# Exemption Request Form

Date of submission:

## 1. Name and contact details

### 1) Name and contact details of applicant:


| | | | |
|---|---|---|---|
| Company: | Spectaris e.V. | Tel.: | +49 30 41 40 21 25 |
| Name: | Dr. Wenko Süptitz | E-Mail: | sueptitz@spectaris.de |
| Function: | Head of Photonics Division | Address: | Werderscher Markt 15, 10117 Berlin, Germany |


## 2. Reason for application:

Please indicate where relevant:

☐ Request for new exemption in:

☐ Request for amendment of existing exemption in

☒ Request for extension of existing exemption in Annex III

☐ Request for deletion of existing exemption in:

☒ Provision of information referring to an existing specific exemption in:

☒ Annex III ☐ Annex IV

No. of exemption in Annex III or IV where applicable: 13a

Proposed or existing wording: Lead in white glasses used for optical applications

Duration where applicable: We apply for renewal of this exemption for the categories marked in section 4 further below for the respective maximum validity periods foreseen in the RoHS2 Directive, as amended. For these categories, the validity of this exemption may be required beyond those timeframes.

☐ Other:

## 3. Summary of the exemption request / revocation request

This exemption renewal request is for the use of lead in optical glass that is used in electrical and electronic equipment. Optical glass containing lead is used in a very wide variety of applications and in many types of equipment. Lead based glass types are used because they have unique combinations of properties and characteristics that cannot be achieved by lead-free optical glass or by different designs. As a result, the technical requirements of the glass and the equipment in which it is used can only be achieved with lead-based optical glass.

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# 4. Technical description of the exemption request / revocation request

**(A) Description of the concerned application:**

1. To which EEE is the exemption request/information relevant?

   Name of applications or products: Please refer to page 9.

a. List of relevant categories: (mark more than one where applicable)

| | |
|---|---|
| ☒ 1 | ☒ 7 |
| ☒ 2 | ☒ 8 |
| ☒ 3 | ☒ 9 |
| ☒ 4 | ☒ 10 |
| ☒ 5 | ☒ 11 |
| ☒ 6 | |

b. Please specify if application is in use in other categories to which the exemption request does not refer:

c. Please specify for equipment of category 8 and 9:

   The requested exemption will be applied in

   ☒ monitoring and control instruments in industry

   ☒ in-vitro diagnostics

   ☒ other medical devices or other monitoring and control instruments than those in industry

2. Which of the six substances is in use in the application/product?

   (Indicate more than one where applicable)

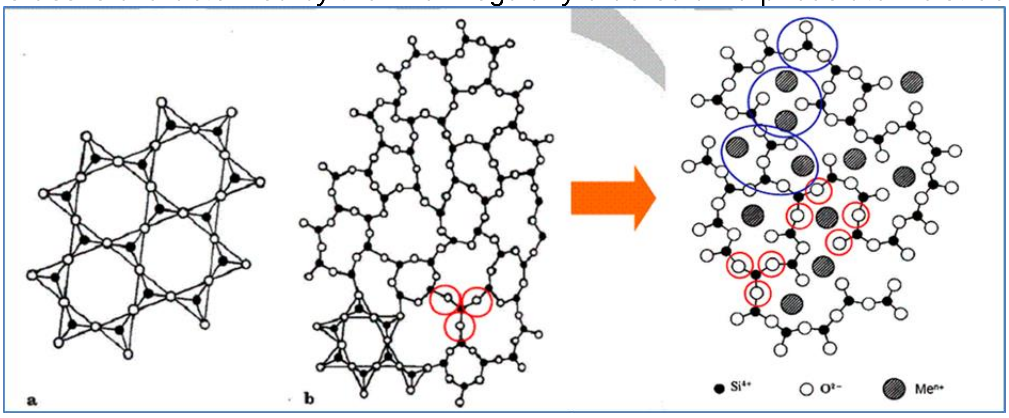
   ☒ Pb ☐ Cd ☐ Hg ☐ Cr-VI ☐ PBB ☐ PBDE

3. Function of the substance: Lead is one of the main constituents of optical glass that are formulated to achieve specific combinations of critical properties

4. Content of substance in homogeneous material (%weight): The family of lead containing optical glass typically contain 40 – 70% by weight of lead oxide, thus 37 - 65% of lead by weight. The complete range over all known optical glass types is 0.5 – 75% wt (excluding lead in glass used for radiation shielding and covered by Annex IV exemption 5).

5. Amount of substance entering the EU market annually through application for which the exemption is requested: 275 tonnes lead per year
   Please supply information and calculations to support stated figure:
   The market demand for lead-containing glass types has been stable since 2014. Based on this stability, we estimate that global production of lead based optical glass used in EEE to be 1,250 tons per year. About 40% of EEE is placed on the EU market so this will contain 500 tons of lead based optical glass. Calculated with the average lead content of approximately 55% lead that would be 275 tons of lead p.a.
6. Name of material/component: "Optical glass" of varied compositions which typically contain Pb, Si, Na, Ca and other elements as various mixed oxide compositions.

Glass is characterized by their non-regularly ordered amorphous atomic structure




crystalline $SiO_2$ amorphous $SiO_2$ multi-component glass

**Figure 1. Atomic structures of silica and multi-component glass**

Glass is produced from different constitutional components:

1. Glass formers form glass network

| | |
|---|---|
| - $SiO_2$ | silicon dioxide |
| - $B_2O_3$ | boron oxide |
| - $P_2O_5$ | phosphorus oxide |

2. Network modifiers break up the network

alkaline oxides:

| | |
|---|---|
| - $L_{i2}O$ | Lithium oxide |
| - $Na_2O$ | sodium oxide |
| - $K_2O$ | potassium oxide |

Alkaline earth oxides such as CaO

Rare earths elements

Etc.

3. Intermediate elements added as oxides may also be bound into the network

- $Al_2O_3$ aluminum oxide
- MgO magnesium oxide

4. Additional agents introducing special properties

- Coloring ions
  Fe, Mn, Cr(III), V, Co, Cu, Cd, Se, .
- Laser active ions
  $Nd^{3+}$, $Yb^{3+}$, $Er^{3+}$, …
- Ionizing radiation stabilization compounds
  - $CeO_2$
- etc.

A crystalline structure with its composition well defined by chemical formula e.g. silicon dioxide: quartz, is:

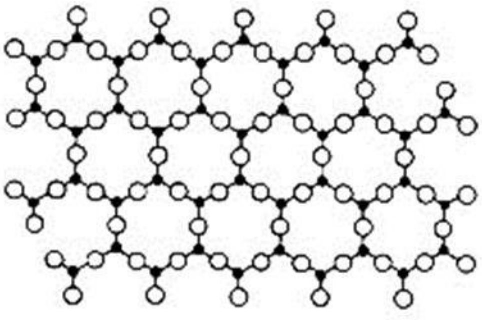


**Figure 2. Atomic structure of crystalline silica**

An amorphous structure still having a well-defined composition and precise chemical formula, e.g.: amorphous silicon dioxide: fused silica.

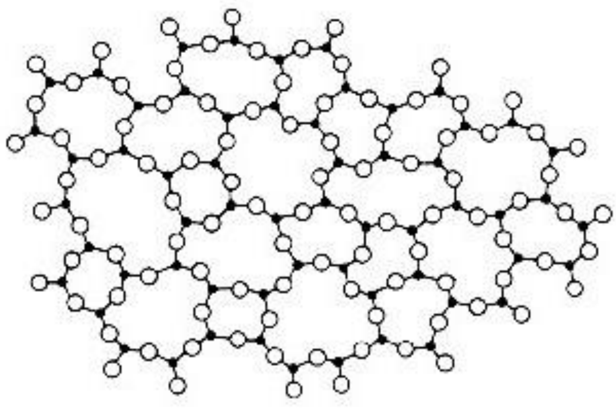


**Figure 3. Atomic structure of amorphous silica**

An amorphous structure produced on the basis of a defined recipe, but without composition that can be well defined by a chemical formula, e.g. sodium - lime glass with a broad range of possible contents of sodium and potassium. In the figure below, only sodium ions are shown for simplicity.

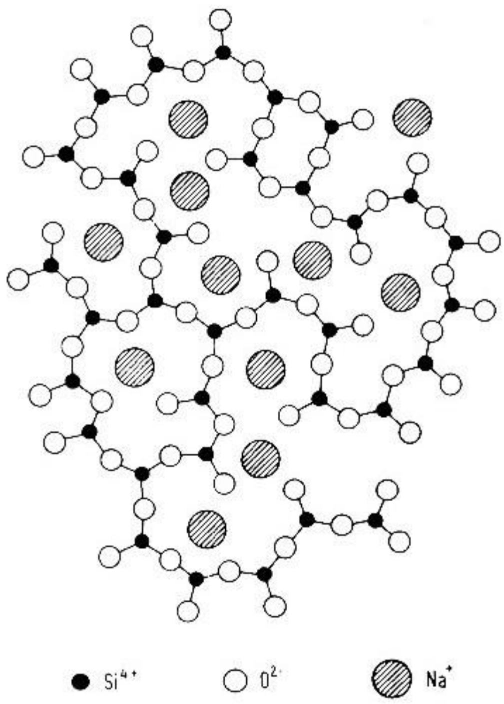



**Figure 4. Atomic structure of a soda-lime glass (showing only Si, O and Na)**

7. Environmental Assessment:
   LCA: ☐ Yes
   ☒ No

**(B) In which material and/or component is the RoHS-regulated substance used, for which you request the exemption or its revocation? What is the function of this material or component?**

Lead containing glass types are produced in continuous melting tanks with a daily production volume of about 2 tonnes. This technique is used also for other glass types such as borosilicate crown, dense crown, barium crown and barium flint glass, which presently comprise more than 30 glass types of the glass production of SCHOTT AG. The production method is optimized for high quality and minimal waste. This production method used for lead containing glass types is identical to the process used for lead-free optical glass types.

The second essential process in optical glass production is fine annealing. Annealing is a heat treatment that alters the physical and sometimes chemical properties of a material to make it more workable and durable. It is needed to finely adjust refractive index and optical dispersion to the very stringent tolerances required and to achieve high homogeneity (consistent purity and properties) and low stress birefringence (see section 4 (C)). Every item of each glass type is subject to this process. There is no difference in the temperature treatment between lead containing and lead free glass.

