
dn/dµ = 0	n/a
Density	5.94 g/cc
Melting Point	1493 °C (1)
Thermal Conductivity	5.1 W m^{-1} K^{-1} at 300K
Thermal Expansion	11.0x10^{-6} (para) 15.8x10^{-6} /K(perp) at 298K (2)
Hardness	Moh 4.5
Specific Heat Capacity	506 J Kg^{-1} K^{-1}
Dielectric Constant	14 (3)
Youngs Modulus (E)	n/a
Shear Modulus (G)	n/a
Bulk Modulus (K)	n/a
Elastic Coefficients	n/a
Apparent Elastic Limit	n/a
Poisson Ratio	n/a
Solubility	Insoluble in water
Molecular Weight	195.9
Class/Structure	Trigonal (hex), $P6_3/mcm$ (2), no cleavage

1) Jones and Shand, J.Crys.Growth. **2** (1968) p361
(2) Sher, Solomon, Lee, and Meuller. Phys.Rev. **144**, p593 (1966)
(3) Electronic Processes in Ionic Crystals (OU Press, NY, 1940) p.41.

Lanthanum Fluoride (LaF_3)

µm	No	Ne	µm	No	Ne	µm	No	Ne
0.254	1.656	1.649	0.436	1.617	1.609			
0.405	1.618	1.612	0.547	1.606	1.602			





Lead Fluoride (PbF_2)

CAUTION: Lead salts are considered TOXIC and should be handled with care.

Lead fluoride has been grown by vacuum Stockbarger, but is not known to be in regular production.

APPLICATIONS: Lead Fluoride has little optical application. Lead Fluoride has been used as a scintillator material as it has excellent stopping power for gamma rays.

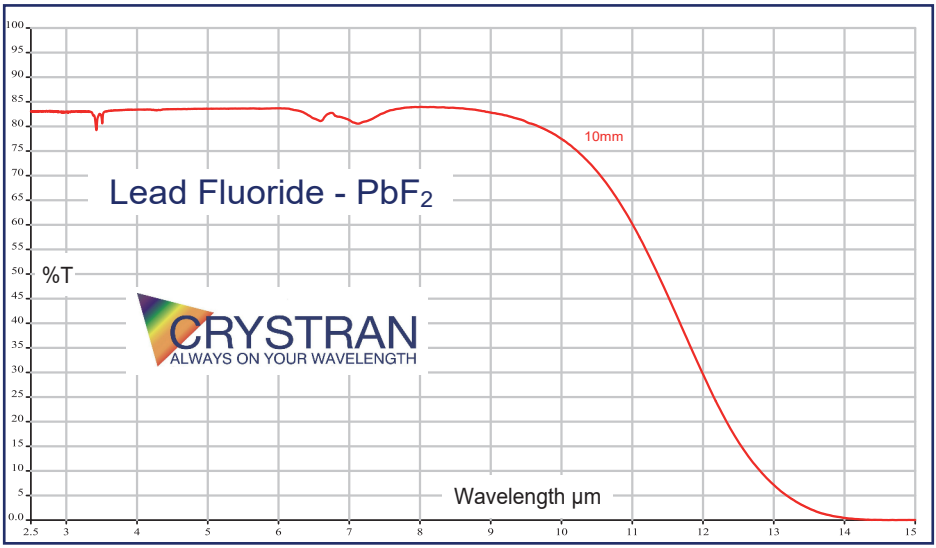
Transmission Range	250nm to 11µm
Refractive Index	1.7808 @ 5µm
Reflection Loss	12.8% @ 5µm (2 surfaces)
Absorption Coefficient	0.018 cm^{-1} @ 4µm
Reststrahlen Peak	n/a
dn/dT	n/a
dn/dµ = 0	3.3µm
Density	7.77 g cm^{-3} (1)
Melting Point	855°C
Thermal Conductivity	n/a
Thermal Expansion	29 x 10^{-6} K^{-1} @ 283K
Hardness	Knoop 200
Specific Heat Capacity	301 J Kg^{-1} K^{-1}
Dielectric Constant	13 @ 1MHz
Youngs Modulus (E)	n/a
Shear Modulus (G)	n/a
Bulk Modulus (K)	n/a
Elastic Coefficients	C_{11}=91, C_{12}=46, C_{44}=23
Apparent Elastic Limit	n/a
Poisson Ratio	n/a
Solubility	0.064 g/100g water at 20°C
Molecular Weight	245.21
Class/Structure	Cubic, CaF2, Fm3m, (111) cleavage

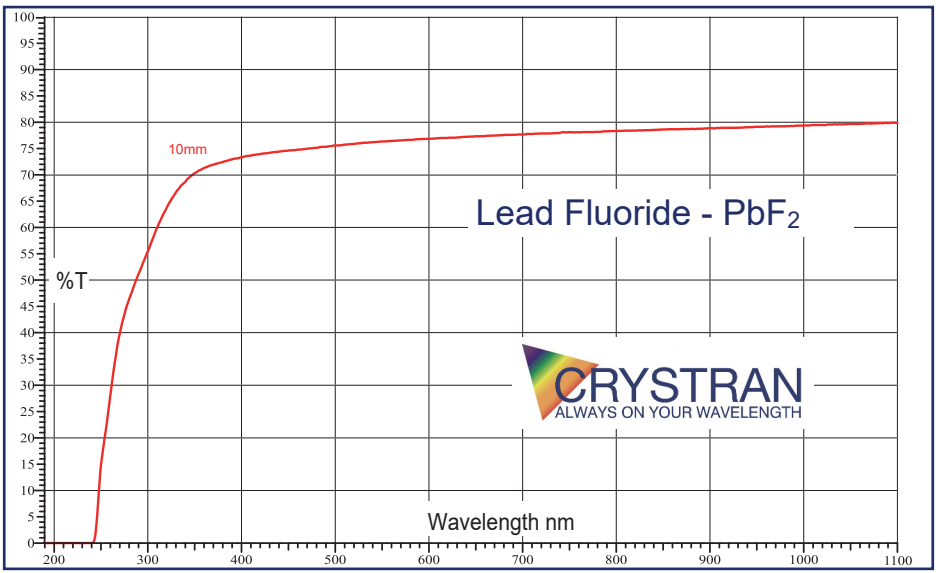
Crystran does not hold stock of this material. This is for information only purposes

(1) Crystran Data

Lead Fluoride (PbF_2)

µm	No	µm	No	µm	No	µm	No
0.3	1.93665	0.6	1.76489	0.9	1.74455	5.0	1.70805
0.4	1.81804	0.7	1.75502	1.0	1.74150	7.0	1.68544
0.5	1.78220	0.8	1.74879	3.0	1.72363	9.0	1.65504





Lithium Fluoride (LiF)

Lithium Fluoride is grown by vacuum Stockbarger technique in ingots approximately 100mm diameter. Lithium Fluoride cleaves easily and must be worked with extreme care. Polishing, particularly steep radii, often causes surface "rip-out".

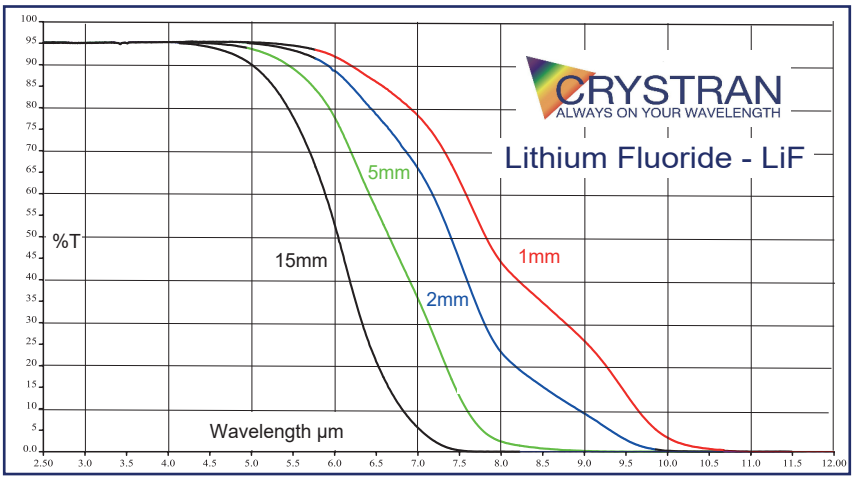
APPLICATIONS: Lithium fluoride is the material with the most extreme UV transmission of all and is used for special UV optics. Lithium fluoride transmits well into the VUV region at the hydrogen Lyman-alpha line (121nm) and beyond. Lithium fluoride is also used for X-ray monochromator plates where its lattice spacing makes it the most useful analysis crystal.

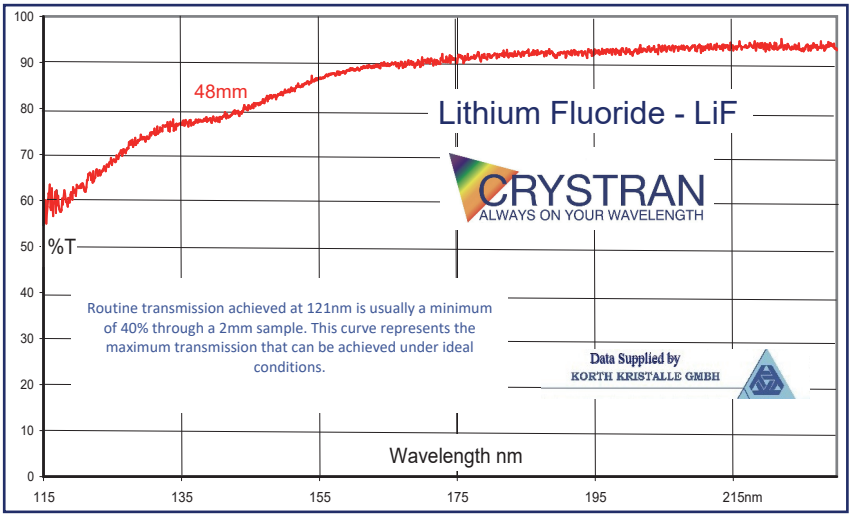
Transmission Range	0.12 to 6µm
Refractive Index	1.392 at 0.6µm (1)
Reflection Loss	5.2% at 0.6µm (2 Surfaces)
Absorption Coefficient	5.9×10^{-3} cm^{-1}at 4.3µm @ 300K (5)
Reststrahlen Peak	25µm
dn/dT	-16×10^{-6} at 1.15µm
dn/dµ = 0	1.3µm
Density	2.639 g/cc
Melting Point	848 °C (6)
Thermal Conductivity	11.3 W m^{-1} K^{-1} at 314 K (2)
Thermal Expansion	37×10^{-6} K^{-1} at 283 K (2)
Hardness	Knoop 102 with 600g indenter (2)
Specific Heat Capacity	1562 J Kg^{-1} K^{-1}
Dielectric Constant	0.1
Youngs Modulus (E)	64.97 GPa (2)
Shear Modulus (G)	55.14 GPa (2)
Bulk Modulus (K)	62.03 GPa (2)
Elastic Coefficients	C_{11}=112; C_{12}=46; C_{44}=63.5 (3)
Apparent Elastic Limit	11.2 MPa (1620 psi) (4)
Poisson Ratio	0.326 (calculated)
Solubility	0.27g / 100g water at 20 °C
Molecular Weight	25.94
Class/Structure	Cubic FCC, Fm3m (#221), NaCl Structure (100) cleavage

(1) Laporte et. al. J.Opt. Soc. Am. V73, No 8, p1062
(2) Combes et. al. J.Opt. Soc. Am. V41, p215. 1951
(3) Huntingdon, Phys Review. V72, p321, 1947
(4) Ballard et. al. J.Opt. Soc. Am. V42, p684. 1952
(5) H.H.Li, Absorption Coefficients, Int.J.Therm, V1, No. I, 1980
(6) T.B.Douglas & J.L.Dever, J. Am. Chem.Soc, 1954,76 (19), p4826

Lithium Fluoride (LiF)

µm	No	µm	No	µm	No	µm	No	µm	No
0.106	1.9130	0.19	1.4455	0.32	1.4060	0.9	1.3880	5.1	1.3240
0.108	1.8330	0.2	1.4391	0.33	1.4048	1.0	1.3871	5.2	1.3213
0.11	1.7770	0.22	1.4291	0.34	1.4037	1.5	1.3832	5.3	1.3186
0.121	1.6240	0.25	1.4189	0.35	1.4028	2.0	1.3788	5.4	1.3158
0.13	1.5690	0.26	1.4164	0.36	1.4019	2.5	1.3732	5.5	1.3129
0.14	1.5300	0.27	1.4141	0.4	1.3989	3.0	1.3666	5.6	1.3099
0.15	1.5030	0.28	1.4121	0.5	1.3943	3.5	1.3587	5.7	1.3069
0.16	1.4840	0.29	1.4103	0.6	1.3918	4.0	1.3494	5.8	1.3038
0.17	1.4690	0.3	1.4087	0.7	1.3902	4.5	1.3388	5.9	1.3007
0.18	1.4850	0.31	1.4073	0.8	1.3890	5.0	1.3266	6.0	1.2975





Magnesium Fluoride (MgF_2)

Magnesium Fluoride is grown by vacuum Stockbarger technique in ingots of various diameters. Magnesium Fluoride is a tough material and polishes well. Therefore, it can be worked to the highest standards. MgF2 is slightly birefringent and usually supplied with the optic axis cut perpendicular to the window faces.

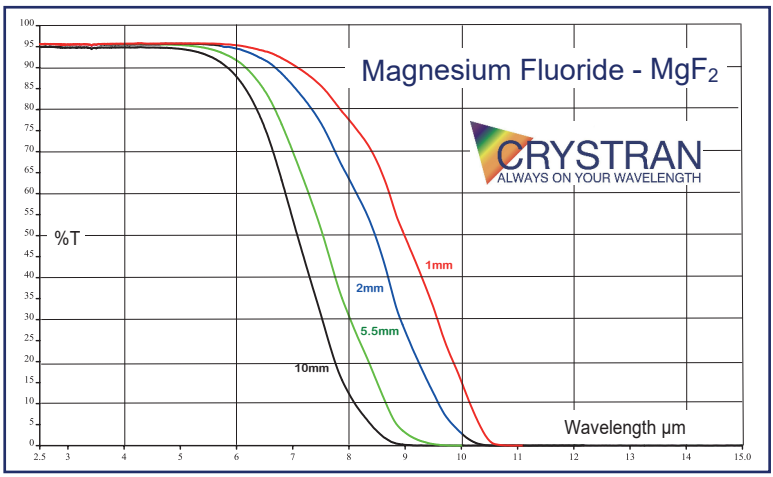
APPLICATIONS: Magnesium Fluoride transmits well into the VUV region to the hydrogen Lyman-alpha line (121nm) and beyond. Magnesium Fluoride is used mostly for UV optics and is excellent for Excimer laser applications.

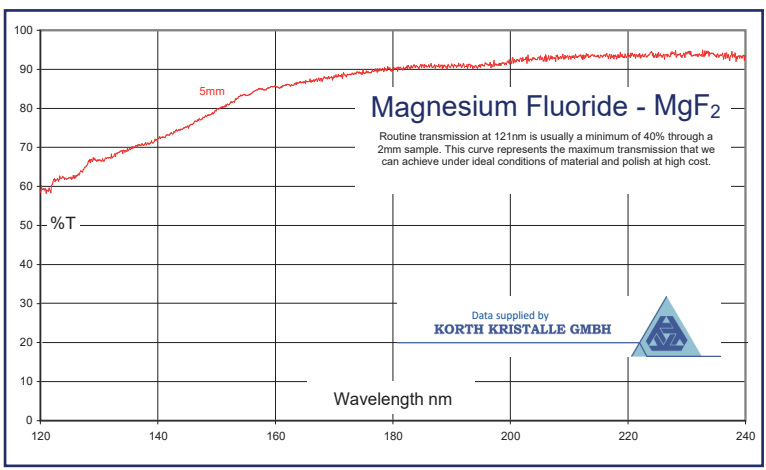
Transmission Range	0.12 to 7µm(1)
Refractive Index	No 1.413 at 0.22µm (4)
Reflection Loss	5.7% at 0.22µm (2 surfaces)
Absorption Coefficient	5.5×10^{-3} cm^{-1} at 2.8µm (5)
Reststrahlen Peak	20µm (1)
dn/dT	2.3 (para) 1.7 (perp) at 0.4µm (1)
dn/dµ = 0	1.4µms
Density	3.1766g/cc at 25°C
Melting Point	1255°C
Thermal Conductivity	21 (para) 33.6 (perp) W m^{-1} K^{-1} at 300K (3)
Thermal Expansion	13.7 (para) 8.9 (perp) x 10^{-6} /K (1)
Hardness	Knoop 415
Specific Heat Capacity	1003 J Kg m^{-1} K^{-1}
Dielectric Constant	4.87 (para) 5.45 (perp) at 1MHz (1)
Youngs Modulus (E)	138 GPa (2)
Shear Modulus (G)	54.66GPa (2)
Bulk Modulus (K)	101.32 GPa (2)
Elastic Coefficients	C_{11}=140 C_{12}=89 C_{44}=57 C_{13}=63 C_{66}=96 (2)
Apparent Elastic Limit	49.6 MPa (7200 psi)
Poisson Ratio	0.276 (2)
Solubility	0.0002g/100g water
Molecular Weight	62.32
Class/Structure	Tetragonal P42/mnm (#136) Rutile Structure. Can cleave on c-axis but not easily.

(1) Duncanson et.al. Proc.Phys.Soc. V72, p1001, 1958
(2) Kandil et.al. J.App.Phys. V52, p749, 1981
(3) Kashnow & MCarthy, J.Phys.Chem. V30, p813, 1969
(4) Laporte et. al. J.Opt. Soc. Am. V73, No 8, p1062
(5) Corning Inc published data

Magnesium Fluoride (MgF_2)

µm	No	Ne	µm	No	Ne	µm	No	Ne
0.1146	1.7530	1.7295	0.190	1.431	1.444	0.546	1.379	1.390
0.1149	1.7420	1.7215	0.2	1.423	1.437	0.7	1.376	1.388
0.1156	1.7235	1.7080	0.220	1.413	1.426	1.087	1.373	1.385
0.1168	1.7000	1.6905	0.248	1.403	1.416	1.512	1.370	1.382
0.1179	1.6800	1.675	0.257	1.401	1.414	2.0	1.368	1.379
0.1198	1.6510	1.652	0.266	1.399	1.412	2.5	1.364	1.375
0.1215	1.628	1.632	0.280	1.396	1.409	3.030	1.360	1.370
0.130	1.566	1.568	0.3	1.393	1.405	3.571	1.354	1.364
0.140	1.5095	1.523	0.330	1.389	1.402	4.0	1.349	1.359
0.150	1.480	1.494	0.337	1.389	1.401	4.546	1.341	1.350
0.160	1.461	1.475	0.350	1.387	1.400	5.0	1.334	1.343
0.170	1.448	1.462	0.355	1.386	1.399	5.556	1.324	1.332
0.180	1.439	1.453	0.4	1.384	1.396	6.060	1.314	1.321





Magnesium Oxide (MgO)

Magnesium Oxide is grown in relatively small sizes, mainly in Japan and China.