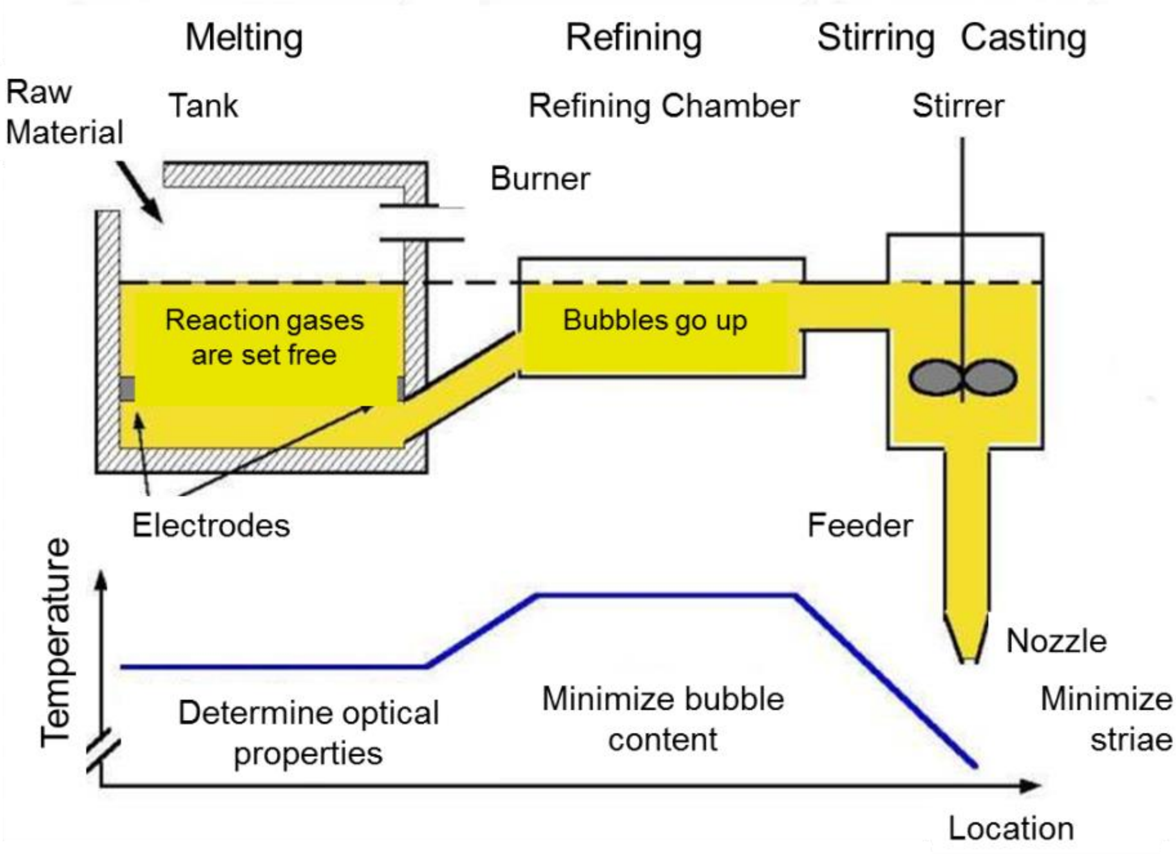



**Figure 5: Continuous melting tank for optical glass: Raw material is fed regularly into the melting tank; molten glass flows through the refining chamber and then the stirrer to the nozzle. It is then cast into the desired delivery form as strips, blocks, rods or large castings**

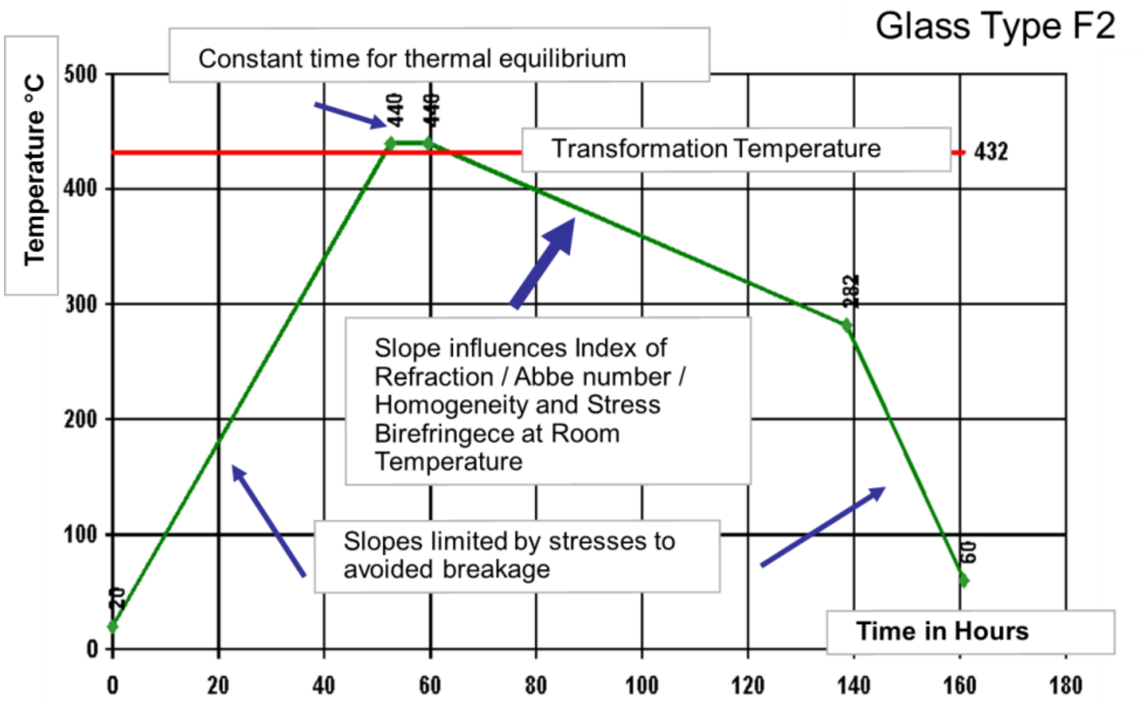



**Figure 6: Fine annealing is a tempering process, where the glass is cooled down in a special range with linearly falling temperature. This needs furnaces with highly homogeneous temperature volume and precise control. The transformation temperature (red line) corresponds to the crystallisation / glass phase transition and the green line is the temperature of the glass during the short annealing process in which the glass network undergoes thermally induced rearrangement**

The main processing steps of optical glass purchased from glass manufacturers such as SCHOTT, OHARA or HOYA are as bulleted below. There are no differences whether these are Pb-free or Pb-containing glass:

- sawing and cutting into smaller pieces
- surfacing/shaping by coarse grinding
- surfacing/shaping by fine grinding
- surfacing/shaping by lapping
- surfacing/shaping by rough polishing (pre-polishing)
- centration (to adjust for the proper optical axis)
- surfacing/shaping by fine polishing
- cleaning
- deposition of antireflective coating layers (AR-coating)
- assembly of thus manufactured optical elements (i.e.: lenses, prisms etc.) together with metal parts (i.e. lens element mounts), polymer parts, electronics, subassemblies etc. to the final product

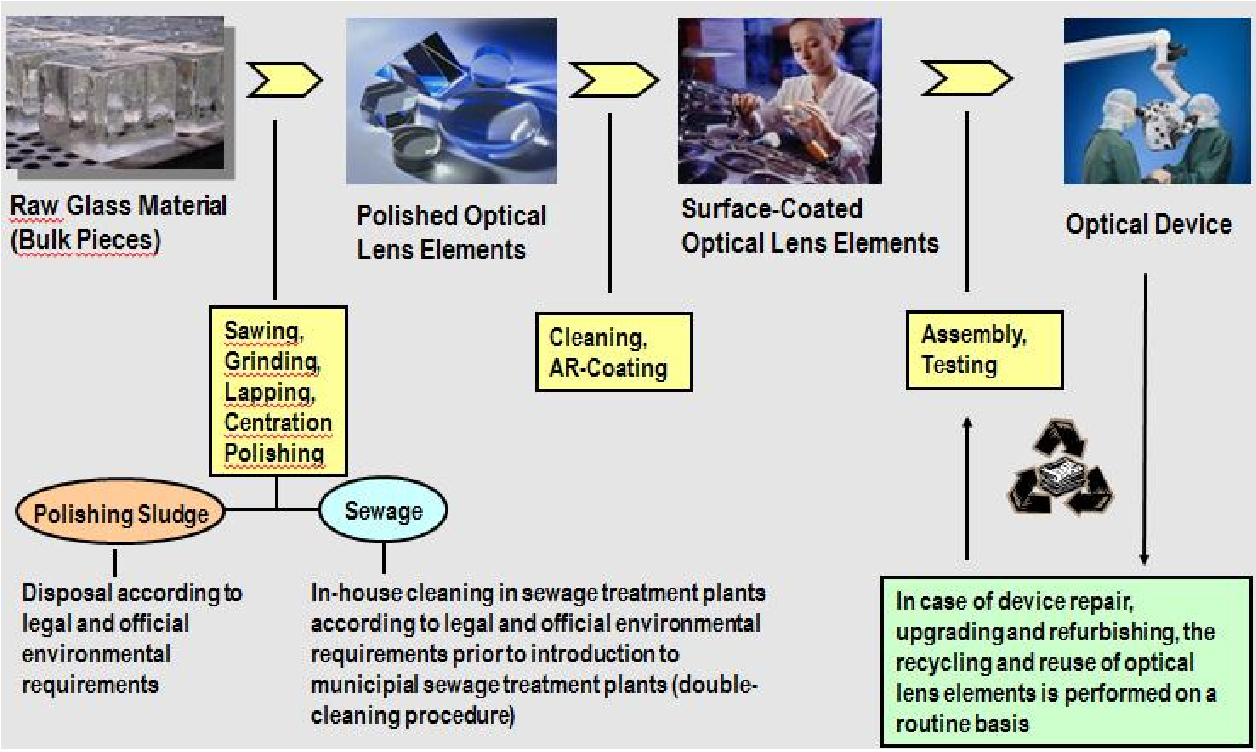



**Figure 7: Processing steps of optical glass**

Measurement and testing of glass between the various steps within the process chain and for the final assembled product itself are the same irrespective whether Pb-containing or Pb-free glass is processed.

Optical glass containing lead is used in very many different types of EEE.

Illustrative examples include the following uses:

- Lenses for professional photographic cameras (category 4) – these consist of multiple concave and convex lens elements, which are made with a variety of types of glass each having different but essential characteristics. These lenses need to be precisely designed to achieve the best optical performance.
- Lenses for video and television cameras, camcorders, movie projectors and for photo-laboratory equipment (category 4) – these are even more complex than still camera lenses requiring more individual lenses. Lenses with 12 or more elements are not unusual. As there is a significant thickness of glass that light must pass, the transmission performance in the entire visible spectrum of all glass types used must be as high as possible.
- Cine photography (category 4) – requires the use a variety of high-quality lenses. The characteristics, such as image quality and colour location of an individual lens of a given focal length must be taken into consideration, but unlike still photography, the lens must be regarded as part of a set of lenses of different focal lengths (prime and zoom lenses). Sets of objective lenses (groups of specially selected lenses) are matched to each other and thus form a contiguous set, where one part (lens) cannot be replaced by another one easily, as it requires matching to the other lenses.

  In cinema movies, a sequence will be cut into takes from different views and distances which is achieved by using lenses with different focal lengths. The observer’s eye is very sensitive to colour changes (or as it is called in photography: colour or white balance) between different takes of the same scenery.

**Figure 8: Pictures of a lily as shot with a digital camera (left) and with colour balance correctly adjusted to the illumination conditions (right) changing from a colder to a warmer perception (from Wikipedia "Colour balance").**
**If such changes in colour balance occur from one take to another of the same scenery, this would be very disturbing to the viewer**

One company's advertisements state that their lenses are colour matched to the other lenses in the same range, to guarantee seamless cuts between scenes and to avoid time-consuming colour matching in post. Many of these lenses need to use leaded glass.

In consequence, the distribution in both the image quality and the colour location of all the lenses required within one set of lenses must be reduced to a level where any differences are too small to be noticeable. The loss of one or two lenses (e.g. due to withdrawal of exemption 13a), depending on the quality of the focal lengths in a batch, could jeopardize the usability of an entire set. This also relates to cases of replacements for irreparable lenses that are sold in sets (see additional information for explanation).

- Lenses for high performance binoculars and telescopes having electrical functions (category 4).
- Optical systems designed for telecom applications in the near IR spectral range from 1000 to 1500 nm (category 3).
- Digital projectors and rear projection televisions (category 4). Lead glass lenses and prisms are used because these are the only types of glass that have high % transmission at shorter wavelengths and do not cause distortion of the image when the glass temperature increases by heating from the intense light source. This is because the refractive index is less affected by temperature changes than lead-free glass. Heating the glass also affects focusing of the image causing distortion but lead glass lenses can compensate for temperature changes to avoid distortion.
- Endoscopes used for inspection of engineered products (category 6 or 9).
- Medical endoscopes (category 8).
- Fibres for high quality illumination units for medical operation microscopes in microsurgery (category 8).
- Surgical microscopes (category 8).
- Professional ophthalmic instruments (category 8).
- Optical lenses made of lead-glass are used in medical devices to manipulate and focus the laser light onto tissue to create incisions in the eye with very high accuracy for eye surgery (category 8).
- Temperature compensated high end optical imaging systems for medical applications (category 8).
- Temperature compensated high end optical imaging systems for printing and photolithography applications used for industrial tools (category 6). More details on why lead glass is needed for photolithography are given below.
- Optics used in instruments for applications and diagnosis in the near UV-region such as bio-fluorescence, gene analyses and print-scanners (categories 8 and 9).

- Spectrometers (visible and ultra-violet (UV) light) used for chemical analysis and for environmental monitoring (category 9).
- Polarimeters are used to characterize the optical activity of substances. This is for example important for enantiomeric[1] purity control of pharmaceutical substances to prevent harmful secondary effects of enantiomeric contaminations. It is thought that only one of the enantiomeric forms of the thalidomide drug (the Contergan-scandal from 1957 to 1962) directly caused birth abnormalities. A central element of polarimeters are Faraday modulators containing glass rods which excel via their ability to rotate the polarization plane of linear polarized light when a magnetic field is applied. These glass rods must have a high optical dispersion (Verdet-constant) to fulfil their function. High dispersion can only be obtained by adding lead to the glass formulation. To date, there is no alternative to lead in high-dispersive glass.
- Colour correction lenses used for most of the above applications. These correct for colour aberration (see Section 4 (C) below), eliminate stray light and unwanted reflections to achieve the best possible image quality.
- Relay lens **–** these are used to invert images and are used in periscopes, endoscopes, telescopes, microscopes, etc.
- CNC video measuring systems, which are used to measure the dimensions of very small objects such as engineered parts such as for aircraft, e.g. precision made fuel valves and small watch components, silicon wafers for semiconductor and Microelectrical Mechanical System (MEMS) devices. These use high brightness lamps with prisms and lenses which need to have a high internal transmittance at all visible wavelengths and a very low (near zero) photoelastic constant (β) to avoid distortion that would give less accurate measurements. The optical properties of the glass must be affected by temperature as little as possible (i.e. low birefringence) and the glass should have a high thermal conductivity to avoid distortion due to temperature gradients in the lens or prism (category 9).
- Light guides and lenses for optical microscopes, endoscopes and in IVD equipment. Lead in the glass is needed for high % transmittance at shorter wavelengths, high refractive index and as it has the anomalous dispersion properties required for chromatic aberration compensation. Lead-glass light guides are also used for other applications. Microscopes are used for many different areas of technology (category 8 and 9) – see more detailed description below.
- Optical telecommunications lenses, such as in optical transceivers, light collimation, optical amplifiers, switches, isolators and transponders (category 3). Optical transceivers are also used as components of medical devices and monitoring and control instruments to transmit data via the Ethernet (categories 8 and 9).
- Laser optics for commercial printers. Large cylindrical lenses are used which must be lead-glass for optimum temperature stabilisation (category 11).
- Optics for lasers used for communications, monitoring and control instruments, cutting, welding, etc. These include prisms and lenses.
- Photolithography (category 11).
- Aspherical lenses (these have a complex surface structure used to achieve high quality images).
- Lead-glass may also be used in many other types of equipment, such as lighting applications (crystal glass which may be used in lighting applications is covered by exemption 29), toys and leisure products, medical devices and automatic dispensers (e.g. Automatic Teller Machine - ATMs).

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[1] An enantiomer is one of two molecules that are mirror images of each other and are non-superposable

**Optical microscope applications**: Optical microscopy methods have a significant impact on the European research landscape covering research on cancer, AIDS, Alzheimer, as well as routine diagnostics like fluorescence-in-situ-hybridization, pathology, and digital slides. Not being able to use lead-containing glass would hence severely harm the academic research as well as pharmaceutical R&D in the European Union. Furthermore, clinical analytics would become equally hindered with unpredictable and probably undesirable consequences to the EU health system.

The following are examples of uses of optical microscopy. These examples include a number of applications in research and routine microscopy, as well as in the bio-medical and industrial field relying on high or at least reasonable transmission in the near-UV spectral range. A summary of Microscopic devices for UV-Light, important tools in biological and medical research, prepared by Carl Zeiss AG and Carl Zeiss Microscopy GmbH (used of optical glass components is provided as an Annex (see section 9.2).

Examples are:

- Confocal microscopy is a type of fluorescence microscopy with a special emphasis on the 405nm excitation wavelength (i.e. blue light – lead-free high refractive index glass has poor blue light transmission) which can be efficiently used to excite fluorescent markers. This ‘relatively’ short wavelength is also used for confocal material science and topography as the spatial resolution increases with lower wavelength. Lead-based glass must be used to achieve high transmission at the 405nm wavelength.
- Laser micro dissection crucially depends on UV lasers (355nm) to cut and separate cells and tissue. Specially designed microscopes are used in which the laser beam that is used to separate and then remove individual cells passes through the microscope lenses that are also used to view the cells. High light transmission is needed at all wavelengths to be able to see individual cells as well as for high transmission at the UV laser’s wavelength of 355nm. At this short wavelength, only lead-based glass has high percentage of light transmission as well as all the other essential characteristics that are also required, as described below. A selection of publications is given in Appendix 1 (see 9.2.1) and recent publications (since 2015) that utilise this equipment is provided in Appendix 2 (see 9.2.2).
- Fluorescence microscopy as a standard research and routine analysis tool depends on high or at least ‘reasonable’ transmittance in the near-UV range. Specific examples are:
    - Ratio imaging with fluorophores (fluorescent dye) such as FURA (an aminopolycarboxylic acid) that can be exited at 340nm and 380nm and are routinely used to monitor intracellular $Ca^{2+}$ concentration and cellular regulation. This fluorophore was developed by R. Tsien who was awarded the Nobel prize in chemistry 2008 and the method is cited in thousands of scientific publications. This technique is also used in the study of Parkinson’s disease, Myocardiocyten Stroke and Epilepsy[2] by measurement of the ratio of the emissions at different wavelengths as this is directly correlated to the amount of intracellular calcium.
    - “Fluorescence Recovery After Photobleaching” (FRAP) denotes an optical technique capable of quantifying the two-dimensional lateral diffusion of a

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[2] The role of calcium and mitochondrial oxidant stress in the loss of substantia nigra pars compacta dopaminergic neurons in Parkinson's disease. Neuroscience. 2011 Dec 15;198:221-31. doi: 10.1016/j.neuroscience.2011.08.045. Epub 2011 Aug 25. Review. Schreckenberg R, Dyukova E, Sitdikova G, Abdallah Y, Schlüter KD. Mechanisms by which calcium receptor stimulation modifies electromechanical coupling in isolated ventricular cardiomyocytes. Pflugers Arch. 2014 Apr 1. Maroto M, de Diego AM, Albiñana E, Fernandez-Morales JC, Caricati-Neto A, Jurkiewicz A, Yáñez M, Rodriguez-Franco MI, Conde S, Arce MP, Hernández-Guijo JM, García AG.Multi-target novel neuroprotective compound ITH33/IQM9.21 inhibits calcium entry, calcium signals and exocytosis. Cell Calcium. 2011 Oct;50(4):359-69. doi: 10.1016/j.ceca.2011.06.006. Epub 2011 Aug 11. Sun DA1, Sombati S, Blair RE, DeLorenzo RJ. Calcium-dependent epileptogenesis in an in vitro model of stroke-induced "epilepsy". Epilepsia. 2002 Nov;43(11):1296-305.

molecularly thin film containing fluorescently labelled probes, or to examine single cells. This technique is very useful in biological studies of cell membrane diffusion and protein binding.