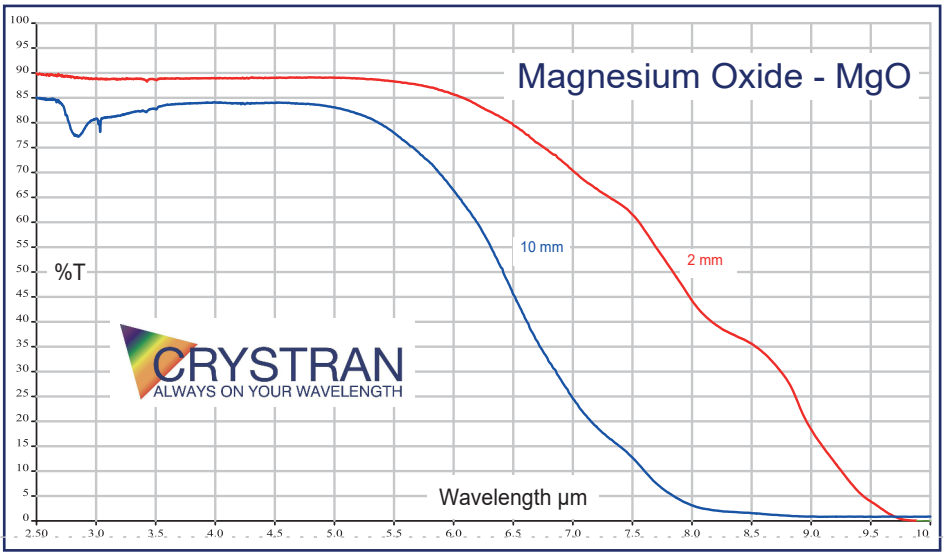
APPLICATIONS: Magnesium Oxide can be used for high temperature windows and substrates. HTSC substrates.

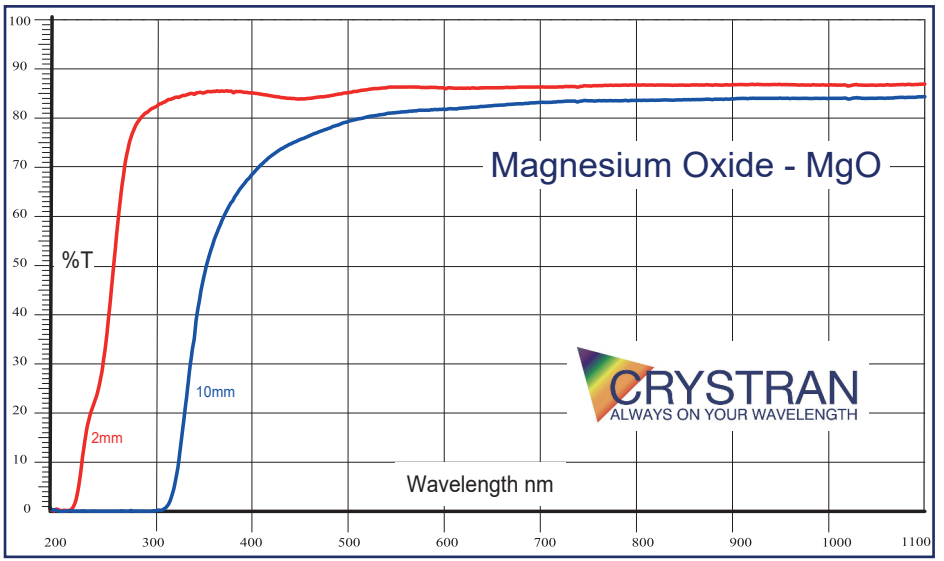
Transmission Range	0.3 to 6µm
Refractive Index	1.7085 at 2µm (1)
Reflection Loss	12.8% at 2µm (2 surfaces)
Absorption Coefficient	0.05 cm^{-1} at 5.5µm
Reststrahlen Peak	n/a
dn/dT	+19 x 10^{-6} K^{-1}
dn/dµ = 0	n/a
Density	3.58 g/cc
Melting Point	2800 °C
Thermal Conductivity	42 W m^{-1} K^{-1} at 273K
Thermal Expansion	10.8 x 10^{-6} K^{-1} at 273K
Hardness	Knoop 692 with 600g indenter
Specific Heat Capacity	877 J Kg^{-1} K^{-1}
Dielectric Constant	9.65 at 1 MHz
Youngs Modulus (E)	249 GPa
Shear Modulus (G)	155 GPa
Bulk Modulus (K)	155 GPa
Elastic Coefficients	C_{11}=294; C_{12}=93; C_{44}=155
Apparent Elastic Limit	138 MPa (20,000 psi)
Poisson Ratio	0.18
Solubility	0.00062g / 100g water
Molecular Weight	40.32
Class/Structure	Cubic FCC, NaCl, Fm3m, (100) cleavage

(1) Handbook of Optical constants of Solids II ISBN 0-12-544422-2

Magnesium Oxide (MgO)

µm	No	µm	No	µm	No	µm	No	µm	No
0.171	2.319	0.276	1.824	0.644	1.734	5.00	1.6373	10.64	1.209
0.180	2.138	0.310	1.795	1.00	1.7229	6.02	1.5957		
0.191	2.039	0.382	1.7668	2.00	1.7085	7.04	1.543		
0.200	1.986	0.436	1.7547	3.00	1.6915	8.07	1.475		
0.230	1.892	0.50	1.754	4.00	1.6679	9.09	1.389		

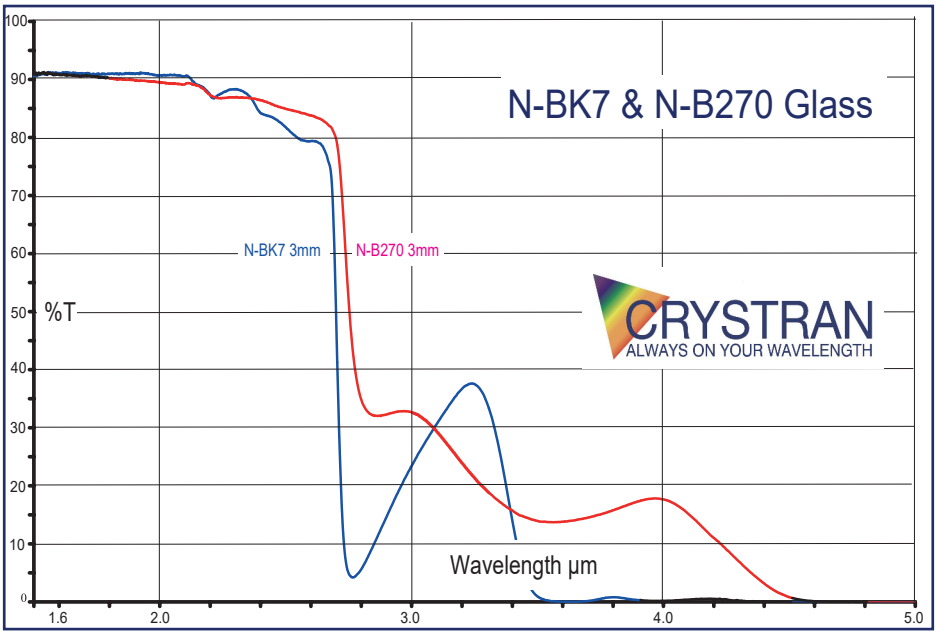


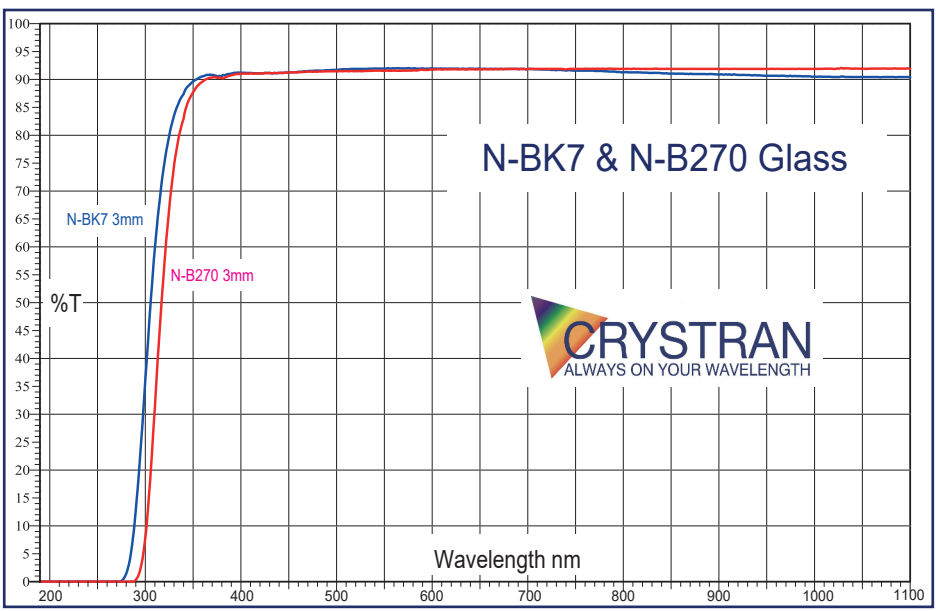


Optical Glass (N-BK7 types)

APPLICATIONS: N-BK7 is a Schott™ designation for the most common Borosilicate Crown glass used for a wide variety of visible applications. The basic data here is given for N-BK7. We recommend that full optical design data on N-BK7 and other glasses be found by referring to the relevant glass manufacturer.

Transmission Range	350nm to 2.5µm
Refractive Index	1.51680 @ 587.5618nm (Yellow Helium Line)
Reflection Loss	8.1% at 587.5618nm (2 surfaces)
Absorption Coefficient	n/a
Reststrahlen Peak	n/a
dn/dT	n/a
$dn/d\mu = 0$	n/a
Density	2.51 g/cc
Melting Point	557°C (Transformation Temperature)
Thermal Conductivity	1.114 W m^{-1} K^{-1}
Thermal Expansion	7.1 x 10^{-6} K^{-1}
Hardness	Knoop 610
Specific Heat Capacity	858 J Kg^{-1} K^{-1}
Dielectric Constant	n/a
Youngs Modulus (E)	82 GPa
Shear Modulus (G)	n/a
Bulk Modulus (K)	34 GPa
Elastic Coefficients	n/a
Apparent Elastic Limit	63.5MPa (9206psi)
Poisson Ratio	0.206
Solubility	Insoluble in water
Molecular Weight	n/a
Class/Structure	Amorphous glass


N-BK7 & N-B270 Glass
N-BK7 3mm
N-B270 3mm
%T
CRYSTRAN
ALWAYS ON YOUR WAVELENGTH
Wavelength µm
100
90
80
70
60
50
40
30
20
10
0
1.6
2.0
3.0
4.0
5.0


N-BK7 & N-B270 Glass
N-BK7 3mm
N-B270 3mm
%T
CRYSTRAN
ALWAYS ON YOUR WAVELENGTH
Wavelength nm
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
200
300
400
500
600
700
800
900
1000
1100

Potassium Bromide (KBr)

Potassium Bromide is produced in large ingots by the Kyropoulos growth method. Potassium Bromide cleaves easily. With care Potassium Bromide can be polished to a high standard under humidity controlled conditions. Polymer coating can be applied.

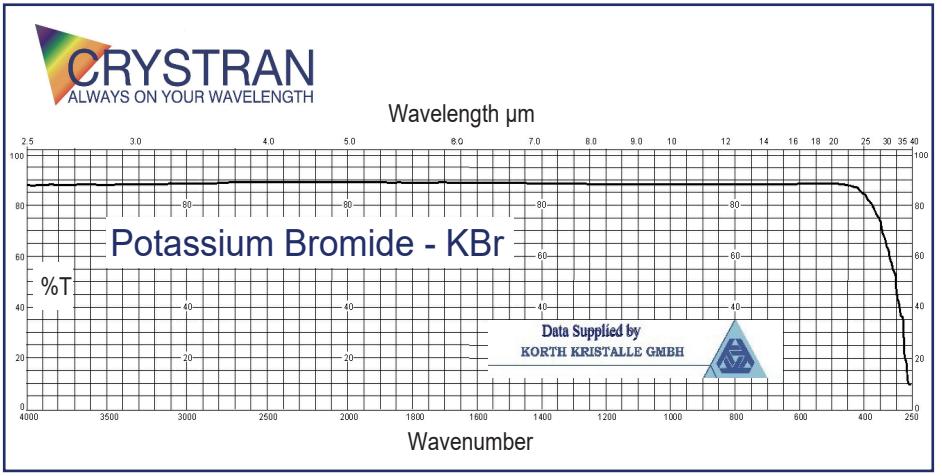
APPLICATIONS: Potassium Bromide is one of the most useful materials for general purpose spectroscopic windows and applications where sensitivity to moisture is unimportant. Potassium Bromide is the most commonly used beamsplitter material for IR spectrophotometers. It can be supplied with a conformal polymer coating to give some protection against atmospheric humidity.

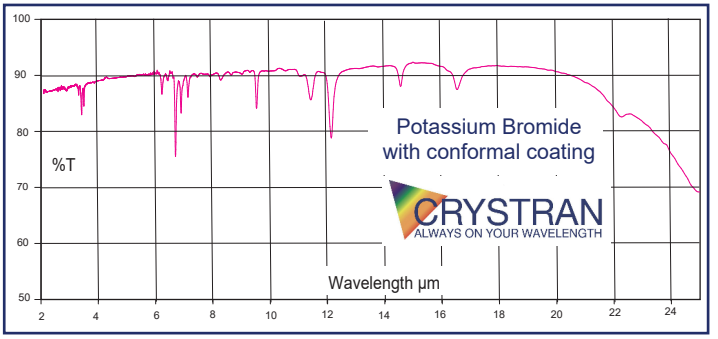
Transmission Range	0.23 to 25µm
Refractive Index	1.527 at 10µm (1)
Reflection Loss	8.3% at 10µm
Absorption Coefficient	3×10^{-6} @ 1064nm : 14×10^{-6} cm^{-1} @ 10.6 (7)
Reststrahlen Peak	77.6µm
dn/dT	-40.83×10^{-6} K^{-1} (1)
$dn/d\mu = 0$	4.2µm
Density	2.753 g/cc (2)
Melting Point	730°C
Thermal Conductivity	4.816 W m^{-1} K^{-1} @ 319K (3)
Thermal Expansion	43×10^{-6} K^{-1} @300K (4)
Hardness	Knoop 7 in <100> with 200g indenter (4)
Specific Heat Capacity	435 J Kg^{-1} K^{-1}
Dielectric Constant	4.9 @ 1MHz (6)
Youngs Modulus (E)	26.8 GPa (4)
Shear Modulus (G)	5.08 GPa (4)
Bulk Modulus (K)	15.03 GPa (4)
Elastic Coefficients	C_{11}=34.5 C_{12}=5.4 C_{44}=5.08 (5)
Rupture Modulus	3.3 MPa (475psi) (4)
Poisson Ratio	0.203
Solubility	53.48g/100g water at 273K
Molecular Weight	119.01
Class/Structure	Cubic FCC, NaCl, Fm3m, (100) cleavage

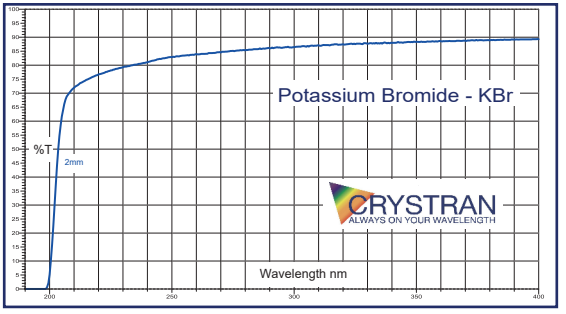
(1) Stephens et. al.; J.Opt. Soc. Am. V43, p111, 1953
(2) Kohler; Z. Physik. Volk 78, p375. 1932
(3) Ballard, McCarthy & Davis; Rev. Sci. Insts, V21, p905, 1970
(4) Combes, et.al.; J.Opt. Soc. Am. V41, p215, 1951.
(5) Huntingdon; Phys.Rev. V72, p321, 1947
(6) Hipple; Dielectric Materials & Applications. Wiley
(7) H.H.Li, Absorption Coefficients, Int.J.Therm, V1, No. I, 1980

Potassium Bromide (KBr)

µm	No	µm	No	µm	No	µm	No	µm	No
0.405	1.5898	0.587	1.5600	3.419	1.5361	11.04	1.5240	25.14	1.4632
0.436	1.5815	0.643	1.5559	4.258	1.5352	14.29	1.5150	28.00	1.4423
0.486	1.5718	0.707	1.5524	6.238	1.5329	17.40	1.5039	30.00	1.4253
0.508	1.5684	1.014	1.5441	8.662	1.5290	19.91	1.4929		
0.546	1.5639	2.440	1.5373	9.724	1.5270	23.86	1.4714		







Potassium Chloride (KCl)

Potassium Chloride is produced in large ingots by the Kyropoulos growth method. Potassium Chloride cleaves easily. With care Potassium Chloride can be polished to a high standard under humidity controlled conditions.

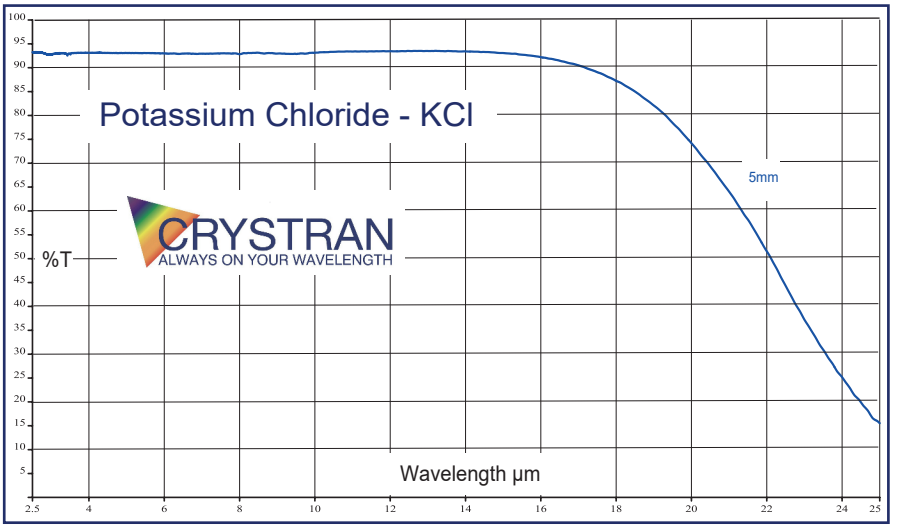
APPLICATIONS: Potassium Chloride is mainly used for CO2 laser protection windows as an inexpensive disposable material with a low refractive index.

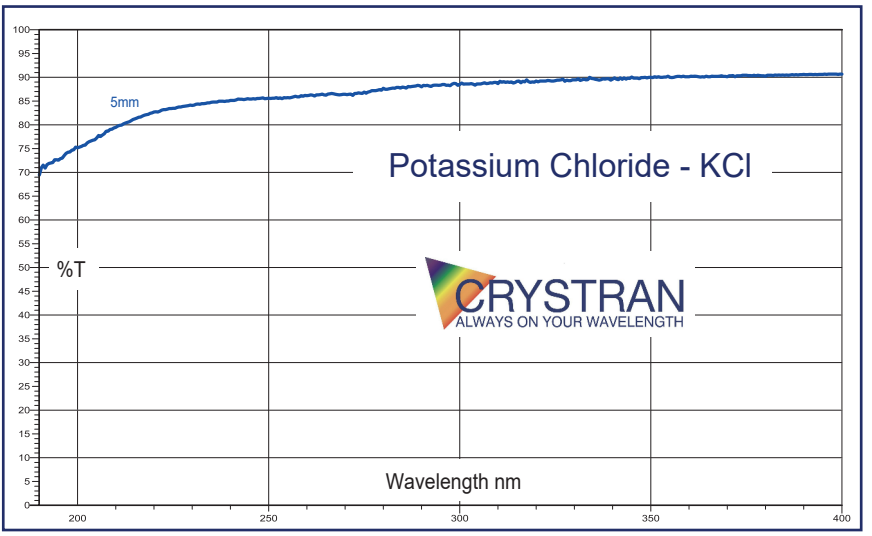
Transmission Range	0.21 to 20µm
Refractive Index	1.45644 at 10µm (2)
Reflection Loss	6.7% at 10µm
Absorption Coefficient	6.5×10^{-3} cm^{-3} at 10.6µm @ 300K (6)
Reststrahlen Peak	63.1µm
dn/dT	-33.2×10^{-6} K^{-1} (1)
dn/dµ = 0	n/a
Density	1.99 g/cc
Melting Point	776°C
Thermal Conductivity	6.53 W m^{-1} K^{-1} at 322K (3)
Thermal Expansion	36×10^{-6} K^{-1} at 300k
Hardness	Knoop 7.2 <110>, 9.3 <100> with 200g (4)
Specific Heat Capacity	690 J Kg^{-1} K^{-1}
Dielectric Constant	4.64 at 1MHz at 300K
Youngs Modulus (E)	29.67 GPa (4)
Shear Modulus (G)	6.24 GPa (4)
Bulk Modulus (K)	17.36 GPa (4)
Elastic Coefficients	C_{11}=39.8; C_{12}=6.2; C_{44}=6.25 (5)
Rupture Modulus	4.4 MPa (635 psi) (4)
Poisson Ratio	0.216
Solubility	34.7g/100g water
Molecular Weight	74.55
Class/Structure	Cubic FCC, NaCl, Fm3m, (100) cleavage

(1) Mentzel; Z. Physik. V 88, p178. 1934
(2) H.H.Li; RI of Alkali Halides. J. Phys and Chem Reference Data V5(2), p421, 1976
(3) Ballard, McCarthy & Davis; Rev. Sci. Insts, V21, p905, 1970
(4) Combes, et.al.; J.Opt. Soc. Am. V41, p215, 1951.
(5) Galt; Phys.Rev. V36, p1460, 1948
(6) H.H.Li, Absorption Coefficients, Int.J.Therm, V1, No. I, 1980

Potassium Chloride (KCl)

µm	No	µm	No	µm	No	µm	No	µm	No
0.185	1.8271	0.982	1.4800	7.0	1.466	15.0	1.43197	23.0	1.36461
0.20	1.7187	1.179	1.47831	8.0	1.4629	16.0	1.42563	24.0	1.35303
0.251	1.5897	2.357	1.47475	9.0	1.46002	17.0	1.41877	25.0	1.34059
0.308	1.54136	2.947	1.47383	10.0	1.45644	18.0	1.41134	26.0	1.32721
0.410	1.50907	3.536	1.47305	11.0	1.45244	19.0	1.40333	27.0	1.31281
0.509	1.4962	4.715	1.47112	12.0	1.44801	20.0	1.39469	28.0	1.29731
0.671	1.48669	5.0	1.47048	13.0	1.44313	21.0	1.38538		
0.883	1.48142	6.0	1.46842	14.0	1.43779	22.0	1.37537		





Potassium Iodide (KI)

Potassium Iodide is produced in large ingots by the Kyropoulos growth method. Potassium Iodide cleaves easily. Potassium Iodide is only useful in controlled laboratory conditions as it is very soft and very water soluble.

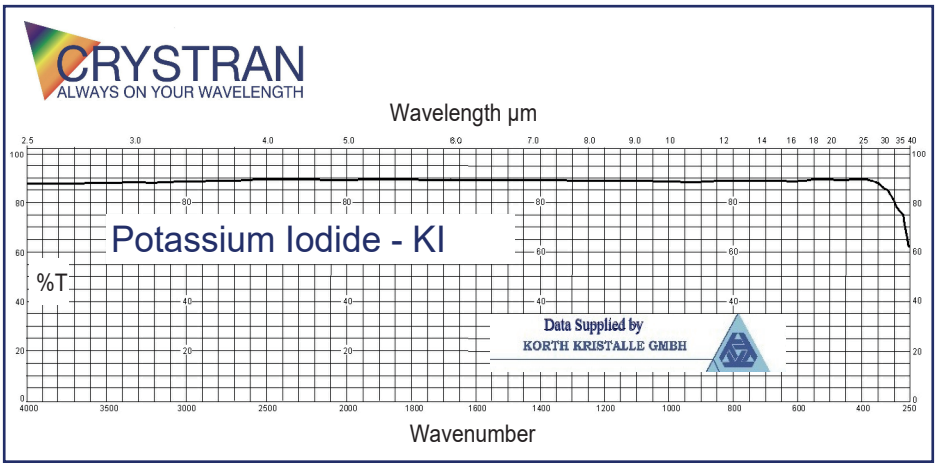
APPLICATIONS: Potassium Iodide has few specific applications but has some uses in the very deep Infra Red.

Transmission Range	0.38 to 35µm
Refractive Index	1.6201 at 10µm (1)
Reflection Loss	10.6% at 10µm (2 surfaces)
Absorption Coefficient	4.5×10^{-3} @ 20µm (2)
Reststrahlen Peak	82 to 100µm
dn/dT	-50×10^{-6} K^{-1}
dn/dµ = 0	2.1µm
Density	3.12 g/cc
Melting Point	682°C
Thermal Conductivity	2.1 W m^{-1} K^{-1} at 298K
Thermal Expansion	43×10^{-6} K^{-1} at 298K
Hardness	Moh 5
Specific Heat Capacity	313 J Kg^{-1} K^{-1}
Dielectric Constant	4.94 at 2 MHz
Youngs Modulus (E)	31.49 GPa
Shear Modulus (G)	6.2 GPa
Bulk Modulus (K)	12 GPa
Elastic Coefficients	C_{11}=27.4; C_{12}=4.3; C_{44}=3.7
Apparent Elastic Limit	n/a
Poisson Ratio	n/a
Solubility	127.5g/100g water at 273K
Molecular Weight	166.02
Class/Structure	Cubic FCC, NaCl, Fm3m, (100) cleavage

(1) K.Korth, Z.Physik. Vol 84, p677-685 (1933)
(2) H.H.Li, Absorption Coefficients, Int.J.Therm, V1, No. I, 1980

Potassium Iodide (KI)

µm	No	µm	No	µm	No	µm	No	µm	No
0.302	1.82769	3.540	1.6275	11.79	1.6172	20.0	1.5964	26.0	1.5729
0.405	1.71843	4.130	1.6268	12.97	1.615	21.0	1.593	27.0	1.5681
0.546	1.67310	5.890	1.6252	14.14	1.6127	22.0	1.5895	28.0	1.5629
0.768	1.6494	7.660	1.6235	15.91	1.6085	23.0	1.5858	29.0	1.5571
1.014	1.6396	8.840	1.6218	18.10	1.603	24.0	1.5819		
2.360	1.6295	10.02	1.6201	19.0	1.5997	25.0	1.5775		



Quartz Crystal (SiO_2)

Quartz is mined naturally, but more commonly produced synthetically in large, long-faceted crystals. Quartz is positive birefringent. Be careful not to confuse terminology in this material, as "Fused Quartz" is often used to denote the glassy non-crystalline form better known as Silica. Normal Quartz is Alpha Quartz and normally RH rotating. LH rotating is available on special order. At temperatures >490°C, Crystal Quartz starts to revert to glassy state, a process which is complete by 530°C.

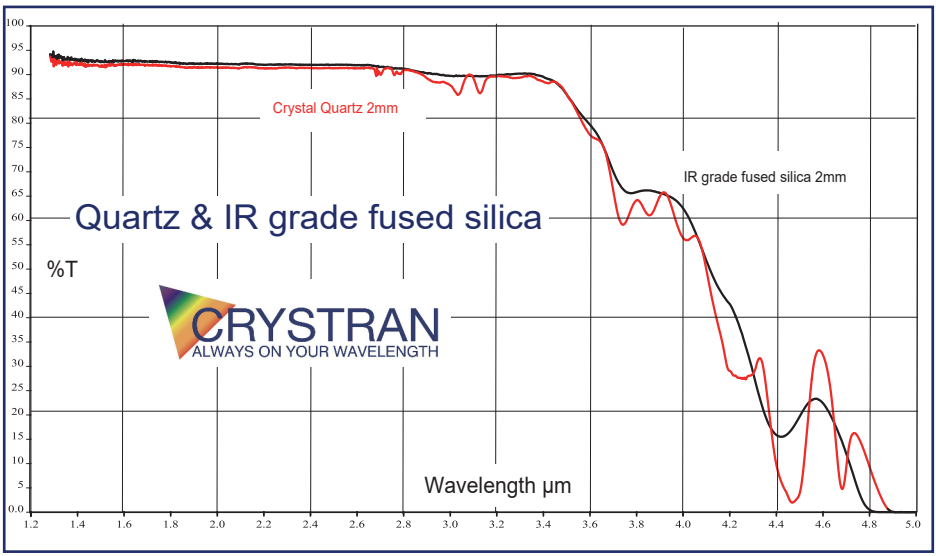
APPLICATIONS: Optically, Crystalline Quartz is used extensively as a wave retardation medium. The birefringent properties of Quartz are of use in quarter-wave plates and in polarisers. Quartz should not be processed or used at temperatures greater than 490°C. Use the QR link on page 30 for notes on quartz .

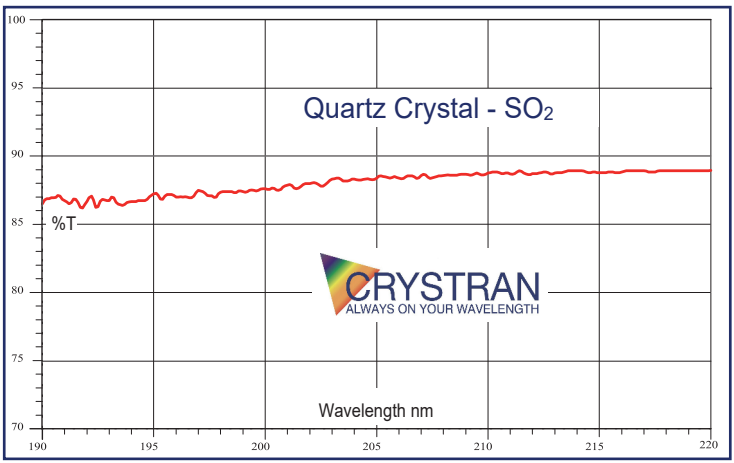
Transmission Range	0.18 to 3.5µm and 40µm to 100µm
Refractive Index	No 1.54421; Ne 1.55333 at 0.6µm
Reflection Loss	8.8% at 0.6µm (2 surfaces)
Absorption Coefficient	n/a
Reststrahlen Peak	n/a
dn/dT (3) (4)	-5.5×10^{-6} (para) & -6.5×10^{-6} K^{-1} (perp) @ 633nm
dn/dµ = 0	1.3µm
Density	2.649 g/cc
Melting Point	1710 °C
Thermal Conductivity	10.7 (para) 6.2 (perp) W m^{-1} K^{-1} at 323 K
Thermal Expansion	7.1 (para) 13.2 (perp) x 10^{-6} K
Hardness	Knoop 741 with 500g indenter
Specific Heat Capacity	710 J Kg^{-1} K^{-1}
Dielectric Constant	4.34 (para) 4.27 (perp) at 30MHz
Youngs Modulus (E)	97.2 (para) 76.5 (perp) GPa
Shear Modulus (G)	31.14 GPa
Bulk Modulus (K)	36.4 GPa
Elastic Coefficients (1) (2)	C_{11}=87 C_{12}=7 C_{44}=58 C_{13}=13 C_{14}=(-)18 C_{33}=106
Apparent Elastic Limit	41MPa (5950psi)
Poisson Ratio	n/a
Solubility	Insoluble in water
Molecular Weight	60.06
Class/Structure	Trigonal (hex) P3(2)21 (RH) and P3(1)21 (LH)

(1)J.V.Atansoff and P.J.Hart, Phys. Rev. Vol.59, pp 85-96 1941
(2)A.W.Lawson, Phys. Rev. Vol 59, pp.838-839, 1941
(3) F.J.Micheli, Ann.Physik 4:7 (1902)
(4) Toyoda & Yabe J. Phys. D: Appl. Phys.,1 6 (1983)

Quartz Crystal (SiO_2)

µm	No	Ne	µm	No	Ne	µm	No	Ne
0.193	1.661	1.675	0.4	1.558	1.567	0.78	1.539	1.548
0.213	1.632	1.645	0.458	1.552	1.561	0.8	1.538	1.547
0.222	1.622	1.634	0.488	1.550	1.559	0.82	1.538	1.547
0.226	1.619	1.630	0.515	1.548	1.557	0.86	1.537	1.547
0.248	1.602	1.613	0.532	1.547	1.556	0.98	1.535	1.546
0.257	1.596	1.607	0.59	1.544	1.553	1.064	1.534	1.543
0.28	1.585	1.596	0.633	1.543	1.552	1.32	1.531	1.539
0.308	1.576	1.586	0.67	1.541	1.551	1.55	1.528	1.536
0.325	1.571	1.581	0.694	1.541	1.550	2.01	1.521	1.529
0.351	1.565	1.575	0.755	1.539	1.548			





Rubidium Bromide (RbBr)

Rubidium Bromide is produced by the sealed-ampoule Stockbarger technique.

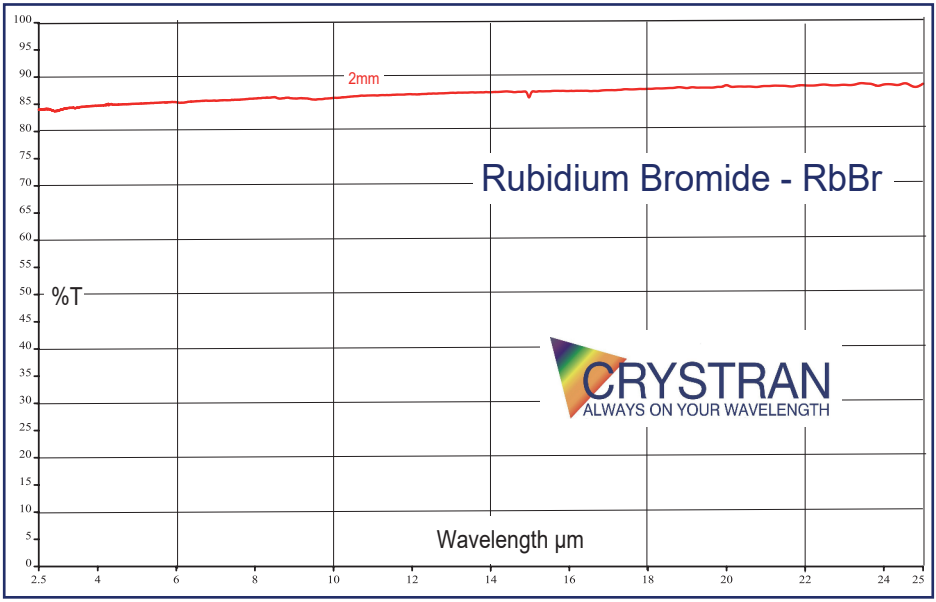
APPLICATIONS: Rubidium Bromide has only specialist applications.

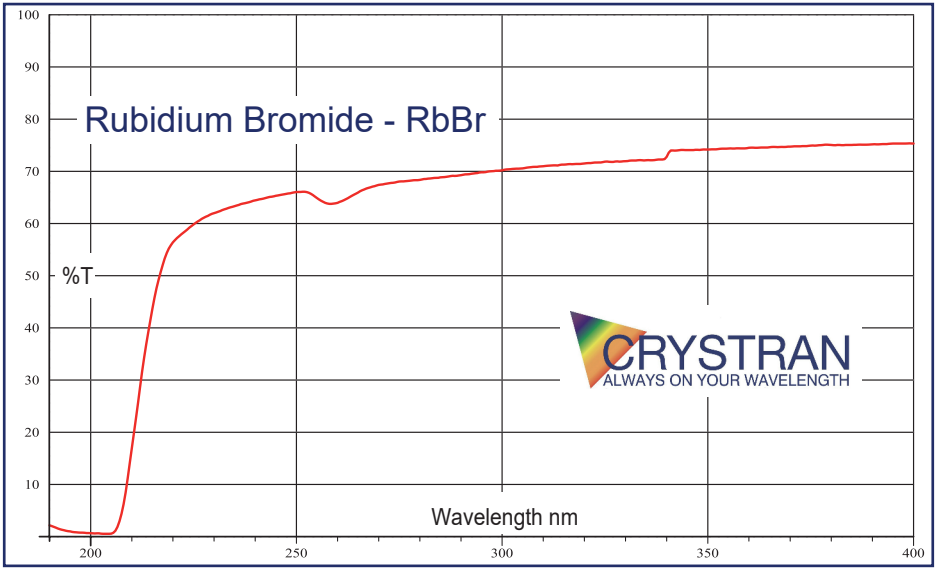
Transmission Range	0.22 to 40µm
Refractive Index	1.525 at 10µm (1)
Reflection Loss	8.2% at 10µm (2 surfaces)
Absorption Coefficient	1.6×10^{-3} cm^{-1} at 10.6µm
Reststrahlen Peak	n/a
dn/dT	-45×10^{-6} K^{-1}
dn/dµ = 0	n/a
Density	3.35 g/cc
Melting Point	682°C
Thermal Conductivity	12.2 W m^{-1} K^{-1} at 378K
Thermal Expansion	36.98×10^{-6} K^{-1} at 273K
Hardness	n/a
Specific Heat Capacity	311 J Kg^{-1} K^{-1}
Dielectric Constant	55
Youngs Modulus (E)	n/a
Shear Modulus (G)	n/a
Bulk Modulus (K)	13.7 GPa
Elastic Coefficients	C_{11}=31.5; C_{12}=4.8; C_{44}=3.82
Apparent Elastic Limit	n/a
Poisson Ratio	n/a
Solubility	98g/100g water
Molecular Weight	165.38
Class/Structure	Cubic FCC, NaCl, Fm3m, (100) cleavage

(1) Handbook Optical Constants, ed Palik, V3, ISBN 0-12-544423-0

Rubidium Bromide (RbBr)

µm	No	µm	No	µm	No	µm	No	µm	No
0.24	1.754	0.6	1.552	1.0	1.538	15.0	1.517	35.0	1.444
0.35	1.603	0.7	1.546	2.0	1.533	20.0	1.505	40.0	1.412
0.4	1.583	0.8	1.543	5.0	1.530	25.0	1.489		
0.5	1.563	0.9	1.540	10.0	1.525	30.0	1.469		





Rubidium Chloride (RbCl)

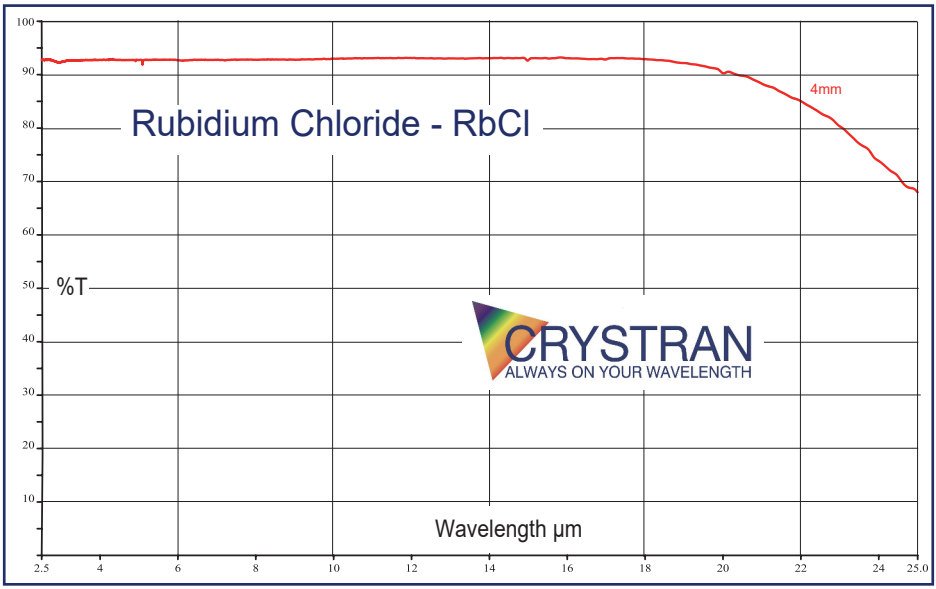
Rubidium Chloride is produced by the sealed-ampoule Stockbarger technique.