  - The use of 4',6-diamidino-2-phenylindole (DAPI) as a fluorescent stain that binds strongly to A-T rich regions in DNA and is a standard marker in immunofluorescence[3].
  - Total Internal Reflection Fluorescence (TIRF) microscopy as a tool that is used to achieve sub-diffraction-limited axial resolution.
  - Laser capture micro dissection is used for the identification and isolation of cells from larger tissue microenvironments and is used for research into Cancer and Alzheimer's disease. This technique requires high % transmission at 348 and 355nm.
  - Parkinson's disease, Epilepsy and Depression are studied using light of 350 – 530nm by activation of proteins using stimulating light sources[4].

Optical microscopes that use leaded glass lenses are widely used for many areas of research. This is possible only by using the highest performance optical microscopes that contain lead-glass lenses. A few examples include:

- Research into cancer therapy to visualise Glioblastoma malignant brain tumours[5].
- Optical microscopes with lead-glass lenses were used to image mouse brain cells in research into brain functions[6].
- High performance optical microscopes are used to develop new bio-printing of 3D tissue structures that aim eventually to create human tissue that can be used for new drug testing[7].

**Photolithography**:

Photolithography utilizes light of mercury lamps that emit light at 365nm and special lenses are used to focus this light and must transmit a high percentage of this 365nm light. Due to the high spectral bandwidth of this mercury line of 2.5nm (FWHM), it is essential that the i-line objective lenses (operating wavelength 365nm) be achromatized through the use of crown and flint lenses. In i-line objectives, the majority of lens elements consists of FK5 crown glasses with low color dispersion. The unleaded versions of theses glass types are also already being used without any disadvantages to the optical design.

The flint lenses with larger color dispersion which are necessary for color correction (types LLF1 and/or PBL1Y, and LF5 and/or PBL25Y) contain lead and have the characteristics that are unique for lithography because of the lead oxide component, which provides the essential high colour dispersion at simultaneously extremely low absorption (i.e. high % transmission).

In every optical system, light absorption leads to a loss of transmission. In a lithographic system, transmission loss is noticeable in that, with the existing lamp output, fewer wafers per hour can be illuminated. As lamp output cannot be increased as desired with these systems, a reduced transmission translates into the reduced productivity of the machines,

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[3] Cancer: Stoehr, R., P. Wild, et al. (2003). "Lasermicrodissection – An important prerequisite for the molecular-genetic analysis of bladder cancer." Pathol Res Pract 199: 355-362. Alzheimer's R&D Chadi, G., J. R. Maximino, et al. (2009). "The importance of molecular histology to study glial influence on neurodegenerative disorders. Focus on recent developed single cell laser microdissection." J Mol Histol 40(3): 241-250.

[4] 7 Tye K. M., Deissenroth, K., Optogenetic investigation of neural circuits underlying brain disease in animal models. Nature Neurosci.13, 251-266 (2012).

[5] http://www.youtube.com/watch?v=5QwwtxpNgEA&feature=youtu.be

[6] http://www.nytimes.com/2014/02/25/science/the-brains-inner-language.html?_r=1

[7] http://wyss.harvard.edu/viewpressrelease/141/

which reduces competitiveness of EU industry. In addition, the energy consumption then increases significantly, as the energy input for the bulb, stage movement, microclimate and for the operation of the required cleanroom (some ten kWs) is distributed across fewer illuminations.

The local unequal heating of the lens elements is even more critical for the performance of a lithography objective. Due to the induced variations in refractive index by local unequal heating of the lens elements this will lead to a loss of the high imaging quality required to display the finest structures close to the resolution limit. Therefore, for lithographic applications, it is essential to use glass types with extremely low light absorption coefficients.

In the visible spectral range, titanium dioxide, for example is a standard alternative to lead dioxide in glass. However, at 365nm, titanium dioxide does not display acceptable percent light transmission, therefore, the available lead-free alternative glass types are unsuitable for use as lenses for ultraviolet applications.

Currently, the best lead-free alternative to the LLF1 or PBL1Y (vd[8] = 45.75 and/or 45.73) glass is Ohara glass S-NBM51 with vd = 44.27. In this glass, lead oxide is essentially replaced by niobium oxide, however, for manufacturing reasons, sections of titanium dioxide are still present and as a result, the absorption in the UV range is increased, as already mentioned above[9]. However, for this glass, which is the best substitute available, the transmission of S-NBM51 at 365nm is far below that of LLF1 and/or PBL1Y, and therefore the above-mentioned effects of transmission loss and lens heating, causing image distortion will occur. Thus, the degree of pure transmission for LLF1 in lithographic quality at 365 nm for 100 mm thickness is 97.6%, while with lead-free S-NBM51, it is only 55.0% transmission. However, all other glass types besides S-NBM51 are far worse in relation to pure transmission. Thus, at an assumed total glass thickness of 100mm, flint glass in an i-line objective, 45% of the light would be absorbed through the flint lenses alone and the productivity of the machine would be reduced by 45% at the same energy consumption level.

A design with only one flint glass type such as S-NBM51 or LLF1 is shown below as an example, to quantify the problem of lens heating. This example system consists of 25 FK5 lenses and 6 LLF1 lenses (marked in yellow), which are needed for color correction.

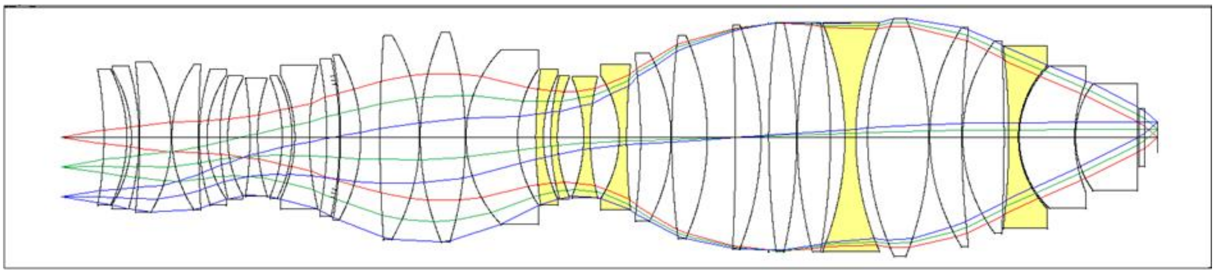

**Figure 9. Illustration of i-line photolithography lens assembly, with LLF1 lead-glass lenses coloured yellow**

The total beam path in LLF1 for the main beam of the axis bundle is 45mm, for aperture rays, it is 142mm. Total absorption in the flint lenses is 1.0% for the main beam and 3.2% for the aperture ray. If the material LLF1 were replaced by the Ohara glass S-NBM51 for these lenses, without any change to the remaining design, the absorption would be 22.3% for the main beam and 66.9% for the aperture ray, i.e. the absorption and thus the lens heating would increase by a factor of 7 times.

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[8] Vd = Abbe number

[9] M . Morishita, M. Onozawa, NIOBIUM OXIDE IN ENVIRONMENTAL FRIENDLY OPTICAL GLASS, Niobium Science & Technology: Proceedings of the International Symposium Niobium 2001 (Orlando, Florida, USA)

As the lens heating as described above has a direct influence on the imaging quality, the lamp output would need to be reduced by approx. factor 7 in order to arrive at a similar imaging quality. As a result, the overall throughput of the machine is reduced by 85%.

The following table provides a summary of these values.

**Table 1. Comparison of percentage of light absorbed by lead-based glass (LLF1) and lead-free glass (S-NBM51)**

| Beam | Beam path [mm] | Absorption [%] | |
|---|---|---|---|
| | | LLF1 | S-NBM51 |
| Main beam | 45 | 3.2 | 22.3 |
| Aperture rays | 142 | 9.7 | 66.9 |

Such a machine, which would only bring one seventh of the productivity at the same capital investment and ongoing costs, would not be saleable on the market. As EU manufacturers could not compete with non-EU manufacturers, this technology cannot be used in the EU without this exemption.

In addition, such a development would also be costly as the refractive index of S-NBM51 at 365nm with n=1.64927 is significantly higher than that of PBL1Y, where n=1.57931. A move to S-NBM51 would therefore essentially mean a complete re-development of the objective lens assembly, because the glass types cannot simply be exchanged due to their different refractive indices. In addition, this glass does not have the appropriate lithographic quality, i.e. the material homogeneity fails to fulfill the strict requirements for lithography by a large margin. Therefore, lead-free designs that would not provide the required quality are not practical.

**Summary**

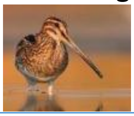
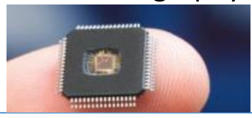
Since unleaded flint glass have very low transmission for 365nm (i-line) wavelength light, even with a complete redesign, it is not possible to build an i-line lithography system whose performance is consistent with market requirements.

With the best available glass, the productivity of such a system would be reduced by 85% – the purely physical and inevitable transmission loss alone reduces the productivity by approx. 50%. Even in 2019, there are no new developments with respect to lead-free types of glass or lenses with refractive index ($n_d$) < 1.6 and Abbe number (vd) between 40 and 50. Even the 5742 lenses ($n_d$ = 1.57653, vd = 42.1) offered by Nikon for these purposes and presumably used in their own lithography objectives contain 35% lead.

There is a broad spectrum of optical devices for commercial and professional usage. In most cases lead free glass types are used but for some uses, the properties of lead containing glass are essential to achieve unique features and performance. There are two reasons why a differentiation between professional and non-professional devices would not be productive:

1) Although certain types of products are intended solely for the professional market, these products are sometimes also bought and used by non-professional users, such as stereo-microscopes or high performance photographic lenses. It is their personal interest to buy and use such high-performance devices.
2) There are still some consumer products which need the properties of lead containing glass types. One example is projection systems which become very hot during use. For these, the special thermal behaviour of some lead containing glass is needed.

**Table 2. Selected Devices and their users.**

| Device | Professional users | Non-professional users | Typical Application |
|---|---|---|---|
| **Stereo-Microscope** | **X** | **X** | Botanic / Zoology  |
| **Laserscanning-Microscope** | **X** | | Medicine / Cytology  |
| **Photographic lenses** | **X** | **X** | Architecture  |
| **Binoculars and Telescopes** | **X** | **X** | Ornithology  |
| **Lithographic lenses** | **X** | | Photolithography  |
| **Projectors** | **X** | **X** | Presentations / Movies  |

Spectaris does not propose to differentiate between professional devices and consumer devices within this exemption.