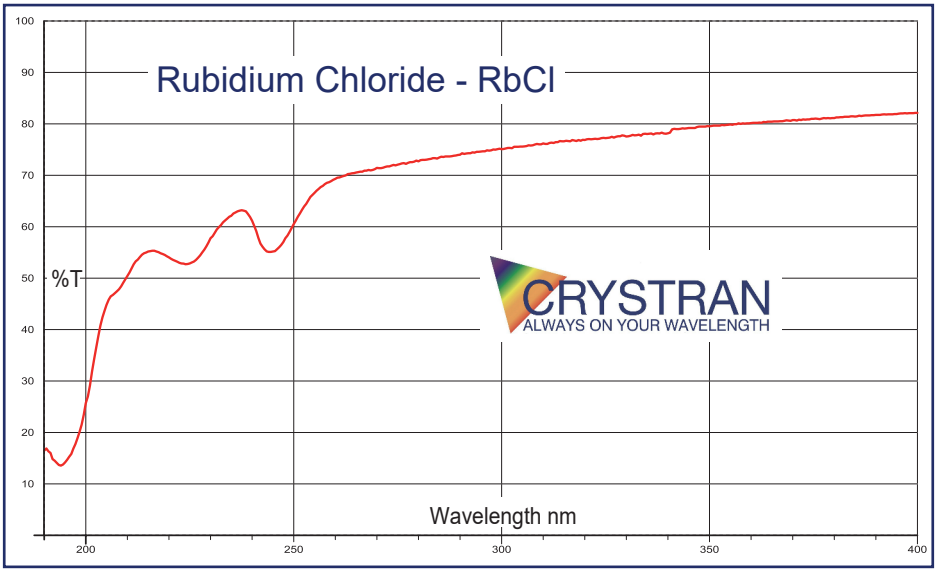
APPLICATIONS: Rubidium Chloride has only specialist applications.

Transmission Range	0.2 to 25µm
Refractive Index	1.46 at 10.6µm
Reflection Loss	6.8% at 10.6µm (2 surfaces)
Absorption Coefficient	1×10^{-3} cm^{-1} at 10.6µm
Reststrahlen Peak	n/a
dn/dT	-39×10^{-6} K^{-1}
dn/dµ = 0	n/a
Density	2.8 g/cc
Melting Point	715°C
Thermal Conductivity	7.6 W m^{-1} K^{-1}
Thermal Expansion	36×10^{-6} K^{-1} at 300K
Hardness	n/a
Specific Heat Capacity	418 J Kg^{-1} K^{-1} at 283K
Dielectric Constant	55
Youngs Modulus (E)	n/a
Shear Modulus (G)	n/a
Bulk Modulus (K)	16.3 GPa
Elastic Coefficients	C_{11}=36.4; C_{12}=6.3; C_{44}=4.7
Apparent Elastic Limit	n/a
Poisson Ratio	n/a
Solubility	77g/100g water
Molecular Weight	120.92
Class/Structure	Cubic FCC, NaCl, Fm3m, (100) cleavage

Rubidium Chloride (RbCl)

µm	No	µm	No	µm	No	µm	No	µm	No
0.248	1.60	0.488	1.50	0.633	1.49	1.55	1.48	10.60	1.46
0.351	1.53	0.59	1.49	1.06	1.48	2.8	1.48		





Rubidium Iodide (RbI)

Rubidium Iodide is produced by the sealed-ampoule Stockbarger technique. It is the most deliquescent of the rubidium salts.

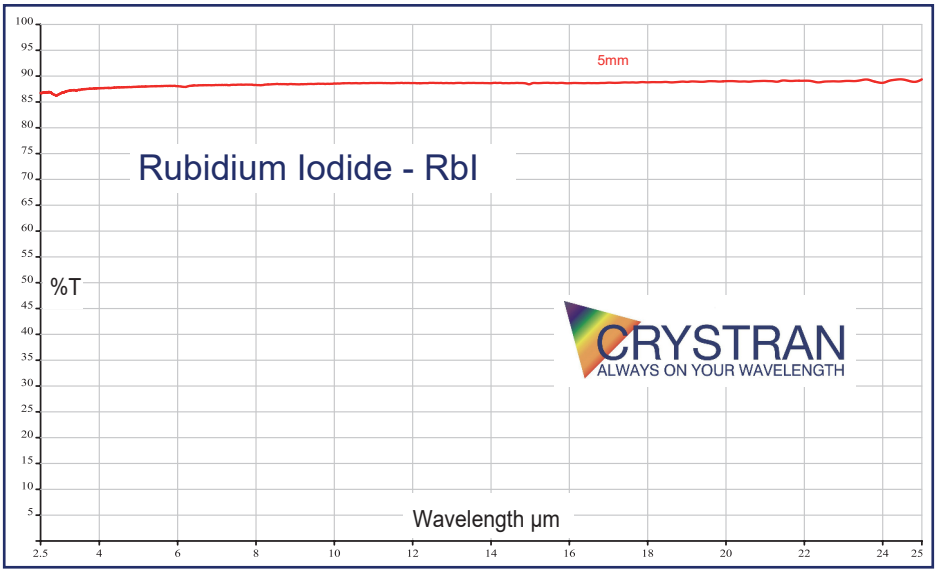
APPLICATIONS: Rubidium Iodide has only specialist applications.

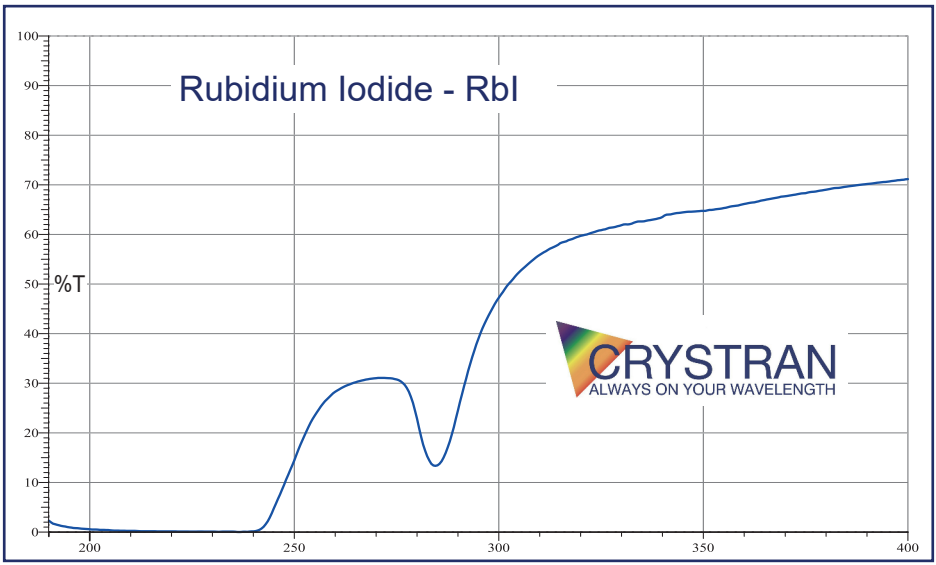
Transmission Range	0.3 to 50µm
Refractive Index	1.609 at 10µm (1)
Reflection Loss	10.4% at 10µm (2 surfaces)
Absorption Coefficient	n/a
Reststrahlen Peak	n/a
dn/dT	$-56 \times 10^{-6}\ K^{-1}$
$dn/d\mu = 0$	n/a
Density	3.55 g/cc
Melting Point	642°C
Thermal Conductivity	$9.9\ W\ m^{-1}\ K^{-1}$
Thermal Expansion	$39 \times 10^{-6}\ K^{-1}$ at 283K
Hardness	n/a
Specific Heat Capacity	$242\ J\ Kg^{-1}\ K^{-1}$ at 283K
Dielectric Constant	n/a
Youngs Modulus (E)	n/a
Shear Modulus (G)	n/a
Bulk Modulus (K)	11 GPa
Elastic Coefficients	C_{11}=27.6; C_{12}=3.7; C_{44}=2.79
Apparent Elastic Limit	n/a
Poisson Ratio	n/a
Solubility	152g/100g water
Molecular Weight	212.37
Class/Structure	Cubic FCC, NaCl, Fm3m, (100) cleavage

(1) Handbook Optical Constants, ed Palik, V3, ISBN 0-12-544423-0

Rubidium Iodide (RbI)

µm	No	µm	No	µm	No	µm	No	µm	No
0.25	2.059	0.80	1.631	5.0	1.612	30.0	1.573	50.0	1.486
0.35	1.736	1.0	1.624	10.0	1.609	40.0	1.537	55.0	1.452
0.50	1.663	2.0	1.615	20.0	1.596	45.0	1.514	60.0	1.411





Rutile (TiO_2)

Rutile is grown by the Czochralski method typically up to 25mm diameter and up to 80mm long.

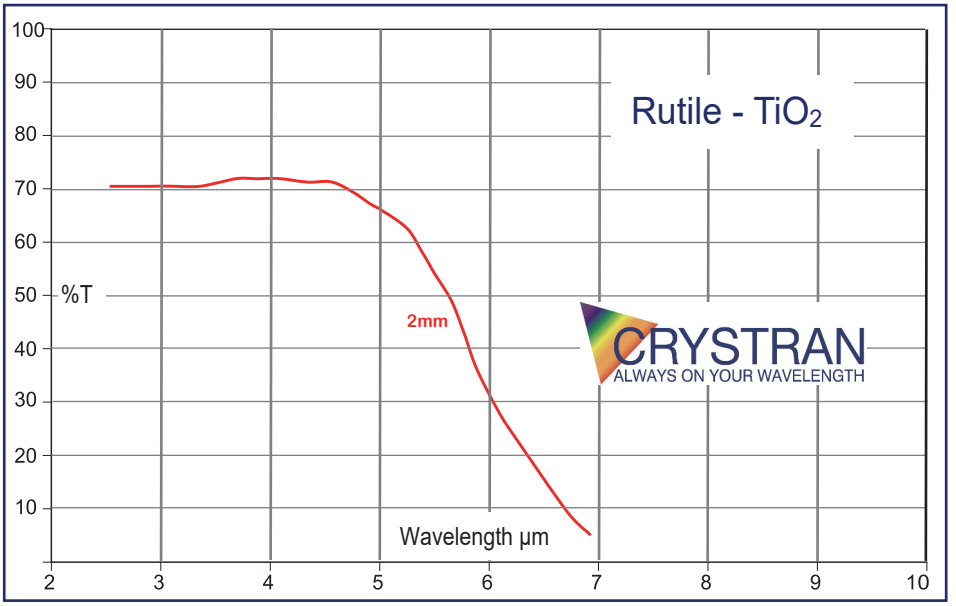
APPLICATIONS: Rutile is a high index material used mainly for optical coupling prisms and also as substrates for epitaxial growth.

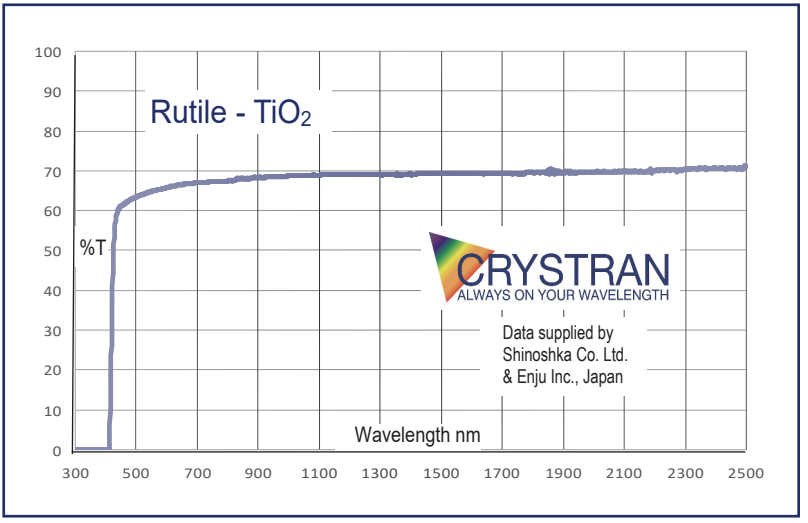
Transmission Range	0.43 to 5.0µm
Refractive Index	No 2.555 at 0.69µm (1)(2)
Reflection Loss	30% at 2µm (2 surfaces)
Absorption Coefficient	n/a
Reststrahlen Peak	n/a
dn/dT	n/a
dn/dµ = 0	2.81µm
Density	4.252 g/cc
Melting Point	1840°C
Thermal Conductivity	12.5 (para) 8.7 (perp) W m^{-1} K^{-1}
Thermal Expansion	9.2 (para) 7.1 (perp) x 10^{-6} /°C
Hardness	Knoop 879 with 500g indenter
Specific Heat Capacity	711 J kg^{-1} K^{-1}
Dielectric Constant	160 at 1 MHz
Youngs Modulus (E)	n/a
Shear Modulus (G)	n/a
Bulk Modulus (K)	n/a
Elastic Coefficients	C_{11}=269;C_{12}=177;C_{13}=146;C_{33}=480;C_{44}=124
Apparent Elastic Limit	4.8 MPa (700 psi)
Poisson Ratio	0.28
Solubility	Insoluble in water
Molecular Weight	79.9
Class/Structure	Tetragonal, P42/mnm, (#136) Rutile Structure.

(1) Handbook Optical Constants, ed Palik, V1, ISBN 0-12-544423-6
(2) Shenoy; 1EE Poceedings-J, Vol. 139, No. 2, Apr 1992

Rutile (TiO_2)

µm	No	Ne	µm	No	Ne	µm	No	Ne
0.436	2.853	3.216	0.589	2.616	2.903	3.38	2.41	2.58
0.492	2.725	3.051	0.691	2.555	2.836	3.79	2.39	2.57
0.496	2.718	3.042	0.708	2.548	2.826	4.28	2.34	2.51
0.546	2.652	2.958	1.01	2.484	2.747	4.89	2.32	2.49
0.577	2.623	2.921	1.530	2.454	2.710	5.73	2.24	2.43
0.579	2.621	2.919	2.42	2.40	2.59			





Sapphire (Al_2O_3)

Sapphire is grown by a variety of methods. Verneuil and Czochralski methods are usual for standard grade Sapphire material. Higher quality Sapphire, particularly for electronic substrates is manufactured by Kyropulos growth and this can be very pure with excellent UV transmission. Large thin sheets of Sapphire can be made by ribbon growth. Sapphire is slightly birefringent, general purpose IR windows are usually cut in a random way from crystal but for specific applications where the birefringence is an issue, an orientation is selected. Usually this is with the optic axis at 90 degrees to the surface plane and is known as "zero degree" material. Synthetic optical sapphire has no colouration.

APPLICATIONS: Sapphire is used for its extreme toughness and strength. Sapphire is a very useful optical window material for use in the UV, visible, and near infra-red. Use the QR ink on page 30 for our guide to sapphire.

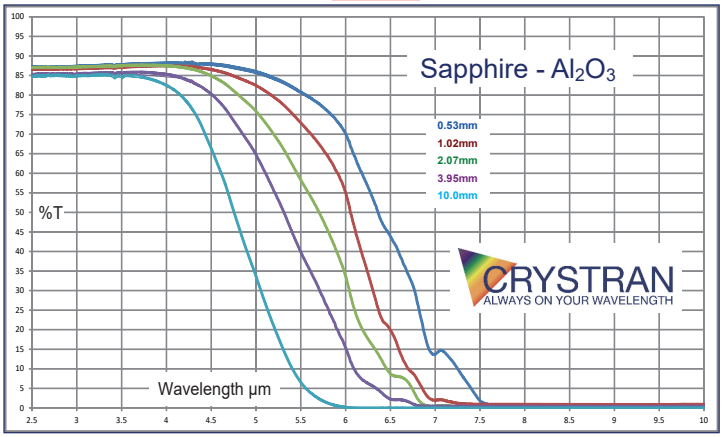
Transmission Range	0.17 to 5.5µm
Refractive Index	No 1.75449; Ne 1.74663 at 1.06µm (1)
Reflection Loss	14% at 1.06µm
Absorption Coefficient	0.3×10^{-3} cm^{-1} at 2.4µm (2)
Reststrahlen Peak	13.5µm
dn/dT	13.1×10^{-6} at 0.546µm (3)
dn/dµ = 0	1.5µm
Density	3.97 g/cc
Melting Point	2040°C
Thermal Conductivity	27.21 W m^{-1} K^{-1} at 300K
Thermal Expansion	5.6 (para) & 5.0 (perp) x 10^{-6} K^{-1} *
Hardness	Knoop 1800 (para) 2200 (perp)
Specific Heat Capacity	763 J Kg^{-1} K^{-1} at 293K (4)
Dielectric Constant	11.5 (para) 9.4 (perp) at 1MHz
Youngs Modulus (E)	335 GPa
Shear Modulus (G)	148.1 GPa
Bulk Modulus (K)	240 GPa
Elastic Coefficients	C_{11}=496 C_{12}=164 C_{13}=115 C_{33}=498 C_{44}=148
Apparent Elastic Limit	300 MPa (45,000 psi)
Poisson Ratio	0.25
Solubility	98×10^{-6} g/100g water
Molecular Weight	101.96
Class/Structure	Trigonal (hex), R3c

** Note that manufacturers appear to disagree at times on figures for thermal expansion.*

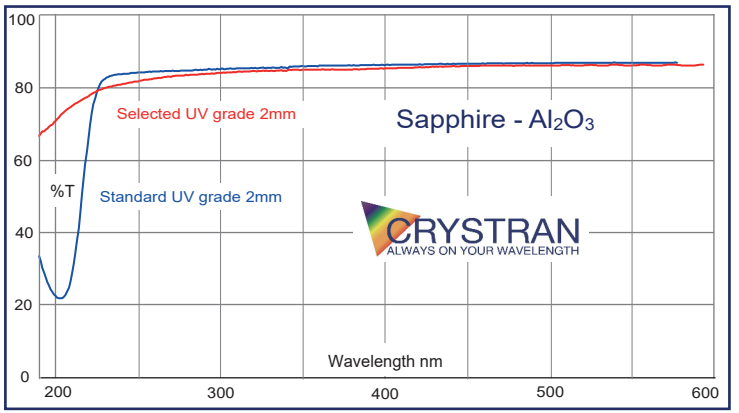
(1) Handbook Optical Constants, ed Palik, V3, ISBN 0-12-544423-0
(2) Harrington et al, Appl.Opt. V15, 1953-1959 (1976)
(3) Malitson, J.Opt.Soc.Am., V52, 1377- 1379 (1962)
(4) Ditmars, et. al., J. Res. Nat. Bur. Stand., 87, (2), 159-163 (1982).

Sapphire (Al_2O_3)

µm	No	Ne	µm	No	Ne	µm	No	Ne
0.193	1.9288	1.9174	0.458	1.7784	1.7702	1.550	1.7462	1.7384
0.213	1.8890	1.8784	0.488	1.7753	1.7671	2.010	1.7375	1.7297
0.222	1.8754	1.8650	0.515	1.7730	1.7649	2.249	1.7323	1.7243
0.226	1.8702	1.8599	0.532	1.7717	1.7636	2.703	1.719	1.711
0.244	1.8506	1.8407	0.590	1.7680	1.7600	2.941	1.712	1.704
0.248	1.8470	1.8372	0.633	1.7659	1.7579	3.333	1.701	1.693
0.257	1.8393	1.8297	0.670	1.7643	1.7563	3.704	1.687	1.679
0.266	1.8330	1.8236	0.694	1.7634	1.7554	4.000	1.674	1.666
0.280	1.8244	1.8151	0.755	1.7614	1.7535	4.348	1.658	1.65
0.308	1.8110	1.8020	0.780	1.7607	1.7527	4.762	1.636	1.628
0.325	1.8047	1.7958	0.800	1.7601	1.7522	5.000	1.623	1.615
0.337	1.8001	1.7921	0.820	1.7596	1.7517	5.263	1.607	1.599
0.351	1.7969	1.7882	0.980	1.7561	1.7482			
0.355	1.7960	1.7883	1.064	1.7545	1.7466			
0.442	1.7804	1.7721	1.320	1.7501	1.7423			



Transmission data table for these curves can be downloaded from the Crystran website



Silica Glass (SiO_2)

Fused Silica is the glassy form of Quartz and is thus isotropic. Fused Silica is tough and hard and has a very low expansion. Normal varieties of Fused Silica contain water which gives strong absorption in the Infra-red. Water-free varieties of Fused Silica are available.