**(C) What are the particular characteristics and functions of the RoHS-regulated substance that require its use in this material or component?**

Glass usually is a transparent solid material that can be made with many different compositions. Glass is traditionally known as clear non-crystalline inorganic materials based on silicates that are used for windows, drinking vessels and decorative objects. Glass is also used for optical components such as lenses, which are used in cameras, microscopes, projectors and many other different applications. The composition of glass is very variable and it is controlled to achieve the desired combination of properties. For most technical applications, it is necessary that the glass has a combination of several specific characteristics. Traditional inorganic soda glass types that are used for windows in buildings are relatively inert and so remain transparent for hundreds of years, but these are not suitable for all optical applications. Various additives are used to control the combination of properties that is required for each application and colourless transparent glass types may contain, apart from sodium and silica, also potassium, boron (e.g. borosilicate glass), arsenic, antimony, calcium, barium and lead. Some amorphous (non-crystalline) polymeric materials that are hard and optically transparent are referred to as “glass polymers” and have unique combinations of properties, although these are different to traditional silicate-based glass.

Each batch-ingredient for a glass is added to achieve specific combinations of properties although each individual optical property, such as high refractive index, can be obtained by several different glass formulations. There are, however, certain combinations of optical properties which can be achieved by only one or a few formulations and some combinations of characteristics are only possible in glass formulations that contain lead. Lead based glass has disadvantages such as higher density, which makes the optics heavier and it is softer than lead-free glass and so it is more easily scratched. However, the combination of optical properties cannot be achieved by any lead-free glass.

Lead is added to types of optical glass that are used in a wide variety of electrical equipment to achieve the following characteristics. Usually more than one of these properties are needed for a specific application and often many are necessary:

- **Medium to high refractive index –** important for optics used in microscopes, camera lenses, etc.
- **Specific Abbe number –** Abbe number is a measure of the variation of refractive index with wavelength so that the refractive index of a glass with a low Abbe number varies across the visible spectrum less than a glass with a high Abbe number. Lead based glass can be formulated to have low Abbe numbers which reduces chromatic aberration (see below) in parallel to having a high refractive index in such lead-based glass. It is important to be able to control Abbe number so that by using combinations of lenses of different materials with different characteristics, very precise optical effects can be obtained. Professional camera lenses and microscopes include several lenses made of several different glass formulations to achieve the required high performance.
- **Colour aberration –** There are two types of colour aberration that are affected by glass composition; lateral and axial. Axial chromatic aberration is due to differences in focal length of different colours whereas lateral chromatic aberration is affected by image size. Axial chromatic aberration is resolved by combining lenses of two different types of glass, one having a larger refractive index than the other. High refractive index lenses are made of lead-based glass for the best optical quality. Chromatic aberration occurs because all optical glass types that are used for lenses have a refractive index that varies with the wavelength of transmitted light (this property is related to the Abbe number). As a result, each colour focuses at a different convergence point, so that colour images appear with coloured fringes and this effect is more pronounced with high refractive index materials.
- **Transmission of light with a high proportion of blue / indigo / violet light –** most types of lead-free glass tend to absorb a high proportion of light having shorter wavelengths (<450nm) whereas lead-based glass types transmit a high proportion of short wavelength visible light to achieve accurate colour reproduction which is important for many applications (more details below).
- **Low stress birefringence (low stress optical constant) –** birefringence is a property of transparent materials where light travelling in one axis is refracted differently to light travelling in an axis at 90˚ to the other axis and this is due to the material having different refractive indices in perpendicular directions. Some types of calcite crystals (e.g. “Iceland Spar”) clearly show this effect; if a crystal is placed onto a printed page, two distinct images can be seen, one being shifted sideways from the other. Clear plastics such as polycarbonate and acrylics are very susceptible to birefringence. This can be seen as rainbow colours when the plastic items are stressed when viewed by polarised light (each wavelength is refracted differently so that incident white light is transmitted as separated colours).
- **Partial dispersion –** Glass types having identical refractive index and Abbe number can have different partial dispersion properties and this can significantly affect image quality. Modulation transfer function (MTF) of a lens is a measure of image quality

where a MTF of 1 is perfect quality with no loss of contrast (see additional information for a more detailed explanation of why partial dispersion is an essential criterion)[10].

- **Achromatism** - see additional information (see section 9.1).
- **Petzval number** - see additional information (see section 9.1).
- **Abnormal dispersion** – this is a quality used to compensate for chromatic aberration.
- **Low photoelastic constant (β)** – important to minimise distortion due to birefringence when stress is imposed on the glass optics. Related to low stress birefringence, described above.
- **Press moulding characteristics** – aspherical lenses are made by forming in moulds before grinding and polishing. The moulded shape needs to be as close to the required dimensions as possible to minimise grinding wastes and this is easier with leaded glass because the melting temperature is lower than with lead-free glass. This has a positive effect by using less energy in such press moulding processes due to up to the 200˚C lower process temperature. Aspheres that are sanded and/or polished after pressing are referred to as “preformed mouldings”.
- **Thermal properties** – Some optical systems require the use of two lens elements that are cemented together (cemented doublets). It is important that both lenses have similar thermal coefficient of expansion to allow for any temperature changes. This is sometimes impossible without lead-based optical glass. Some lens systems are required to maintain focus when the temperature changes (such as due to hot lamps) and this is sometimes possible only with lead-based glass.
- **Ionising radiation resistance and blocking** – Lead has a high atomic weight and density so is very effective as a barrier to ionising radiation. Such optical systems are used in equipment utilising or measuring ionising radiation. The use of lead as shielding for ionising radiation is however covered by RoHS exemption 5 of Annex IV.

### Combinations of essential properties

As stated above, applications usually need many of the above characteristics. Some examples need a combination of high refractive index, a high percentage of short wavelength light transmission and low stress birefringence and these are all achievable only with optical glass containing lead. Lead-free glass types are available which exhibit one or two of these properties only, but none exhibit all three. Furthermore, excellent colour correction as well as other specific combinations of optical characteristics cannot always be achieved with lead-free optical glass. High performance lens systems often consist of many different lenses (some with lead, others lead-free) with each lens required to have a combination of specific properties and many combinations are achievable only with glass containing lead.

A few examples are described below.

### Refractive index and Abbe number

The chart below shows the full range of glass types manufactured by SCHOTT who are the only optical glass manufacturer in Europe. Marked on the chart are lead-containing glass types . Note that these include glass types with both low Abbe number and high refractive index. Only the red dots on the lower right perimeter on the Abbe chart below correspond to lead containing glass. The inset graph (top left) is a plot of Abbe-number (x-axis) against “Partial dispersion” (y-axis). Glass types on the straight line are called normal glass. For excellent colour correction glass types are needed which have a significant deviation from

[10] A more detailed explanation of partial dispersion is available in section 3.4 of „Optical Glass”, Dr. P. Hartmann, SPIE Press, ISBN: 9781628412925, 2014.

the straight line and some lead – glass types (red dots) have this characteristic. These have a so-called “anomalous partial dispersion”.

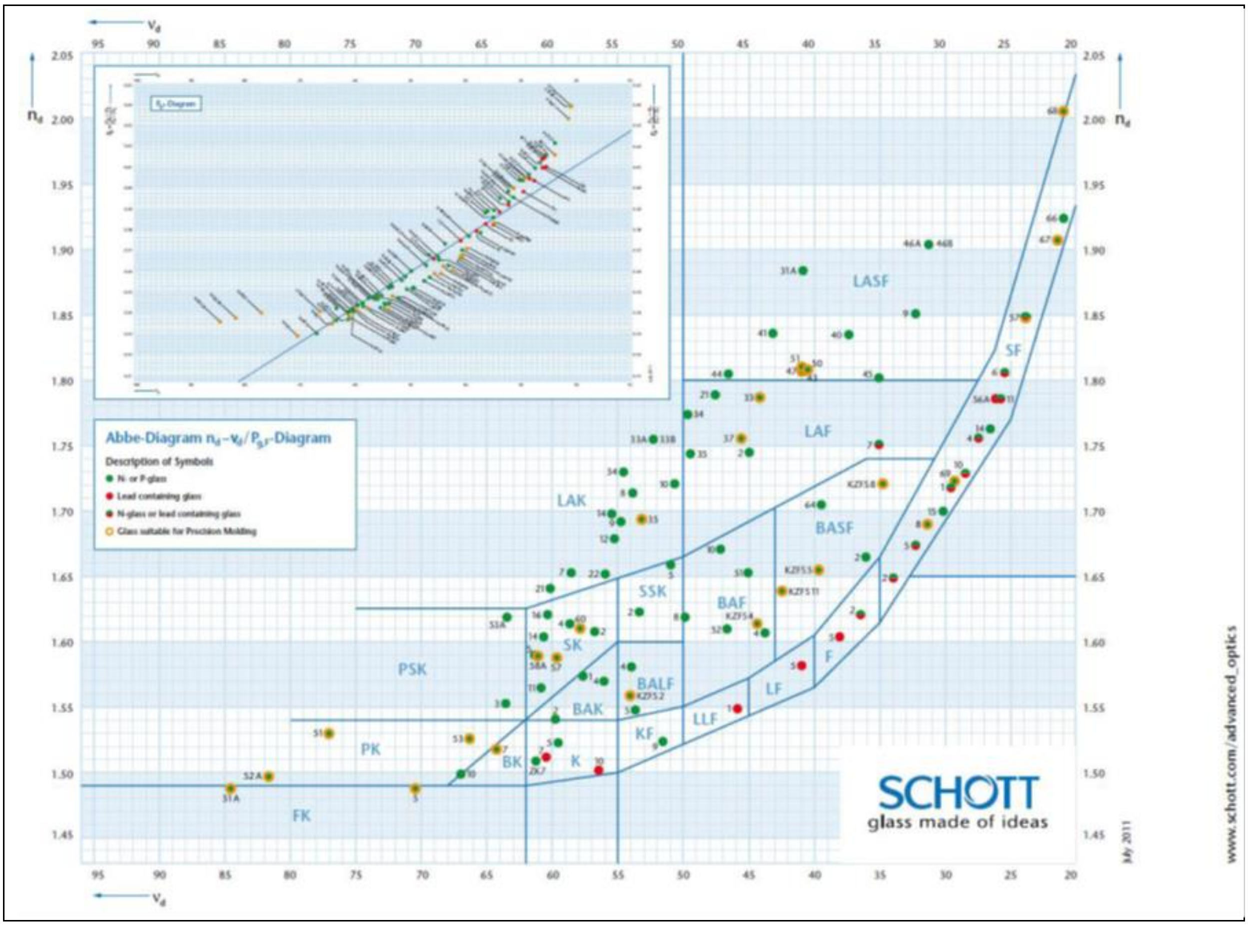



**Figure 10. Chart showing SCHOTT’s range of optical glass and their optical properties. For higher resolution images refer to SCOTT’s website[11]**

Figure 10 shows several types of optical glass with high refractive index and low Abbe number. There are a few lead-free glass types with high refractive index and low Abbe number, but their other properties are different to the lead-based glass and so are not always suitable as substitutes. Figure 10 shows that for most values of refractive index values, the lead-based glass types have the lowest Abbe number; the lead-based glass types mainly being at the right-hand edge of the spread of results.

The figure below shows the corresponding lead-containing glass types made by all optical glass manufacturers (OHARA, Hoya, CDGM, NHG) as pink dots, overlaid onto the SCHOTT diagram, which shows that there is no difference between SCHOTT as the sole European glass producer and Asian glass producers.

[11] Main diagram = https://www.schott.com/d/advanced_optics/0387ab58-e80d-4b4d-aa02-324f4bef4c98/1.16/schott-abbe-diagram-nd-vd-jan-2018-eng_2.pdf

Inset graph = https://www.schott.com/d/advanced_optics/b7a0a1b5-27d4-4c15-8630-134f241c9d79/1.15/schott-abbe-diagram-pgf-jan-2018-eng_2.pdf

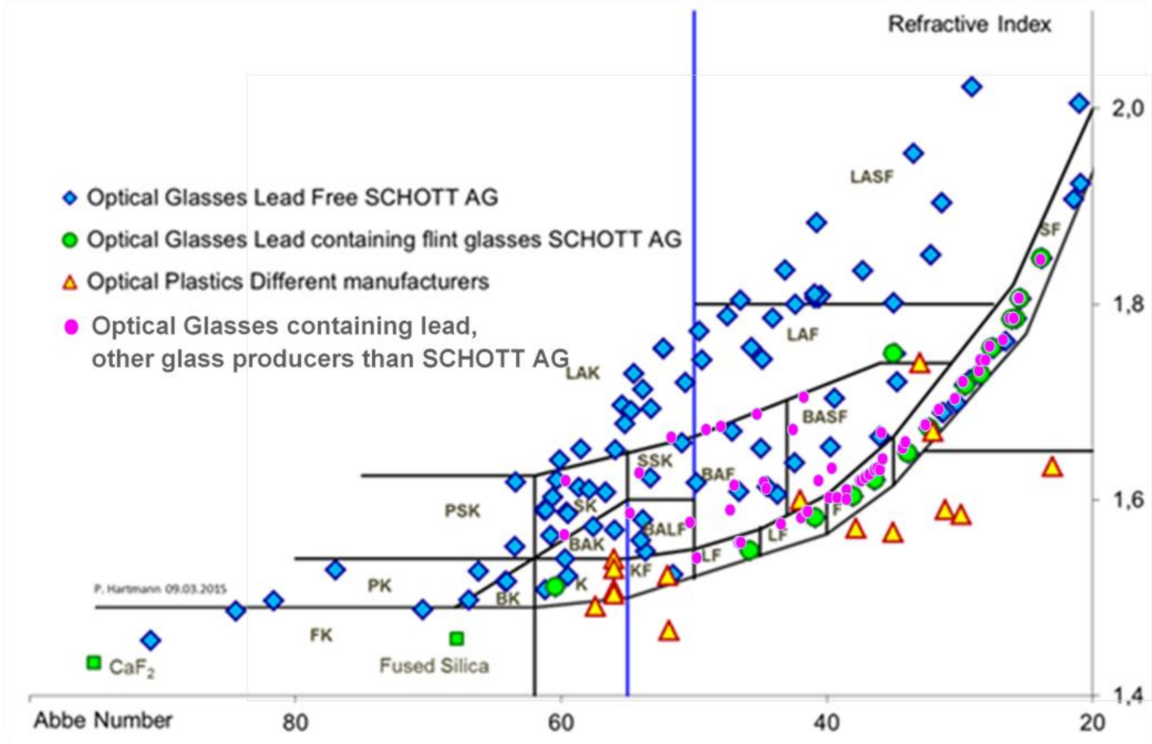



**Figure 11. Comparison of lead-free optical glass made by SCHOTT compared with all lead-based optical glass (x-axis is Abbe number and y-axis is refractive index).**

There is a vast amount of different optical systems each with a manifold of requirements. Present day applications can amount up to 40 or more functional requirements which have to be met simultaneously (hence the need for the large number of glass types shown in Figure 10). Requirements can, for example, include:

- focal length or focal length range for zoom lenses,
- aperture,
- image resolution (MTF at all focal lengths),
- colour trueness,
- high contrast,
- high overall transmission,
- field flatness (sharp image over the total area of the flat sensor chip),
- low intrinsic fluorescence with many of them subdividing in detailed requirements on the different types of aberration effects (monochromatic and colour aberrations).

This means optimization of 40 or more parameters within one design. On the other hand there are not many degrees of freedom than can be adjusted in order to achieve the overall optimum. With optical systems they are: lens curvatures, thicknesses, inter-lens distances and lens materials i.e. optical glass types. So, in general optical designers would need hundreds of glass types to enable their designs. This is in contradiction with the economy of glass supply, which would tend to a strong reduction of the number of glass types. The offered range of glass types is a compromise which is a continuous challenge for both suppliers and users.

**High percentage of light transmission at shorter wavelengths**

Figure 12 below shows the light transmission percentage curve of five examples of glass:

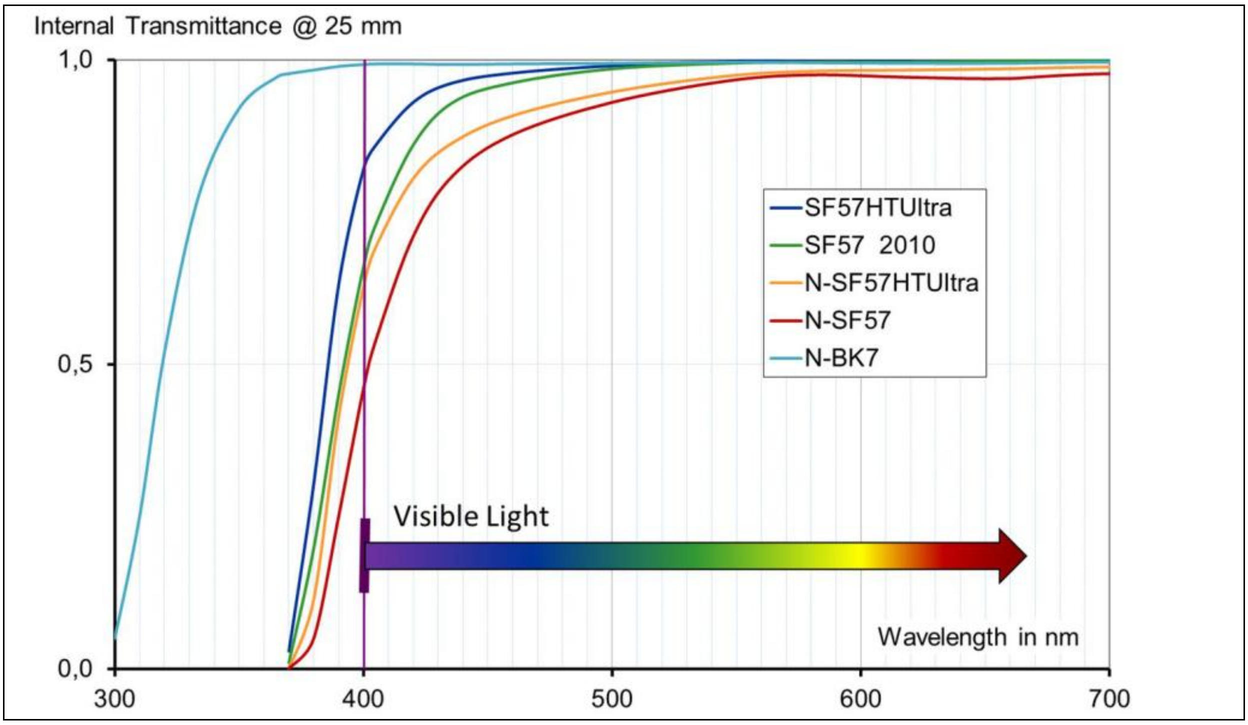



**Figure 12. Graph of light transmission versus wavelength of light**

SF57 and SF57HTUltra lead glass, whereas N-SF57 and N-SF57HTUltra are the lead free equivalents which have similar refractive index and Abbe number to the SF57 versions, but with inferior blue light transmission. N-BK7 (lead-free) is shown for comparison to demonstrate that even better blue light transmission can be achieved, but the other essential optical characteristics of N-BK7 make this unsuitable for many optical applications. The combinations of properties of these glass types are shown below (data from datasheets published by SCHOTT).

**Table 3. Comparison of properties of two lead-based and three lead-free optical glass types**

| Property | SF57 | SF57HTUltra | N-SF57 | N-SF57HTUltra | N-BK7 |
|---|---|---|---|---|---|
| % Light transmission at 400nm | 0.847 | 0.924 | 0.733 | 0.830 | 0.997 |
| Refractive index (589.3nm) | 1.8464 | 1.8464 | 1.8464 | 1.8464 | 1.5167 |
| Abbe number | 23.83 | 23.83 | 23.78 | 23.78 | 64.17 |

Table 3 shows that SF57HTUltra has the best overall combination of optical properties:

A high proportion of shorter wavelength visible light transmission, high refractive index and low Abbe number. Only glass containing lead has all of the essential characteristics needed for many optical applications.

The following example illustrates why a high percentage of light transmission through a lens is important: Assume an optical system consisting of 10 lens elements (typical of professional camera and video lenses). The overall transmission $T = T(i)^{10}$.

**Table 4. Dependence of overall transmision of visible light through a 10 element lens due to transmission of individual lenses**

| Transmission of individual lens element (Ti) | Overall Transmission (10 lens elements) |
|---|---|
| 73,3% | 4,5% |
| 84,7% | 19,0% |
| 92,4% | 45,4 % |

The conclusion from this example is that optical glass with poor transmission characteristics (at any wavelength) leads to a tremendous waste of the light energy fed into the optical system.

A high light transmission percentage at shorter wavelengths is important for many applications. Some illustrative examples are:

**Optical microscopes** use a series of different lenses to obtain the required magnification and image clarity and it is important that the glass absorbs as little light as possible. Optical microscopes typically consist of objective, tube and scanning lenses as shown below.