APPLICATIONS: Fused Silica is a hard, high temperature pure glass. Fused Silica is used for UV and visible components. Infra-red grades of Fused Silica are available for NIR use. Use the QR link on page 30 for our guide to silica glass.

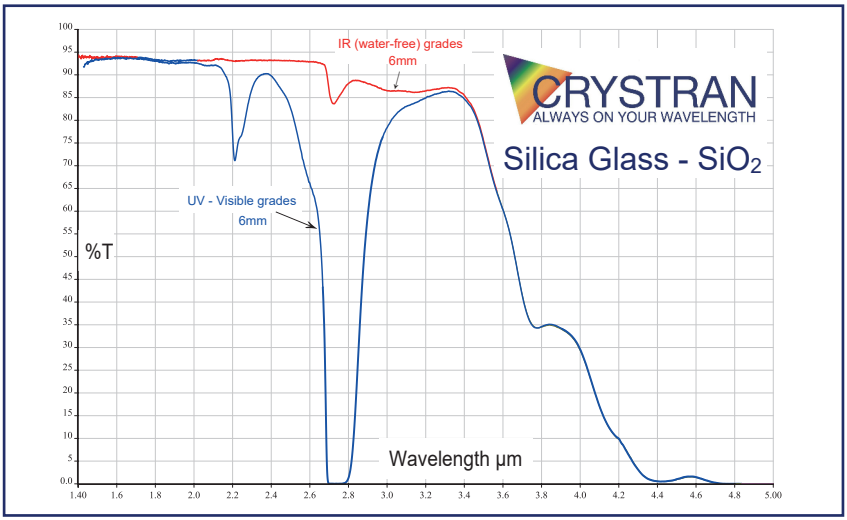
Transmission Range	0.18 to 2.2µm (3µm for IR grades)
Refractive Index	1.47012 at 4µm (1)
Reflection Loss	7.0% at 0.4µm (2 surfaces)
Absorption Coefficient	10×10^{-6} cm^{-1} at 1µm
Reststrahlen Peak	n/a
dn/dT	$+12.9 \times 10^{-6}$ K^{-1} (2)
dn/dµ = 0	1.3µm
Density	2.203 g/cc
Melting Point	1600 °C (softening) *
Thermal Conductivity	1.38 W m^{-1} K^{-1}
Thermal Expansion	0.55×10^{-6} K^{-1} at 300K
Hardness	Knoop 500 with 200g indenter
Specific Heat Capacity	703 J Kg^{-1} K^{-1}
Dielectric Constant	3.78 at 25GHz
Youngs Modulus (E)	73.1 GPa
Shear Modulus (G)	31.2 GPa
Bulk Modulus (K)	36.7 GPa
Elastic Coefficients	n/a
Apparent Elastic Limit	55 MPa (7980 psi)
Poisson Ratio	0.17
Solubility	Insoluble in Water
Molecular Weight	28.09
Class/Structure	Amorphous glass

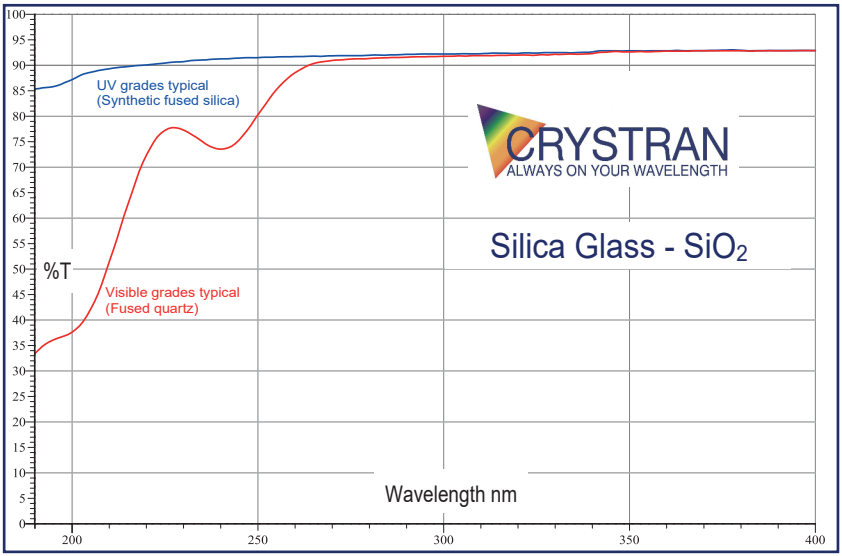
** The normal maximum working temperature is 1050°C*

(1) Handbook Optical Constants, ed Palik, V1, ISBN 0-12-544420-6
(2) Toyoda & Yabe J. Phys. D: Appl. Phys.,1 6 (1983)

Silica Glass (SiO_2)

µm	No	µm	No	µm	No	µm	No	µm	No
0.20	1.55051	0.55	1.46008	0.90	1.45175	1.7	1.44217	2.8	1.42377
0.25	1.50745	0.60	1.45804	1.0	1.45042	1.8	1.44087	3.0	1.41925
0.30	1.48779	0.65	1.45653	1.1	1.4492	1.9	1.43951	3.2	1.41427
0.36	1.47529	0.70	1.45529	1.2	1.44805	2.0	1.43809	3.37	1.41099
0.40	1.47012	0.75	1.45424	1.3	1.44692	2.2	1.43501		
0.45	1.46557	0.8	1.45332	1.5	1.44462	2.4	1.43163		
0.50	1.46233	0.85	1.4525	1.6	1.44342	2.6	1.42789		





Silicon (Si)

Silicon is grown by Czochralski pulling techniques (CZ) and contains some oxygen which causes an absorption band at 9µm. To avoid this, Silicon can be prepared by a Float-Zone (FZ) process. Optical Silicon is generally lightly doped (15 to 40 ohm cm) for best transmission above 10µm. Silicon has a further pass band 30 to 100µm which is effective only in very high resistivity uncompensated material. Doping is usually Boron (p-type) and Phosphorus (n-type).

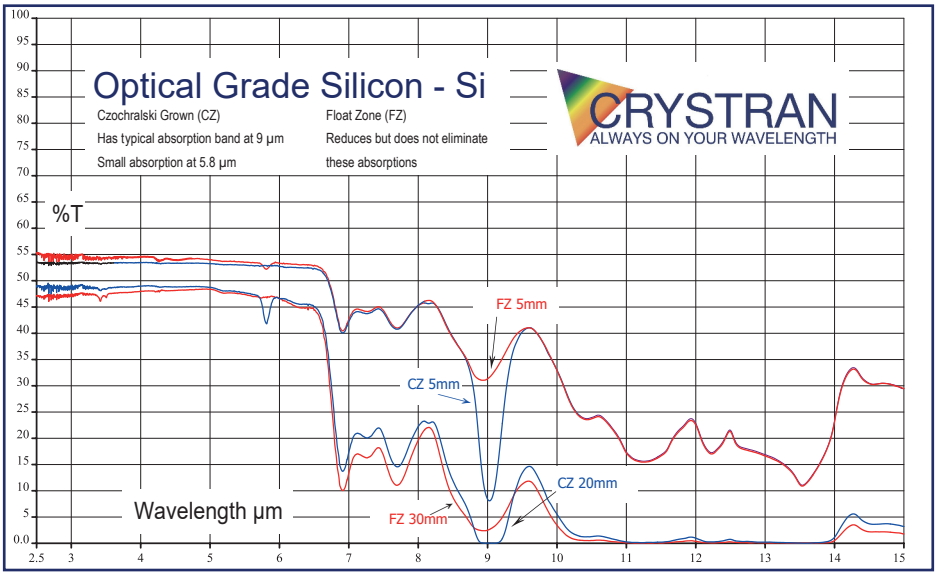
APPLICATIONS: Silicon is used as an optical window primarily in the 3 to 5 micron band and as a substrate for production of optical filters. Large blocks of Silicon with polished faces are also employed as neutron targets in Physics experiments

Transmission Range	1.2 to 15µm and 30 to >100µm (1)
Refractive Index	3.4223 @ 5µm (1) (2)
Reflection Loss	46.2% at 5µm (2 surfaces)
Absorption Coefficient	0.01 cm^{-1} at 3µm
Reststrahlen Peak	n/a
dn/dT	160 x 10^{-6} /°C (3)
dn/dµ = 0	10.4µm
Density	2.33 g/cc
Melting Point	1420 °C
Thermal Conductivity	163.3 W m^{-1} K^{-1} at 273 K
Thermal Expansion	2.6 x 10^{-6} K^{-1} at 20°C
Hardness	Knoop 1150
Specific Heat Capacity	703 J Kg^{-1} K^{-1}
Dielectric Constant	13 at 10 GHz
Youngs Modulus (E)	131 GPa (4)
Shear Modulus (G)	79.9 GPa (4)
Bulk Modulus (K)	102 GPa
Elastic Coefficients	C_{11}=167; C_{12}=65; C_{44}=80 (4)
Apparent Elastic Limit	124.1MPa (18000 psi)
Poisson Ratio	0.266 (4)
Solubility	Insoluble in Water
Molecular Weight	28.09
Class/Structure	Cubic diamond, Fd3m

(1) Handbook Optical Constants, ed Palik, V1, ISBN 0-12-544420-6
(2) Li, Refractive Index of Germanium etc, J.Phys Chem, V9, p561, 1980
(3) Icenogle et al, Appl. Opt. V15, 2348 (1976)
(4) Wortman & Evans, V36, (1), P153 (1965)

Silicon (Si)

µm	No	µm	No	µm	No	µm	No	µm	No
1.357	3.4975	1.813	3.4608	3.303	3.430	5.5	3.4213	8.5	3.4182
1.367	3.4962	1.97	3.4537	3.5	3.4284	6.0	3.4202	10.0	3.4179
1.395	3.4929	2.153	3.4476	4.0	3.4257	6.5	3.4195	10.5	3.4178
1.5295	3.4795	2.325	3.4430	4.258	3.4245	7.0	3.4189	11.04	3.4176
1.66	3.4696	2.714	3.4358	4.5	3.4236	7.5	3.4186		
1.709	3.4664	3.0	3.4320	5.0	3.4223	8.0	3.4184		



Silver Bromide (AgBr)

Silver Bromide is grown in small ingots by sealed ampoule Stockbarger techniques. Silver Bromide is malleable and deep yellow, it darkens in sunlight, but less readily than Silver Chloride.

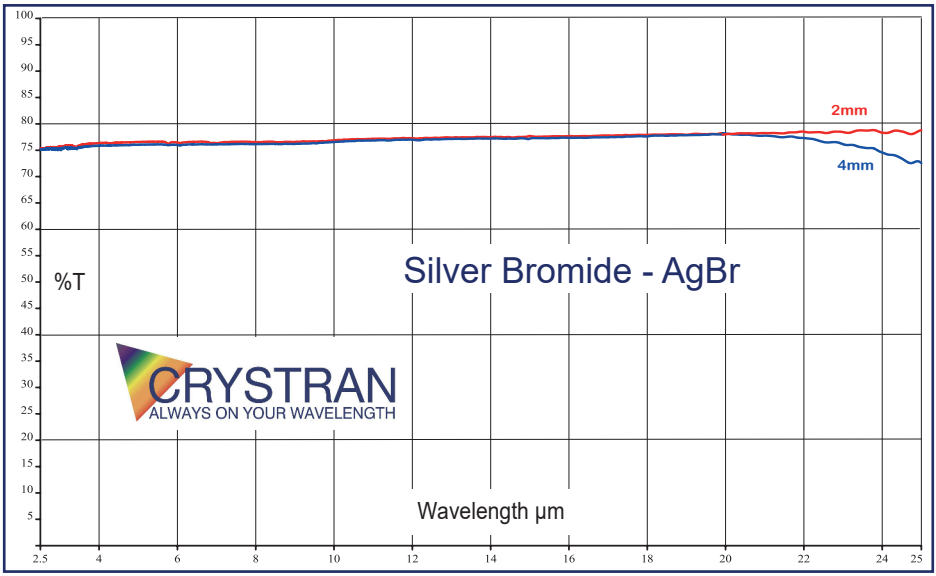
APPLICATIONS: Silver Bromide is useful material for very deep Infra Red applications where sensitivity to moisture is a problem. Silver Bromide crystal growth was developed relatively recently by the standards of many IR materials. The parameters of Silver Bromide have not been researched as thoroughly as those of Silver Chloride. This soft crystal deforms under heat and pressure and can be forged in polished dies to create Infra Red windows and lenses.

Transmission Range	0.45 to 35µm (1)
Refractive Index	2.167 at 10µm (1) (2)
Reflection Loss	23.9% at 10µm (2 surfaces)
Absorption Coefficient	Not known
Reststrahlen Peak	112.7µm
dn/dT	Not known
dn/dµ = 0	Not known
Density	6.473 g/cc
Melting Point	432 °C
Thermal Conductivity	1.21 W m^{-1} K^{-1} at 273 K
Thermal Expansion	30 x 10^{-6} K^{-1} at 273 K
Hardness	Knoop 7
Specific Heat Capacity	292 J Kg^{-1} K^{-1}
Dielectric Constant	13.1 at 1MHz (2)
Youngs Modulus (E)	31.97 GPa
Shear Modulus (G)	Not Known
Bulk Modulus (K)	44.03 GPa
Elastic Coefficients	C_{11}=56.3 C_{12}=32.3 C_{44}=7.25
Apparent Elastic Limit	30.3 Mpa (4400psi)
Poisson Ratio	Not Known
Solubility	12 x 10^{-6}g/100g water at 20°C
Molecular Weight	187.78
Class/Structure	Cubic FCC, NaCl, Fm3m, No cleavage, cold flows

(1) Handbook of Optical Constants, ed Palik, V3, ISBN 0-12-544423-0
(2) White; Optical Properties of Silver Bromide. J.Opt. Soc. Am. V62, N2, (1973)

Silver Bromide (AgBr)

µm	No	µm	No	µm	No	µm	No	µm	No
0.391	2.416	0.496	2.313	0.6	2.25	0.781	2.205	12.66	2.162
0.477	2.33	0.55	2.27	0.65	2.24	9.926	2.167		



Silver Chloride (AgCl)

Silver Chloride is grown into small ingots by the sealed-ampoule Stockbarger techniques. Silver chloride is malleable and milky-white it darkens in sunlight, but mild darkening does not affect the IR performance.

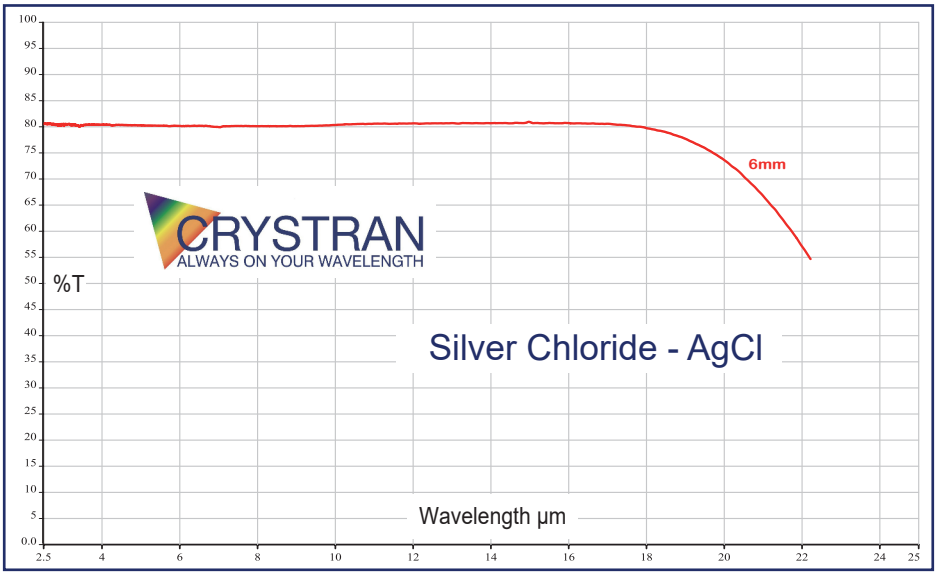
APPLICATIONS: Silver Chloride is a useful material for deep IR applications where sensitivity to moisture is a problem. This soft crystal deforms under heat and pressure and can be forged in polished dies to create IR windows and lenses. A major use for Silver Chloride is in the manufacture of small disposable cell windows for spectroscopy, known as mini-cells. These windows have a depression of controlled thickness pressed into the surface. The inherent cost of Silver Chloride material is offset against ease of manufacture.

Transmission Range	0.4 to 25µm (1)
Refractive Index	1.98 at 10µm (1)
Reflection Loss	19.5% at 10µm (2 surfaces)
Absorption Coefficient	n/a
Reststrahlen Peak	81.5µm
dn/dT	$-61 \times 10^{-6}\ K^{-1}$
dn/dµ = 0	4.5µm
Density	5.59 g/cc
Melting Point	457 °C
Thermal Conductivity	$1.15\ W\ m^{-1}\ K^{-1}$ at 278 K
Thermal Expansion	$31 \times 10^{-6}\ K^{-1}$ at 302 K
Hardness	Knoop 9.5 with 200g indenter
Specific Heat Capacity	$355\ J\ Kg^{-1}\ K^{-1}$
Dielectric Constant	12.3 at 1MHz
Youngs Modulus (E)	19.98 GPa
Shear Modulus (G)	7.099 GPa
Bulk Modulus (K)	44.04 GPa
Elastic Coefficients	C_{11}=60.1 C_{12} =36.2 C_{44}=6.25
Apparent Elastic Limit	26.2MPa (3800 psi)
Poisson Ratio	0.4
Solubility	52×10^{-6} g/100g water at 50°C
Molecular Weight	143.34
Class/Structure	Cubic FCC, NaCl, Fm3m, No cleavage, cold flows

(1) Handbook of Optical Constants, ed Palik, V3, ISBN 0-12-544423-0

Silver Chloride (AgCl)

µm	No	µm	No	µm	No	µm	No	µm	No
0.5	2.09658	5.0	1.99745	9.5	1.98255	14.0	1.95807	18.5	1.92194
1.0	2.02239	5.5	1.99618	10.0	1.98034	14.5	1.95467	19.0	1.91710
1.5	2.01047	6.0	1.99483	10.5	1.97801	15.0	1.95113	19.5	1.91208
2.0	2.00615	6.5	1.99339	11.0	1.97556	15.5	1.94743	20.0	1.90688
2.5	2.00386	7.0	1.99185	11.5	1.97297	16.0	1.94358	20.5	1.90149
3.0	2.0023	7.5	1.99021	12.0	1.97026	16.5	1.93958		
3.5	2.00102	8.0	1.98847	12.5	1.96742	17.0	1.9354		
4.0	1.99983	8.5	1.98661	13.0	1.96444	17.5	1.93109		
4.50	1.99866	9.0	1.98464	13.5	1.96133	18.0	1.9266		



Sodium Chloride (NaCl)

Sodium Chloride is produced in large ingots by the Kyropoulos growth method. Sodium Chloride cleaves easily. With care Sodium Chloride can be polished to a high standard under humidity controlled conditions

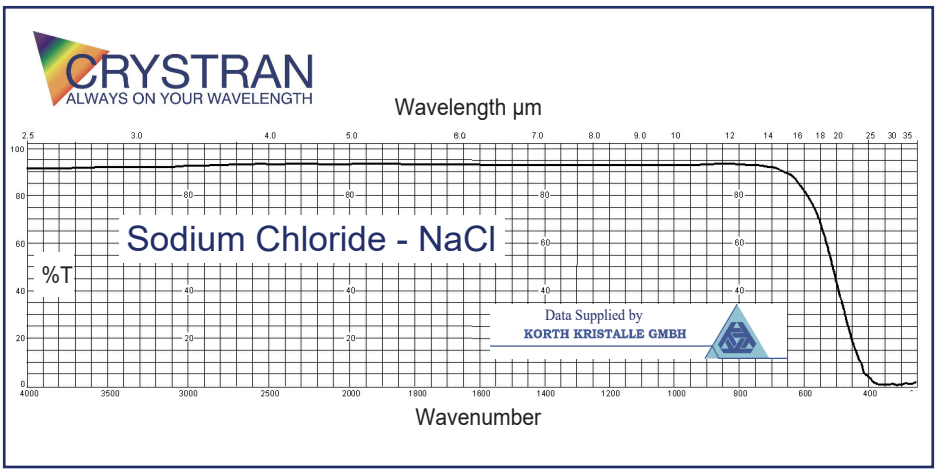
APPLICATIONS: Sodium Chloride, common rock salt, is one of the most useful materials for general purpose spectroscopic windows and applications where sensitivity to moisture is unimportant.

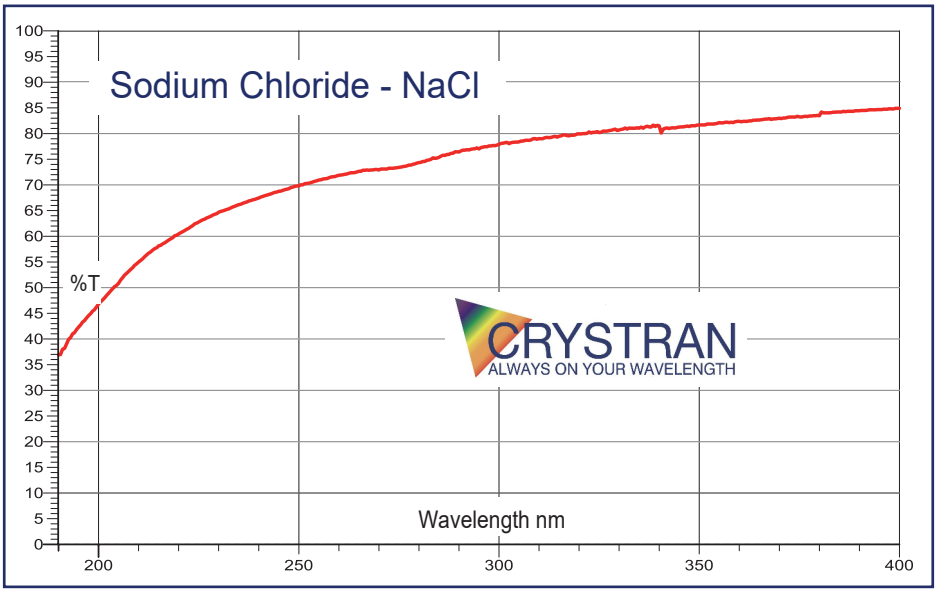
Transmission Range	0.2 to 15µm
Refractive Index	1.49065 at 10.6µm
Reflection Loss	7.5% at 10.6µm (2 surfaces)
Absorption Coefficient	7×10^{-6} cm^{-1} at 1.06µm (1)
Reststrahlen Peak	50.1µm
dn/dT	-40.83×10^{-6} K^{-1}
dn/dµ = 0	n/a
Density	2.17 g/cc
Melting Point	801 °C
Thermal Conductivity	6.5 W m^{-1} K^{-1} at 273K
Thermal Expansion	44×10^{-6} K^{-1}
Hardness	Knoop 18.2 in <100> with 200g indenter
Specific Heat Capacity	854 J Kg^{-1} K^{-1}
Dielectric Constant	5.9 at 1MHz
Youngs Modulus (E)	39.98 GPa
Shear Modulus (G)	12.61 GPa
Bulk Modulus (K)	24.42 GPa
Elastic Coefficients	C_{11}=48.5; C_{12}=12.3; C_{44}=12.61
Rupture Modulus	3.9 MPa (560 psi) (2)
Poisson Ratio	0.252
Solubility	35.7g/100g water at 273K
Molecular Weight	58.45
Class/Structure	Cubic FCC, NaCl, Fm3m (#221), (100) cleavage

(1) H.H.Li, Absorption Coefficients, Int.J.Therm, V1, No. I, 1980
(2) Combes, et.al.; J.Opt. Soc. Am. V41, p215, 1951.

Sodium Chloride (NaCl)

µm	No	µm	No	µm	No	µm	No	µm	No
0.589	1.54427	0.972	1.53253	9.0	1.501	12.5	1.47568	17.8	1.41649
0.64	1.54141	1.054	1.53153	9.50	1.4998	13.5	1.4666	19.8	1.38559
0.76	1.53682	1.555	1.53815	10.6	1.49065	14.6	1.45572	20.57	1.3735
0.884	1.53395	2.074	1.52736	11.4	1.48476	16.0	1.4399	22.3	1.3403





Sodium Fluoride (NaF)

Sodium Fluoride is produced by vacuum Stockbarger techniques. The Sodium Fluoride is very difficult to anneal and cleaves readily limiting the useful size of pieces to about 80mm. Sodium Fluoride polishes well but must be kept in dry air to maintain the quality of the surfaces and retain the deep UV transmission needed for Cerenkov radiation from this material.

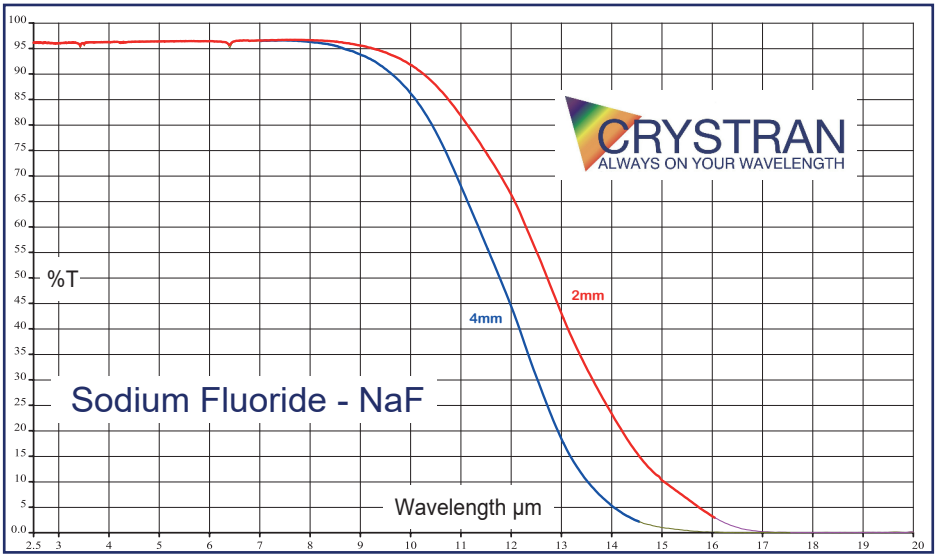
APPLICATIONS: Sodium Fluoride has the lowest refractive index of all common optical materials which makes it of interest as a Cerenkov radiator in Particle Physics research. Crystran Ltd. has supplied Sodium Fluoride material which has been made into large arrays at CERN. It is used in Ring Imaging Cerenkov Counters (RICH)

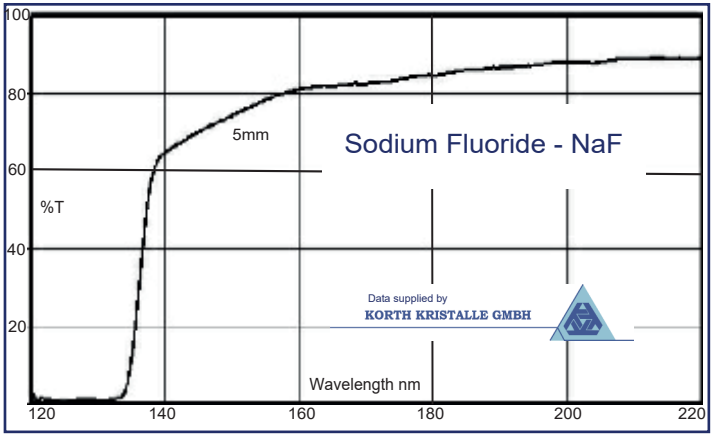
Transmission Range	0.14 to 11µm
Refractive Index	1.3255 at 0.6µm
Reflection Loss	3.9% at 0.6µm
Absorption Coefficient	1×10^{-3} cm^{-1} at 7µm @ 300K (1)
Reststrahlen Peak	35.8µm
dn/dT	-13×10^{-6} K^{-1} at 293K
$dn/d\mu = 0$	1.7µm
Density	2.79 g/cc @20°C
Melting Point	980°C
Thermal Conductivity	3.746 W m^{-1} K^{-1} at 273K
Thermal Expansion	36×10^{-6} /K at 300K
Hardness	Knoop 60 in <100>
Specific Heat Capacity	1088 J Kg^{-1} K^{-1}
Dielectric Constant	6 at 1 MHz
Youngs Modulus (E)	79.01 GPa
Shear Modulus (G)	12.70 GPa
Bulk Modulus (K)	47.9 GPa
Elastic Coefficients	C_{11}=79.01; C_{12}=12.7; C_{44}=47.9
Apparent Elastic Limit	3.2 MPa (Estimated)
Poisson Ratio	0.326
Solubility	4.22g/100g water at 18°C
Molecular Weight	42.0
Class/Structure	Cubic FCC, NaCl, Fm3m, (100) cleavage

(1) H.H.Li, Absorption Coefficients, Int.J.Therm, V1, No. I, 1980

Sodium Fluoride (NaF)

µm	No	µm	No	µm	No	µm	No	µm	No
0.14	1.55	0.203	1.3772	0.707	1.32372	4.1	1.308	10.3	1.233
0.145	1.499	0.302	1.34232	0.811	1.32272	5.1	1.301	11.3	1.209
0.161	1.438	0.405	1.33194	0.912	1.32198	6.1	1.292	12.5	1.18
0.175	1.410	0.486	1.32818	1.014	1.3215	7.1	1.281	13.8	1.142
0.186	1.393	0.546	1.3264	2.0	1.3170	8.1	1.269	15.1	1.093
0.199	1.3805	0.589	1.32549	3.1	1.313	9.1	1.252	16.7	1.029





Spinel ($MgAl_2O_4$)

Spinel is a naturally occurring material often used as a gemstone. Optical spinel is a fused compacted ceramic material formed from spinel powder. It is polycrystalline with a grain size in the range of 25µm to 150µm.

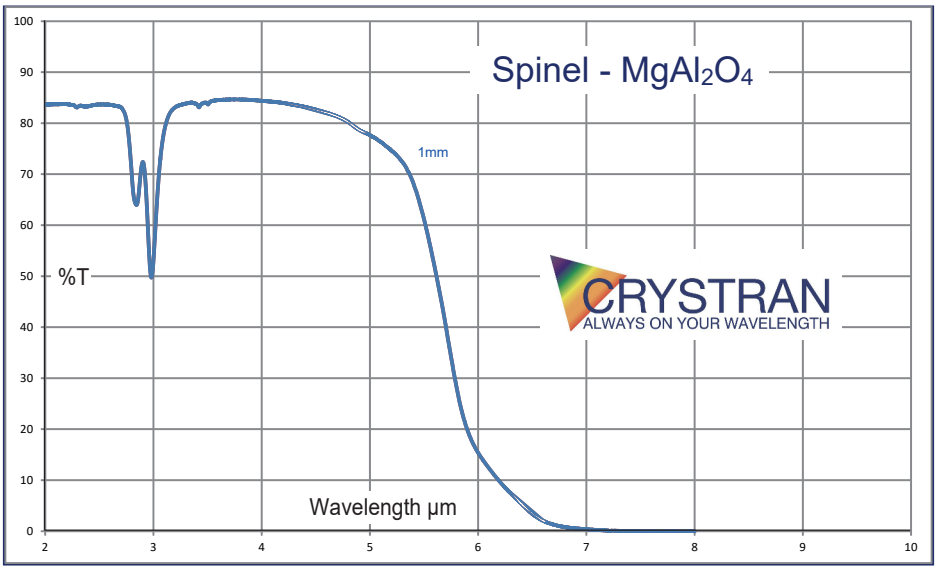
APPLICATIONS: Spinel is becoming favoured for use for in harsher environments requiring extreme strength. As a sintered ceramic material it exhibits more strength than single crystal material.

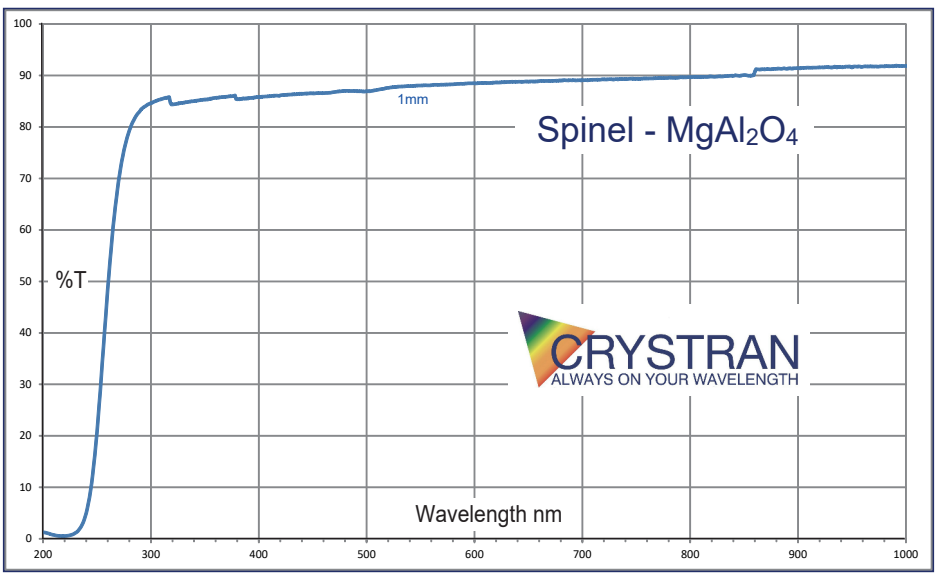
Transmission Range	0.3 to 5µm
Refractive Index	1.71 at 0.6µm
Reflection Loss	13% at 0.6µm
Absorption Coefficient	0.02 cm^{-1} at 0.6µm
Reststrahlen Peak	NA
dn/dT	12 x 10^{-6} K^{-1}
dn/dµ = 0	NA
Density	3.58 g/cc
Melting Point	2135°C
Thermal Conductivity	14.6 W m^{-1} K^{-1} (varies with porosity)
Thermal Expansion	6.5 x 10^{-6} /K
Hardness	Knoop 1140 with 1000g indenter (8 Moh)
Specific Heat Capacity	1086 J Kg^{-1} K^{-1}
Dielectric Constant	8
Youngs Modulus (E)	195 GPa
Shear Modulus (G)	157 Gpa
Bulk Modulus (K)	200 Gpa
Elastic Coefficients	C_{11}=298; C_{12}=154; C_{44}=157 (2)
Apparent Elastic Limit	170 MPa (24,600 psi)
Poisson Ratio	0.26
Solubility	Insoluble
Molecular Weight	142.27
Class/Structure	Cubic. $Fd\bar{3}m$ (# 227) Irregular cleavage (111) Polycrystalline in optical usage.

(1) https://www.mindat.org/min-3729.html
(2) Schreiber, Elastc Moduli of Single Crystal Spinel, J.App.Phys 38, 2508 (1967)

Spinel ($MgAl_2O_4$)

µm	No	µm	No	µm	No	µm	No	µm	No
0.36	1.7461	0.70	1.7111	2.0	1.686	4.0	1.635	6.667	1.491
0.40	1.7368	1.042	1.702	2. 5	1.677	5.0	1.594	6.897	1.473
0.50	1.7229	1.25	1.698	3.125	1.662	5.556	1.565		
0.60	1.7156	1. 471	1.695	3.704	1.645	6.25	1.522		





Strontium Fluoride (SrF_2)

*S*trontium fluoride is produced by the vacuum Stockbarger growth technique.

APPLICATIONS: Strontium Fluoride has only specialist applications. Optically, Strontium Fluoride has properties intermediate to Calcium and Barium Fluoride.

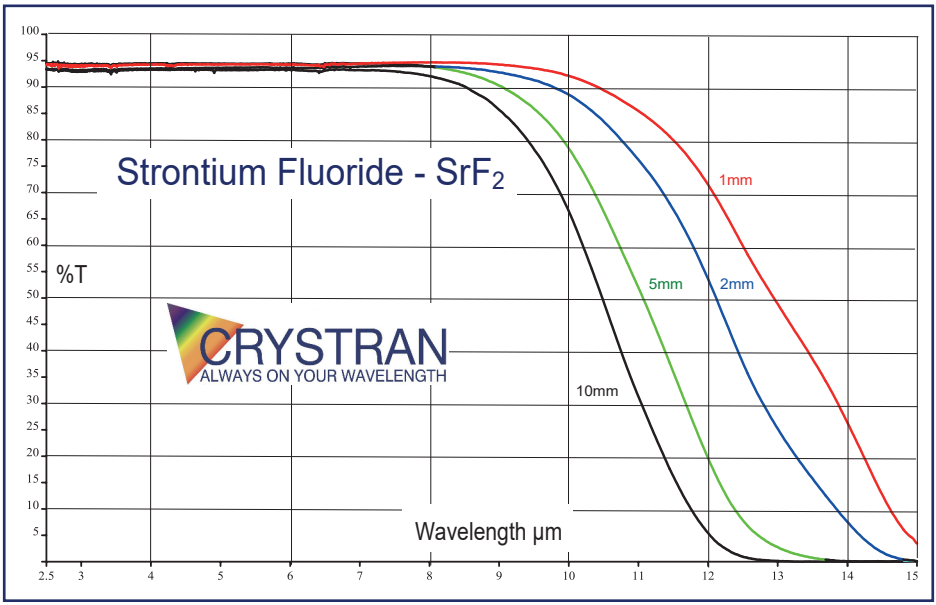
Transmission Range	0.15 to 11µm
Refractive Index	1.439 at 0.55µm (1)
Reflection Loss	6.3% at 0.55µm (2 surfaces)
Absorption Coefficient	$<1 \times 10^{-3}$ cm^{-1} at 5µm
Reststrahlen Peak	46µm
dn/dT	-12×10^{-6} K^{-1}
dn/dµ = 0	n/a
Density	4.24 g/cc
Melting Point	1450°C
Thermal Conductivity	8.3 W m^{-1} K^{-1} at 293K (2)
Thermal Expansion	18.4×10^{-6} K^{-1} at 293K
Hardness	Knoop 154 (100) & 140 (110)
Specific Heat Capacity	543 J Kg^{-1} K^{-1}
Dielectric Constant	7.69 at 2 MHz
Youngs Modulus (E)	89.91 GPa
Shear Modulus (G)	34.6 GPa
Bulk Modulus (K)	24.65 GPa
Elastic Coefficients	C_{11}=124; C_{12}=45; C_{44}=31.7
Apparent Elastic Limit	36.5 MPa (5300 psi)
Poisson Ratio	0.25
Solubility	0.012g/100g water at 27°C
Molecular Weight	125.62
Class/Structure	Cubic $Fm\bar{3}m$ (#225) Fluorite structure Cleaves on (111)

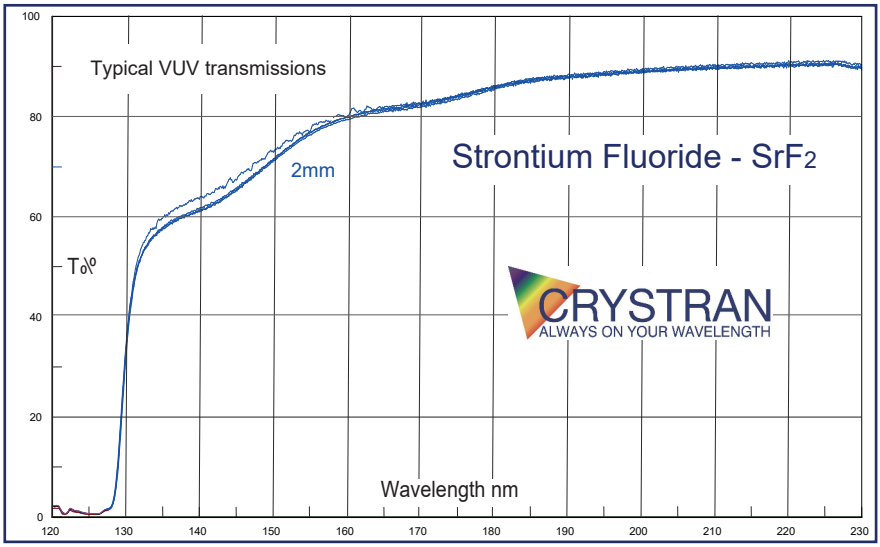
(1) Handbook of Optical Constants, ed Palik, V3, ISBN 0-12-544423-0

(2) A figure of 1.42 W/(mK) is in wide circulation but is plainly incorrect based on observation of UKRI STFC (2019). Logically the Tc should be intermediate between BaF2 and CaF2. OSTI.GOV gives (p44) 0.016 cal cm-1 s C-1 for 25°C which converts to 6.7 W m-1 K-1. OSA PUBLISHING confirms (p95) the Tc for CaF2 as 9.71W m-1K-1 and offers for SrF2 as 8.3 W m-1 K-1 which we use here.