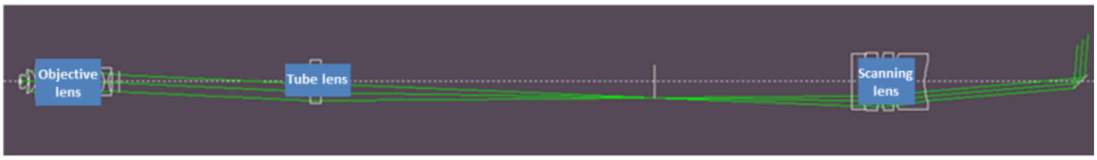



**Figure 13. Light path in an optical microscope**

Without lead-based glass, very little blue – indigo light will reach the observers eye so that any blue / violet items are not visible and for many applications light of wavelengths in the UV/blue range (e.g. 355 or 405nm) is needed. UV wavelengths are also necessary for fluorescence microscopy. The same effect is also important with other high performance optical instruments where colour accuracy is predominant, such as professional still, video and television cameras, binoculars and telescopes.

This is a serious issue with fluorescence microscopes which require a high transmission % in the UV / blue / violet range as well as high refractive index to allow the user to see small features in biological specimens.

High performance optical microscopes require many different lenses made from several different types of high-quality optical glass. Glass types with a variety of optical properties are required which together provide the required performance. Among these properties are the refractive indices, dispersion and light transmission. A high percentage of light transmission in the blue spectral range and especially in the near ultra-violet part of the light spectrum and other essential characteristics are required for microscopes and this combination of properties can only be achieved with glass types that contain lead.

Because the refractive index of glass varies with wavelength, i.e. when a lens diffracts light, white light is split into its constituent colours and so it is necessary for other lenses to be added that recombine these colours to obtain excellent colour correction to prevent colour distortion of magnified images. It is possible to achieve the specific combinations of optical characteristics needed for microscopes only with lenses made with lead-containing as well as lead-free optical glass. High performance lens systems usually consist of many different lenses each of which is required to have a combination of specific properties and many combinations are achievable only with glass containing lead.

Glass families are defined by specific ranges of their combination of refractive index and dispersion (Abbe-number). Class families, such as the SCHOTT F, FS, KZFS, LF and LLF are especially vital for optical design to obtain maximum image quality, i.e. high contrast and optimal definition. This is because these glass families and the corresponding glass types are indispensable for colour correction (to compensate for longitudinal (X-axis) and lateral (Y-axis) chromatic aberrations) in the most demanding applications, such as with “high-end” professional microscopes.

Without leaded glass, optical design would need more lens elements to achieve some of the optical characteristics, but other characteristics will be impossible to achieve. Using more lens elements causes a higher level of stray light and reflections and the image quality will be significantly reduced.

**Colour correction in microscopes**

The most important and distinguished members in the portfolio of high-performance objective lenses are the families Apochromates, W-Apochromates, C-Apochromates, α-Apochromates. They have in common that apochromatic colour correction is achieved over a broad spectral range. The fact that this optical property is of eminent importance can be deduced from the fact that a whole ISO standard is devoted to it, for details of the specific properties we hence refer to this international standard[12].

Here we would like to limit ourselves to the classical apochromatic theory that is laid out in textbooks[13,14]. As a working definition we can request axial colour correction for four different wavelengths as indicated in Figure 14[15].

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[12] ISO 19012-2 Designation of microscope objectives – Part 2: Chromatic correction

[13] H. Gross (Ed.) "Handbook of optical systems”, Vol 1-5, Wiley,

[14] A. E. Conrady, "Applied Optics and Optical Design”, Part one and two, Dover, 1985

[15] H. Gross, Lectures, University Jena, 2012

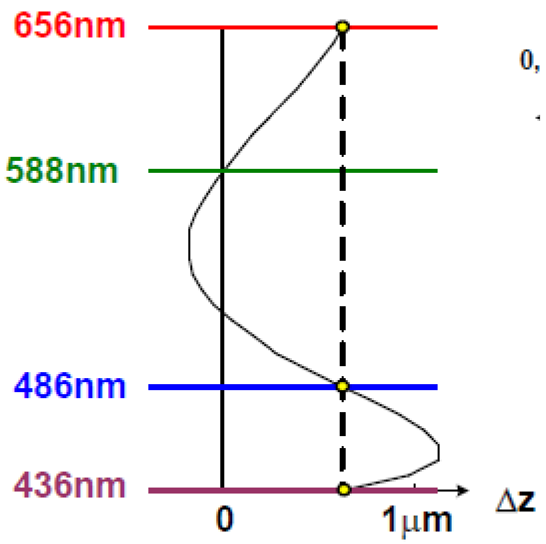



**Figure 14 Colour Wavelengths**

This typically requires at least three lenses and the choice of at least one special glass (lead-based) with significant anomalous partial dispersion. Below in Figure 15 (right diagram) is a "lead-free" example. However, lead-free glass however is unsuitable in microscope applications because the lead-free glass types that have suitable Abbe number and refractive index have poor light transmission in the blue to UV range. In many applications, the size of "T" in Figure 15 should be as large as possible and this is possible only if a suitable leaded glass lens is included.

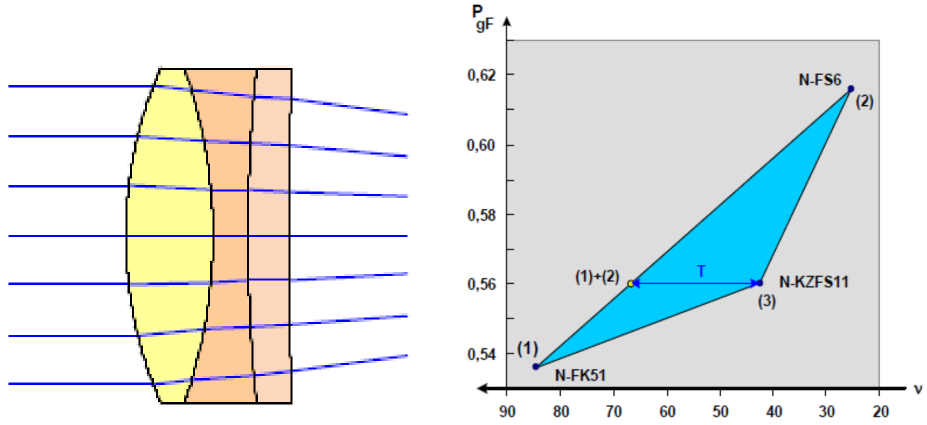



**Figure 15. Schematics of an Apochromate**

The diagram on the right-hand side above shows an example of a glass choice. Of particular importance here is the point (2) which represents the SCHOTT glass N-SF6. The prefix "N" stands for a new lead-free glass that corresponds to the older lead containing glass type SF6, which is one of the very few SF (lead-containing) glass types that are still available in the SCHOTT glass catalogue.

**Optical Transmission**

Internal transmission through a glass lens is another crucial optical property that depends strongly on the weight percentage of PbO, $TiO_2$ or other materials. This is exemplified in the following figure (provided by SCHOTT).

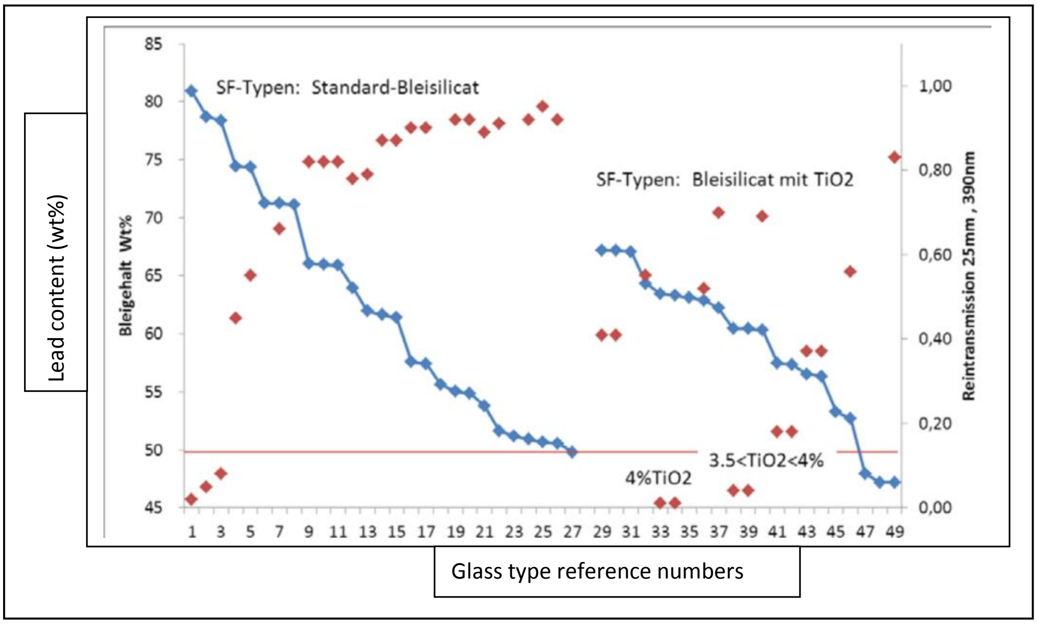
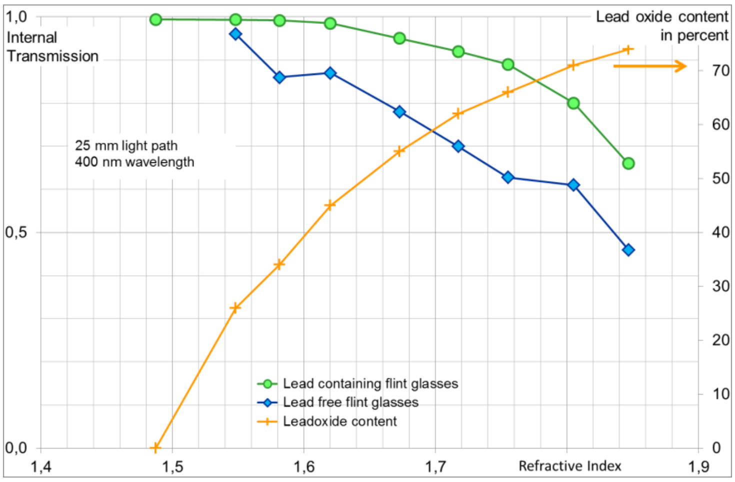