Strontium Fluoride (SrF_2)

µm	No	µm	No	µm	No	µm	No	µm	No
0.15	1.594	0.61	1.43740	1.51	1.43003	6.01	1.38934	9.1	1.3283
0.20	1.504	0.71	1.43560	2.01	1.42761	7.01	1.37308	9.6	1.3151
0.31	1.45725	0.81	1.43435	3.01	1.42159	8.01	1.35362	10.6	1.2854
0.41	1.44556	0.91	1.43343	4.01	1.41337	8.1	1.3517	11.1	1.2686
0.51	1.44029	1.01	1.43269	5.01	1.40269	8.6	1.3405		





Thallium Bromide (TlBr)

CAUTION: Thallium salts are considered TOXIC and should be handled with care.

Thallium Bromide crystals are grown by sealed-ampoule Stockbarger technique. Thallium salts are toxic, and Thallium Bromide has enough solubility to require extreme caution. Careful handling with plastic gloves covered with soft cotton gloves as appropriate to delicate optics is required.

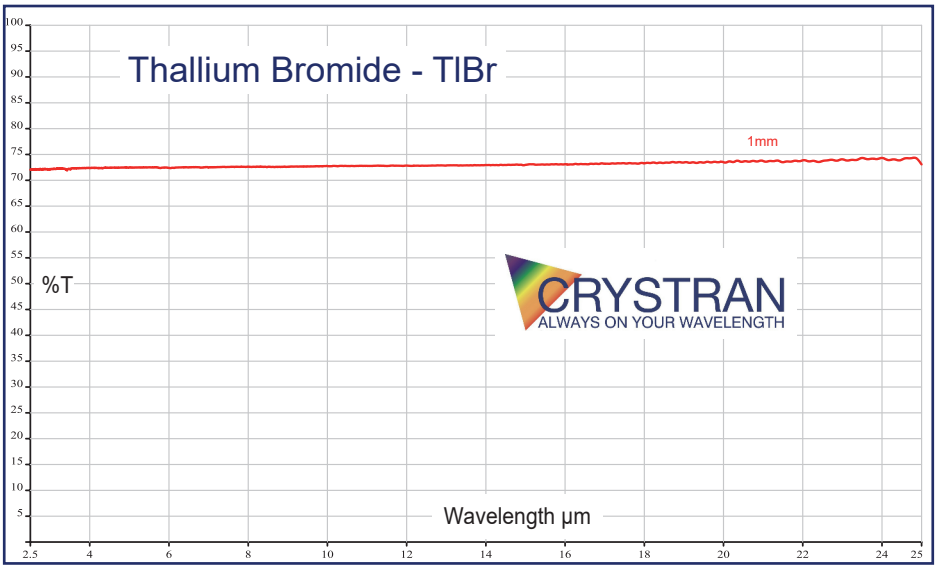
APPLICATIONS: Thallium Bromide has little practical application.

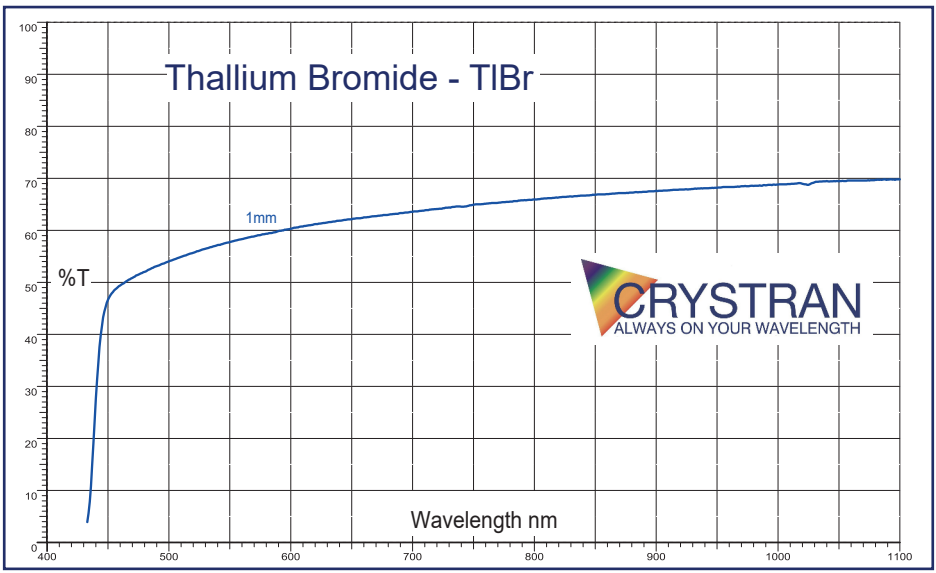
Transmission Range	0.5 to 40µm
Refractive Index	2.338 at 10µm (1)
Reflection Loss	27.7% at 10µm
Absorption Coefficient	n/a
Reststrahlen Peak	172µm
dn/dT	n/a
dn/dµ = 0	8.5µm
Density	7.453 g/cc (1)
Melting Point	460.5 °C (1)
Thermal Conductivity	0.586 W m^{-1} K^{-1} at 343K
Thermal Expansion	51 x 10^{-6} K^{-1} at 300K
Hardness	Knoop 11.9 with 500g indenter
Specific Heat Capacity	188 J Kg^{-1} K^{-1} (3)
Dielectric Constant	30.3 at 1 MHz
Youngs Modulus (E)	29.5 GPa (2)
Shear Modulus (G)	7.58 GPa (2)
Bulk Modulus (K)	22.47 Gpa (2)
Elastic Coefficients	C_{11}=37.8; C_{12}=14.8; C_{44}=7.56 (2)
Apparent Elastic Limit	20.7 MPa (3000 psi)
Poisson Ratio	0.281
Solubility	0.05g/100g water ar 25°C
Molecular Weight	248.31
Class/Structure	Cubic CsCl, Pm3m, no cleavage (1)

(1) Handbook of Optical Constants, ed Palik, V3, ISBN 0-12-544423-0
(2) Arenberg, Measurements made at Naval Research Labs, USA 1948-49
(3) Kelly, Bureau of Mines Bulletin, No 371, p51. 1934

Thallium Bromide (TlBr)

µm	No	µm	No	µm	No	µm	No	µm	No
0.438	2.652	0.578	2.424	0.750	2.350				
0.546	2.452	0.650	2.384	10.00	2.338				





Thallium Chloride (TlCl)

CAUTION: Thallium salts are considered TOXIC and should be handled with care.

Thallium Chloride crystals are grown by sealed-ampoule Stockbarger technique. Thallium salts are toxic, and Thallium Chloride has enough solubility to require extreme caution. Careful handling with plastic gloves covered with soft cotton gloves as appropriate to delicate optics is required

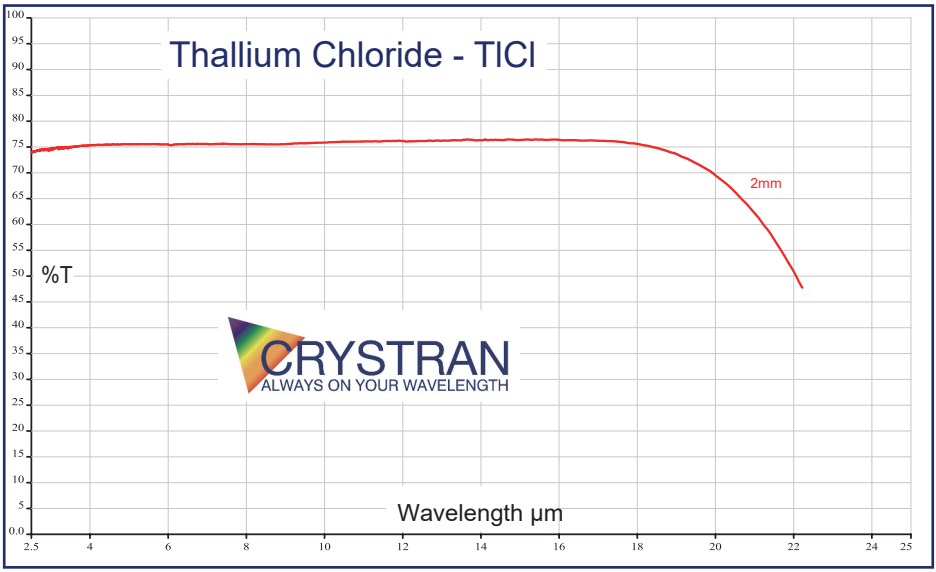
APPLICATIONS: Thallium Chloride has little practical application.

Transmission Range	0.5 to 30µm
Refractive Index	2.193 at 10µm (1)
Reflection Loss	24.5% at 10µm (2 surfaces)
Absorption Coefficient	n/a
Reststrahlen Peak	131µm
dn/dT	n/a
dn/dµ = 0	3.5µm
Density	7.018 g/cc (1)
Melting Point	430.2 °C (1)
Thermal Conductivity	0.75 W m^{-1} K^{-1} at 311K
Thermal Expansion	53 x 10^{-6} K^{-1} at 300K
Hardness	Knoop 12.8 with 500g indenter
Specific Heat Capacity	218 J Kg^{-1} K^{-1}
Dielectric Constant	31.9 at 1 MHz
Youngs Modulus (E)	31.71 Gpa (2)
Shear Modulus (G)	7.58 GPa (2)
Bulk Modulus (K)	23.57 Gpa (2)
Elastic Coefficients	C_{11}=40.1; C_{12}=15.3; C_{44}=7.6 (2)
Apparent Elastic Limit	20.7 MPa (3000 psi)
Poisson Ratio	0.276
Solubility	0.32g/100g water at 20°C
Molecular Weight	239.85
Class/Structure	Cubic CsCl, Pm3m, no cleavage planes (1)

(1) Handbook of Optical Constants, ed Palik, V3, ISBN 0-12-544423-0
(2) Arenberg, Measurements made at Naval Research Labs, USA 1948-49

Thallium Chloride (TlCl)

µm	No	µm	No	µm	No	µm	No	µm	No
0.436	2.4	0.578	2.253	0.650	2.223	10.00	2.193		
0.546	2.27	0.589	2.247	0.750	2.198				



Yttrium Aluminium Garnet (YAG)

YAG crystal is produced by the Czochralski growth process up to approximately 100mm diameter.

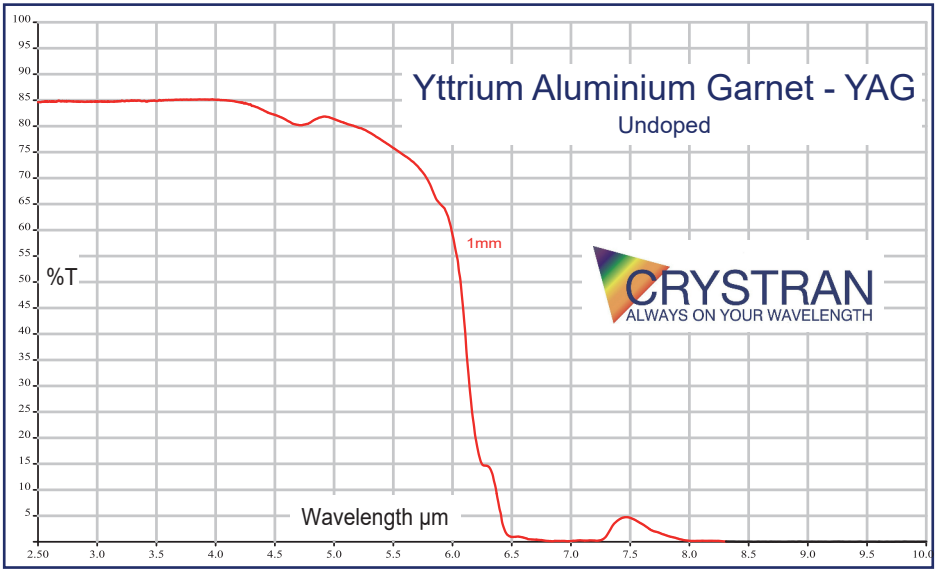
APPLICATIONS: YAG (Yttrium aluminium oxide $Y_3Al_5O_{12}$) is an active laser crystal when dopants such as Nd, Tm, Er, and Cr are used. Being cubic there is no double refraction and it is sometimes used for a window material substituting for sapphire.

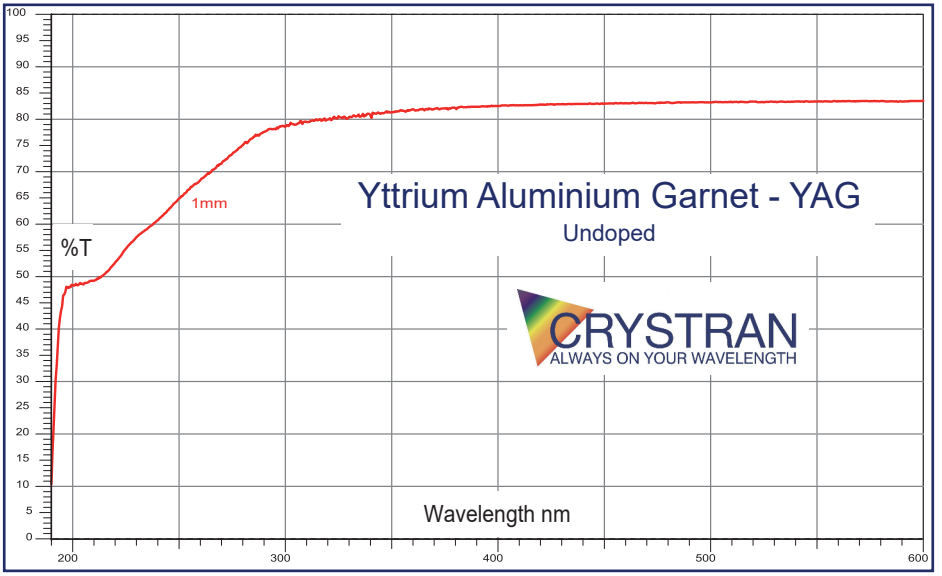
Transmission Range	0.21 to 5.5µm
Refractive Index	1.81523 at 1.06µm (1)
Reflection Loss	16.7% at 1.06µm
Absorption Coefficient	n/a
Reststrahlen Peak	n/a
dn/dT	$+9.1 \times 10^{-6}$ K^{-1} at 1064nm (2)
dn/dµ = 0	n/a
Density	4.56 g/cc
Melting Point	1940 °C
Thermal Conductivity	12.9 W m^{-1} K^{-1}
Thermal Expansion	7.8 (111), 7.7 (110), 8.2×10^{-6} K^{-1} (100)
Hardness	Knoop 1215
Specific Heat Capacity	590 J Kg^{-1} K^{-1}
Dielectric Constant	11.7
Youngs Modulus (E)	300 GPa
Shear Modulus (G)	n/a
Bulk Modulus (K)	n/a
Elastic Coefficients	C_{11}=333; C_{12}=111; C_{44}=115
Apparent Elastic Limit	280 MPa
Poisson Ratio	0.28
Solubility	Insoluble in water
Molecular Weight	593.62
Class/Structure	Cubic garnet, m3m

(1) Handbook of Optical Constants, ed Palik, V3, ISBN 0-12-544423-0
(2) Wilson, Thermo-Optic Coefficients. PhD dissertation. U Southern Calif. Jan 1980

Yttrium Aluminium Garnet (YAG)

µm	No	µm	No	µm	No	µm	No	µm	No
0.266	1.9278	0.808	1.8217	1.333	1.8146	2.014	1.8123		
0.354	1.8725	0.946	1.8186	1.444	1.8140	2.097	1.8121		
0.532	1.8368	1.030	1.8173	1.500	1.8137	2.123	1.8121		
0.800	1.8245	1.064	1.8169	1.640	1.8132	2.940	1.8113		





Zinc Selenide (ZnSe)

Zinc Selenide is produced by synthesis from Zinc vapour and H_2Se gas, forming as sheets on a graphite substrate. Zinc Selenide is microcrystalline in structure, the grain size being controlled to produce maximum strength. Single crystal ZnSe is available, but is not common but has been reported as having lower absorption and thus more effective for CO_2 optics.

APPLICATIONS: ZnSe is used widely for IR components, windows and lenses, and for spectroscopic ATR prisms. Zinc Selenide is one of the materials of choice for CO_2 laser optics operating at 10.6µm.

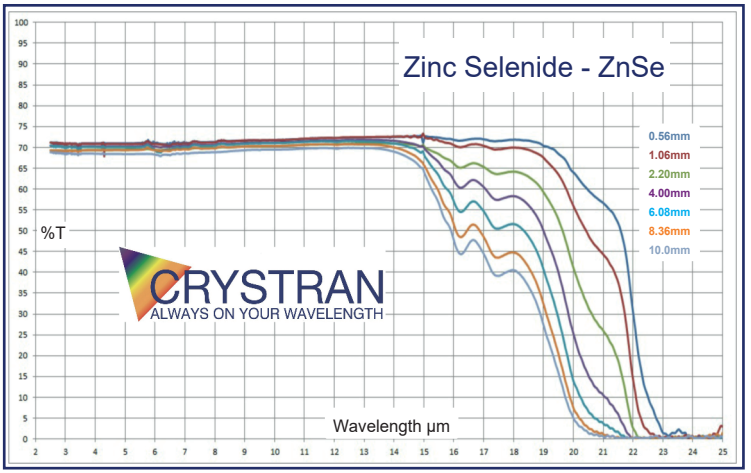
Transmission Range	0.6 to 21.0µm
Refractive Index	2.4028 at 10.6µm
Reflection Loss	29.1% at 10.6µm (2 surfaces)
Absorption Coefficient	0.0005 cm^{-1} at 10.6µm (2) 0.0004 cm^{-1} at 5.25µm (2) 0.0004 cm^{-1} at 3.8µm (2) 0.0007 cm^{-1} at 2.7µm (2) 0.005 cm^{-1} at 1.3µm (2)
Reststrahlen Peak	45.7µm
dn/dT	+61 x 10^{-6} K^{-1} at 10.6µm at 298K
dn/dµ = 0	5.5µm
Density	5.27 g/cc
Melting Point	1525°C *See notes below
Thermal Conductivity	18 W m^{-1} K^{-1} at 298K
Thermal Expansion	7.1 x 10^{-6} K^{-1} at 273K
Hardness	Knoop 120 with 50g indenter
Specific Heat Capacity	339 J Kg^{-1} K^{-1}
Dielectric Constant	n/a
Youngs Modulus (E)	67.2 GPa
Shear Modulus (G)	n/a
Bulk Modulus (K)	40 GPa
Elastic Coefficients	Not Available
Apparent Elastic Limit	55.1 MPa (8000 psi) (1)
Poisson Ratio	0.28
Solubility	0.001g/100g water
Molecular Weight	144.33
Class/Structure	FCC Cubic, F43m (#216), Zinc Blende Structure (Polycrystalline)

** Zinc Selenide oxidizes significantly at 300°C, exhibits plastic deformation at about 500°C and dissociates about 700°C. For safety, Zinc Selenide windows should not be used above 250°C in normal atmosphere*

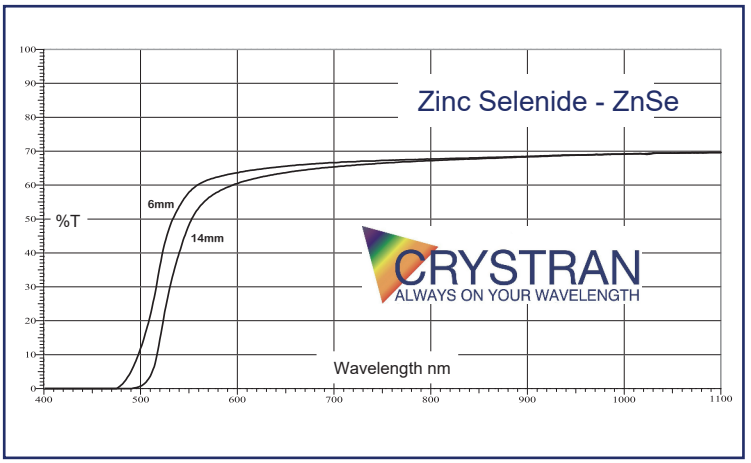
(1) Manufacturing Methods program ZnSe blanks. US Army R&D Feb 1980
(2) Manufacturers Published Data.

Zinc Selenide (ZnSe)

µm	No	µm	No	µm	No	µm	No	µm	No
0.54	2.6754	1.0	2.4892	5.8	2.4266	10.6	2.4028	15.4	2.3623
0.58	2.6312	1.4	2.4609	6.2	2.4251	11.0	2.4001	15.8	2.3579
0.62	2.5994	1.8	2.4496	6.6	2.4235	11.4	2.3974	16.2	2.3534
0.66	2.5755	2.2	2.4437	7.0	2.4218	11.8	2.3945	16.6	2.3487
0.7	2.5568	2.6	2.4401	7.4	2.4201	12.2	2.3915	17.0	2.3438
0.74	2.5418	3.0	2.4376	7.8	2.4183	12.6	2.3883	17.4	2.3387
0.78	2.5295	3.4	2.4356	8.2	2.4163	13.0	2.3850	17.8	2.3333
0.82	2.5193	3.8	2.4339	8.6	2.4143	13.4	2.3816	18.2	2.3278
0.86	2.5107	4.2	2.4324	9.0	2.4122	13.8	2.3781		
0.90	2.5034	4.6	2.4309	9.4	2.4100	14.2	2.3744		
0.94	2.4971	5.0	2.4295	9.8	2.4077	14.6	2.3705		
0.98	2.4916	5.4	2.4281	10.2	2.4053	15.0	2.3665		



Transmission data table for these curves can be downloaded from the Crystran website



Zinc Sulphide (Zinc Sulfide) FLIR (ZnS)

Zinc Sulfide is produced by synthesis from Zinc vapour and H_2S gas, forming as sheets on a graphite substrate. Zinc Sulfide is microcrystalline in structure, the grain size being controlled to produce maximum strength. Forward Looking Infra-Red (FLIR) grade, which is pale yellow and translucent in the visible, is used as deposited without further treatment. It is stronger than multispectral grade. Single crystal ZnS is available, but is not common.

APPLICATIONS: ZnS FLIR is used for IR windows and lenses in the thermal band (8 to 14µm) as a tough front optic in thermal imaging systems, particularly those subjected to harsh environments.

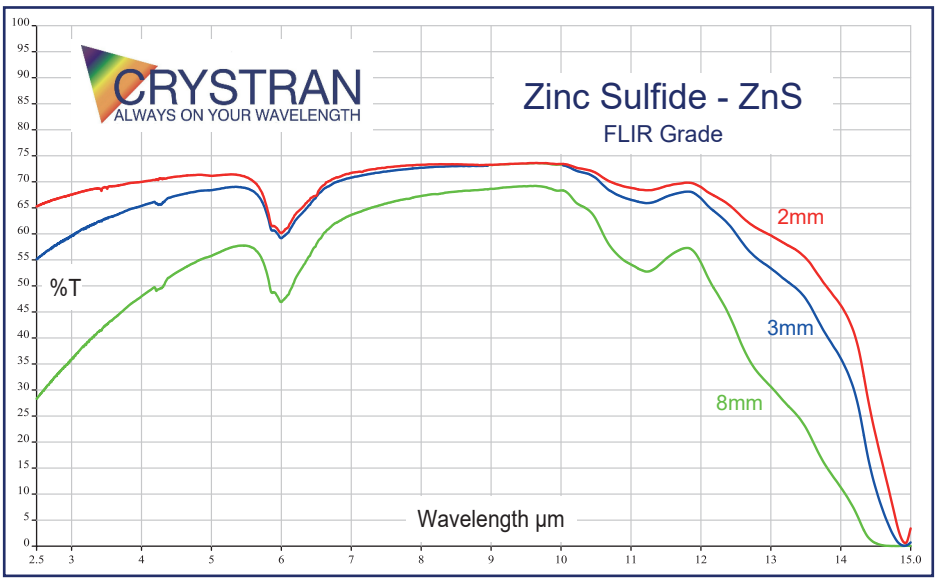
Transmission Range	1.0 to 13µm
Refractive Index	2.192 at 10.6µm
Reflection Loss	24.6% at 10.6µm (2 surfaces)
Absorption Coefficient	0.2 cm^{-1} at 10.6µm (1)
	0.02 cm^{-1} at 3.8µm
Reststrahlen Peak	30.5µm
dn/dT	+43 x 10^{-6} K^{-1} at 3.39µm
dn/dµ = 0	n/a
Density	4.08 g/cc
Melting Point	1827°C *See notes below
Thermal Conductivity	16.7 W m^{-1} K^{-1} at 296K
Thermal Expansion	6.6 x 10^{-6} K^{-1} at 273K
Hardness	Knoop 160 with 50g indenter
Specific Heat Capacity	469 J Kg^{-1} K^{-1}
Dielectric Constant	n/a
Youngs Modulus (E)	74.5 GPa
Shear Modulus (G)	n/a
Bulk Modulus (K)	n/a
Elastic Coefficients	Not Available
Apparent Elastic Limit	103.4 MPa (15,000 psi)
Poisson Ratio	0.29
Solubility	65 x 10^{-6} g/100g water
Molecular Weight	97.43
Class/Structure	Polycrystalline cubic, ZnS, F43m

** Zinc Sulfide oxidises significantly at 300°C, exhibits plastic deformation at about 500°C and dissociates about 700°C. For safety, Zinc Sulfide windows should not be used above 250°C in normal atmosphere.*

(1) Manufacturers Published Data.

Zinc Sulphide (Zinc Sulfide) FLIR (ZnS)

µm	No	µm	No	µm	No	µm	No	µm	No
0.42	2.516	0.90	2.301	4.60	2.248	9.40	2.208	14.2	2.126
0.46	2.458	0.94	2.297	5.00	2.246	9.80	2.203	14.6	2.116
0.50	2.419	0.98	2.294	5.40	2.244	10.2	2.198	15.0	2.106
0.54	2.391	1.00	2.292	5.80	2.241	10.6	2.192	15.4	2.095
0.58	2.371	1.40	2.275	6.20	2.238	11.0	2.186	15.8	2.084
0.62	2.355	1.80	2.267	6.60	2.235	11.4	2.18	16.2	2.072
0.66	2.342	2.20	2.263	7.00	2.232	11.8	2.173	16.6	2.059
0.70	2.332	2.60	2.26	7.40	2.228	12.2	2.167	17.0	2.045
0.74	2.323	3.00	2.257	7.80	2.225	12.6	2.159	17.4	2.03
0.78	2.316	3.40	2.255	8.20	2.221	13.0	2.152	17.8	2.015
0.82	2.31	3.80	2.253	8.60	2.217	13.4	2.143	18.2	1.998
0.86	2.305	4.20	2.251	9.00	2.212	13.8	2.135		



Zinc Sulphide (Zinc Sulfide) Multispectral (ZnS)

Zinc Sulfide is produced by synthesis from Zinc vapour and H_2S gas, forming as sheets on a graphite substrate. Zinc Sulfide is microcrystalline in structure, the grain size being controlled to produce maximum strength. Multispectral grade is then Hot Isostatically Pressed (HIP) to improve the mid IR transmission and produce the visibly clear form. Single crystal ZnS is available, but is not common.

APPLICATIONS: ZnS Multispectral (water-clear) is used for IR windows and lenses in the thermal band (8 to 14µm) where maximum transmission and lowest absorption is required. Also selected for use where visible alignment is an advantage.

Transmission Range	0.37 to 13.5µm
Refractive Index	2.20084 at 10µm (1)
Reflection Loss	24.7% at 10µm (2 surfaces)
Absorption Coefficient	0.2 cm^{-1} at 10.6µm (2)
	0.006 cm^{-1} at 9.27µm(2)
	0.0006 cm^{-1} at 3.8µm (2)
	0.0001 cm^{-1} at 2.7µm (2)
	0.0006 cm^{-1} at 1.3µm (2)
Reststrahlen Peak	30.5µm
dn/dT	+38.7 x 10^{-6} K^{-1} at 3.39µm
dn/dµ = 0	n/a
Density	4.09 g/cc
Melting Point	1827°C *See notes below
Thermal Conductivity	27.2 W m^{-1} K^{-1} at 298K
Thermal Expansion	6.5 x 10^{-6} K^{-1} at 273K
Hardness	Knoop 240 with 50g indenter
Specific Heat Capacity	515 J Kg^{-1} K^{-1}
Dielectric Constant	88
Youngs Modulus (E)	74.5 GPa
Shear Modulus (G)	n/a
Bulk Modulus (K)	n/a
Elastic Coefficients	Not Available
Apparent Elastic Limit	68.9 MPa (10,000 psi)
Poisson Ratio	0.28
Solubility	65 x 10^{-6} g/100g water
Molecular Weight	97.43
Class/Structure	HIP polycrystalline cubic, ZnS, F42m

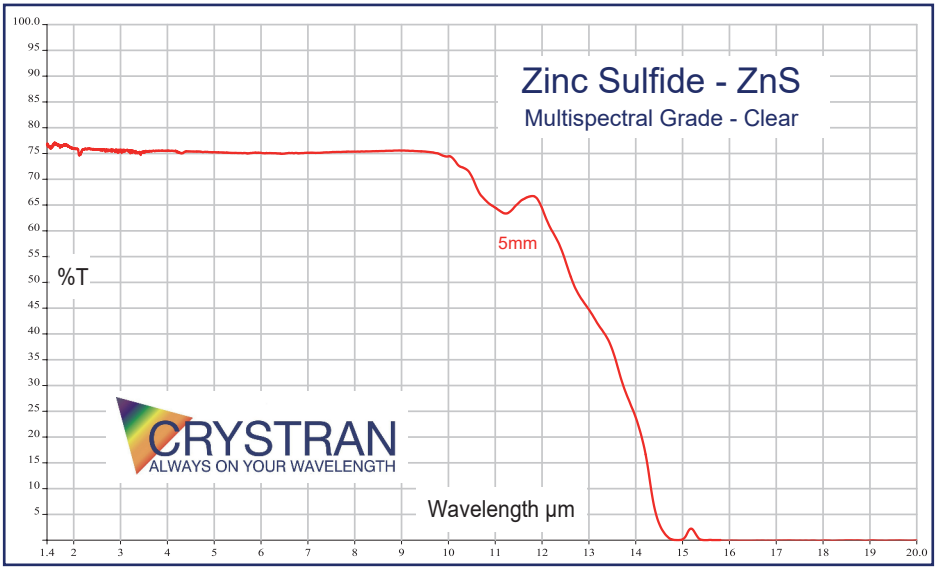
** Zinc Sulfide oxidizes significantly at 300°C, exhibits plastic deformation at about 500°C and dissociates about 700°C. For safety, Zinc Sulfide windows should not be used above 250°C in normal atmosphere.*

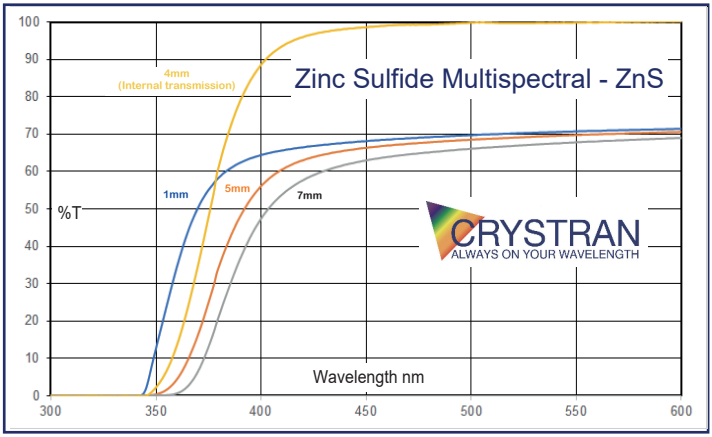
(1) Refractive Indices of Zinc Sulfide. Mary Debenham (NPL) Applied OPtics / Vol 23, No 14 / July 1984
(2) Manufacturers Published Data.

Zinc Sulphide (Zinc Sulfide) Multispectral (ZnS)

MATERIALS DATA

µm	No	µm	No	µm	No	µm	No
0.4047	2.54515	0.6678	2.34033	1.5296	2.27191	9.000	2.21290
0.4358	2.48918	0.7065	2.33073	2.0581	2.26442	10.00	2.20084
0.4678	2.44915	0.780	2.31669	3.000	2.25772	11.25	2.18317
0.480	2.43691	0.7948	2.31438	3.500	2.25498	12.00	2.17101
0.5086	2.41279	0.8521	2.30659	4.000	2.25231	13.00	2.15252
0.5461	2.38838	0.8943	2.30183	4.500	2.24955		
0.5876	2.36789	1.014	2.29165	5.000	2.24661		
0.6438	2.34731	1.1287	2.28485	8.000	2.22334		



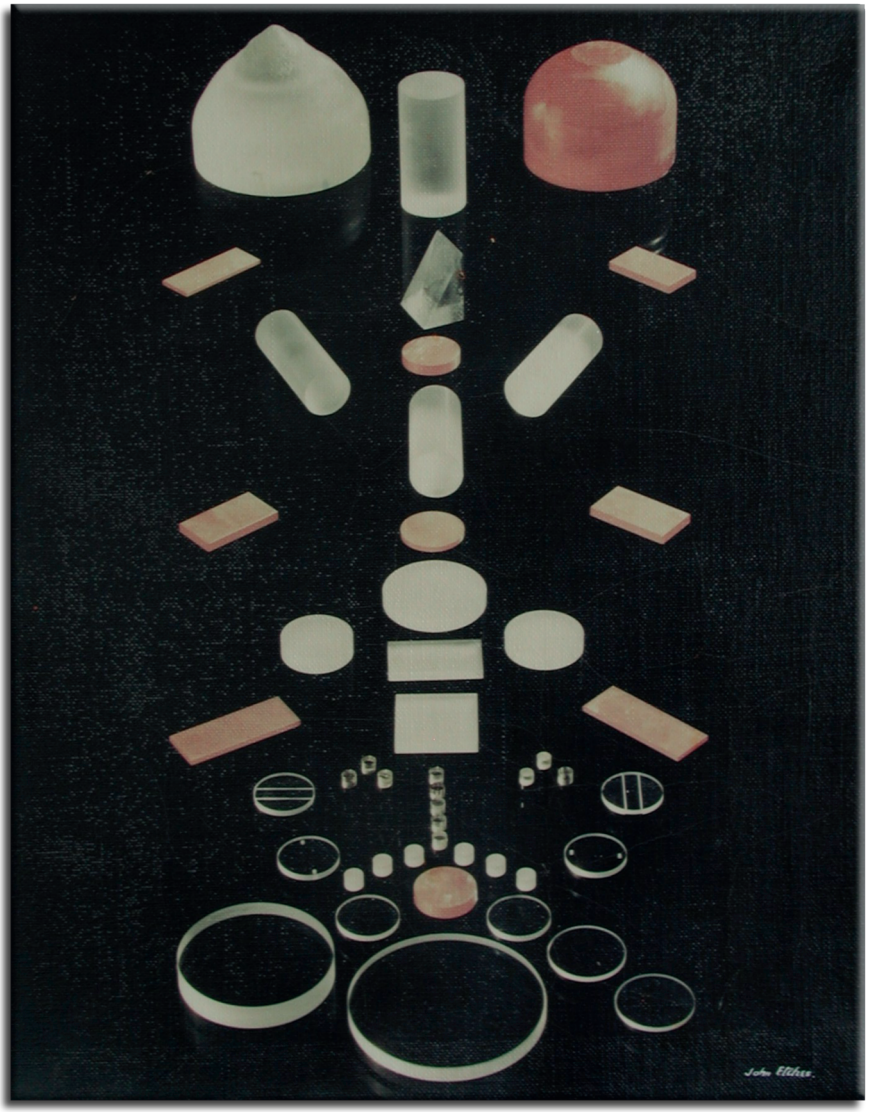


Fundamental Constants

An abbreviated list of the CODATA recommended values of the fundamental constants of physics and chemistry based on the 2014 adjustment.

Quantity	Symbol	Value	Uncert
Speed of light in vacuum	c, c_o	299 792 458 m s^{-1}	(exact)
Magnetic constant	μ_o	$4\pi \times 10^{-7}$ N A^{-2}	(exact)
Electric constant $1/\mu_o c^2$	ε_o	8.854 187 817... $\times 10^{-12}$ F m^{-1}	(exact)
Gravitational Constant	G	6.674 08(31) $\times 10^{-11}$ m^3 kg^{-1} s^{-2}	4.7×10^{-5}
Planck constant	h	6.626 070040(81) $\times 10^{-34}$ J s	1.2×10^{-8}
$h/2\pi$	$\hbar$	1.054 571 800(13) $\times 10^{-34}$ J s	1.2×10^{-8}
Elementary charge	e	1.602 176 6208(98) $\times 10^{-19}$ C	6.1×10^{-9}
Magnetic flux quantum $h/2e$	ϕ_o	2.067 833 831(13) $\times 10^{-15}$ Wb	6.1×10^{-9}
Conductance quantum $2e^2/h$	G_o	7.748 091 7310(18) $\times 10^{-5}$ S	2.3×10^{-10}
Electron mass	m_e	9.109 383 56(11) $\times 10^{-31}$ kg	1.2×10^{-8}
Proton mass	m_p	1.672 621 898(21) $\times 10^{-27}$ kg	1.2×10^{-8}
Fine-structure const $e^2/4\pi\varepsilon_o\hbar c$	α	7.297 352 5664(17) $\times 10^{-3}$	2.3×10^{-10}
Inverse fine-structure constant	α^{-1}	137.035 999 139(31)	2.3×10^{-10}
Rydberg constant $\alpha^2 m_e c/2h$	R_∞	10 973 731.568 508(65) m^{-1}	5.9×10^{-12}
Avogadro constant	N_A, L	6.022 140857(74) $\times 10^{23}$ mol^{-1}	1.2×10^{-8}
Faraday constant $N_A e$	F	96 485.33289(59) C mol^{-1}	6.2×10^{-9}
Molar gas constant	R	8.314 459 8(48) J mol^{-1} K^{-1}	5.7×10^{-7}
Boltzmann constant R/N_A	k	1.380 648 52(79) $\times 10^{-23}$ J K^{-1}	5.7×10^{-7}
Stefan-Boltzmann constant $(\pi^2/60)k^4/\hbar^3c^2$	σ	5.670 367(13) $\times 10^{-8}$ W m^{-2} K^{-4}	2.3×10^{-6}
Non-SI units accepted for use with the SI			
Electron volt: (e/C) J	eV	1.602 176 620 8(98) $\times 10^{-19}$ J	6.1×10^{-9}
(unified) atomic mass unit $\frac{1}{12}$ m (^{12}C)	u	1.660 539 040(20) $\times 10^{-27}$ kg	1.2×10^{-8}

CODATA Recommended Values of the Fundamental Physical Constants: 2014
Peter J. Mohr, Barry N. Taylor, and David B. Newell, NIST, USA (25/06/2015)



Original photograph of crystals and crystal products by John Etches 1983

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