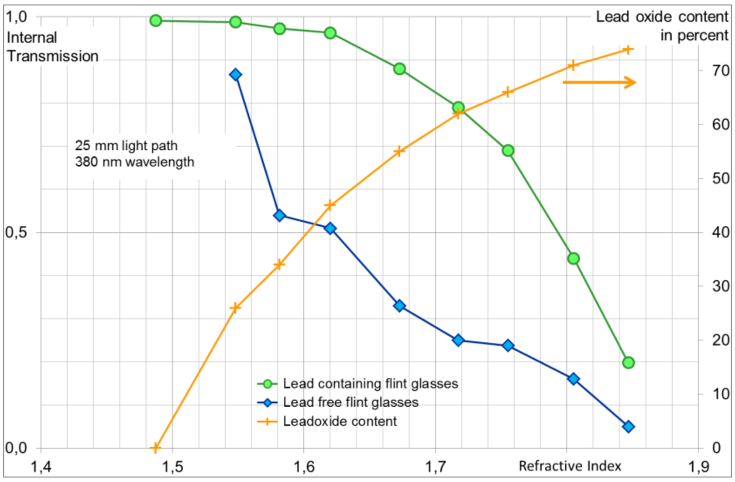

**Figure 16. Relationship between lead and titania ($TiO_2$) content and internal transmission of light for 49 types of glass (x-axis). Blue points (♦) are lead in the glass type as wt% (left y-axis) and red points (♦) are the light internal transmission (right y-axis) through 25mm thick glass with 390nm wavelength light**

This plot shows a nearly linear dependency between lead content and internal transmission for glass types 1 to 27. Substitution of some of the lead content by various quantities of $TiO_2$ (as shown on the right-hand side glass types 28 to 49) reduces the internal transmission significantly, so is not a suitable alternative. While the internal transmission of glass types with high lead content leads to very high levels, substitution by $TiO_2$ as a polyvalent cation tested on substitution or partly substitution of lead gives significantly lower internal transmission and thus $TiO_2$ is not a feasible alternative.

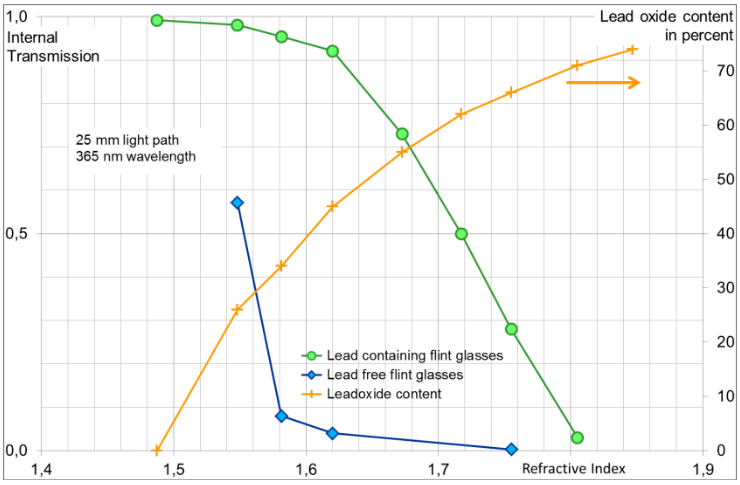
The graphs below show the differences in internal transmission versus refractive index at three different wavelengths for lead-based of various lead content and lead-free glass.




17.a)




17.b)




17.c)

**Figure 17. a-c shows the internal transmittance of optical glass versus refractive index at the three different wavelengths 400 nm (a), 380 nm (b) and 365 nm (c)**

Figure 17 (above) shows that at those wavelengths close to the borderline between visible light and near UV light most glass types lose transmittance sharply (this phenomenon is called UV-edge). The diagrams depict the internal transmittance as a function of the refractive index, which in the case of lead flint glass is closely related to the lead oxide content (given in a separate orange curve with the scale on the right side). The transmission values of the lead-free glass lie clearly below the lead containing glass. The difference between lead containing and lead free (barium, niobium and titanium containing) glass rises with increasing refractive index except for very high indices where internal transmittance is already very low. It gets also higher with shorter wavelengths.

The difference between a lead-based glass and the lead-free substitute can be visualized most easily by plotting the internal transmittance vs. wavelength of light as in the following figure. This compares two nominally similar glass types SF6 and N-SF6 by SCHOTT.

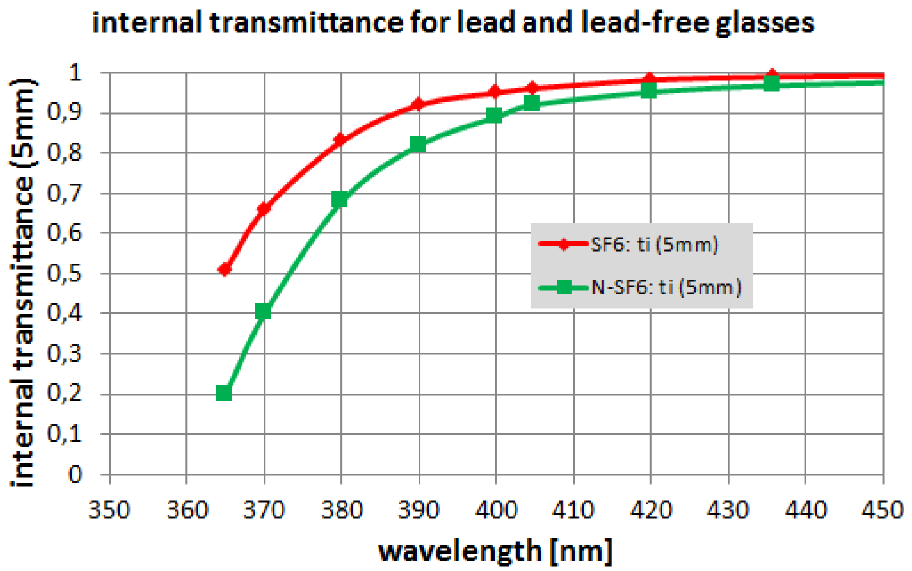



**Figure 18. Spectral curves for SF6 (lead based) and N-SF6 (lead-free) flint glass**

SF6 glass is one of the few remaining SF glass types that is still available in the lead-based form and also in a lead-free N-SF6 version. N-SF6 shows dramatically reduced internal transmittance at a standard wavelength of 365nm through a 5mm glass thickness, whereas, typically the light in microscope objectives travels along much longer paths ranging from 25mm to 100mm. In addition to this dramatically reduced transmittance between 365nm and 410 nm, there is zero transmittance of lead-free glass between 330nm and 360nm (see also Figure 12).

**Optical fibres for illumination units for operation microscopes in microsurgery**. Optical fibres of up to 6 metres in length are used to illuminate patients that are being examined using surgical microscopes during operations. The graph below shows the difference in light transmission across the visible wavelength range for lead and lead-free glass.

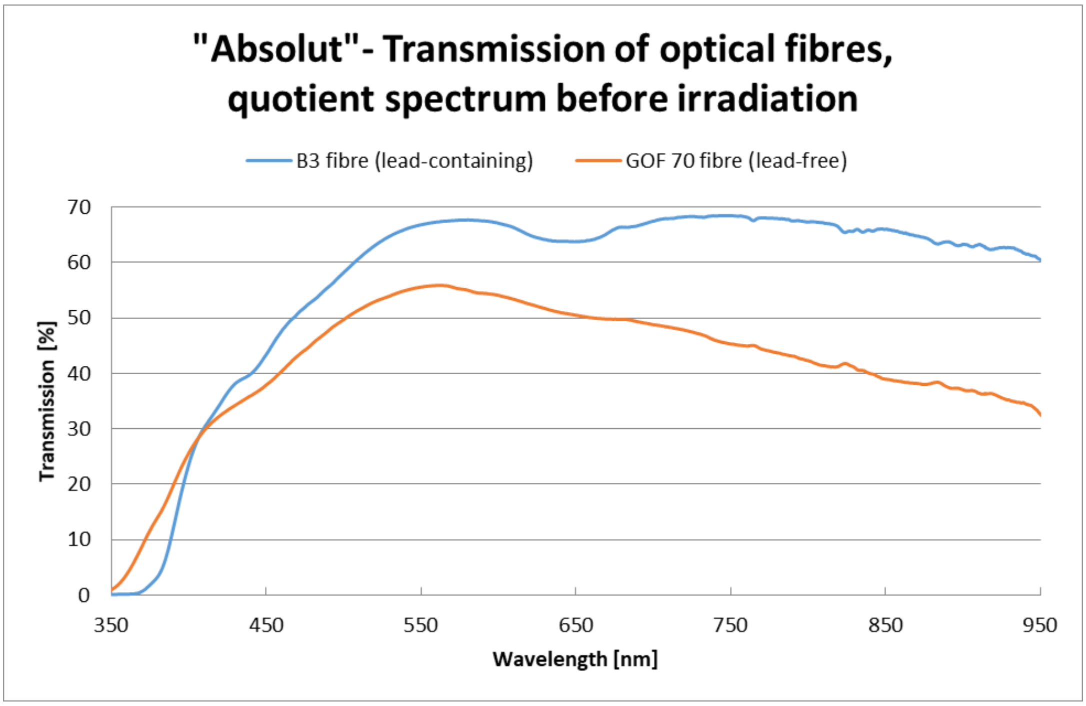



**Figure 19. Comparison of light transmission through lead and lead-free optical fibres used for surgical microscope illumination**

As shown in Figure 19, there is significantly higher light transmission with lead-containing optical fibres than with lead-free. Almost 6m long fibres are required for the application. The longer a fibre, the faster it solarizes (this causes the glass to darken and as a result it will absorb more light), especially when used in low wavelength ranges. A wavelength range of 400-800nm is required with surgical microscopes to obtain clear images. As shown in Figure 19, lead-free optical fibres solarize faster than those containing lead.

To compensate the lower transmission with lead-free optical fibres and the solarisation, a higher light intensity could be fed into the optical fibre, but this would lead to higher heat generation. Heat generation and higher light intensity can threaten patient and user safety so is not acceptable in operating theatres. There is no such safety risk when using a leaded optical fibre in this application.

**Medical endoscopes** have many lenses, including long rod-lenses of 200 to 500mm in length, which are used to examine internal organs which appear as mainly various shades of red. Light passes through the long length of glass before reaching the eye of the doctor or surgeon, so a high percentage of light transmission in all visible wavelengths by this glass is essential. These instruments also need good magnification to see small features. It is essential for a very high percentage of visible light wavelengths to be transmitted including the blue/violet range for doctors and surgeons to be able to clearly see and to differentiate between different types of tissue, such as healthy organs from cancerous tumours. Tumours often have very similar colour and appearance to surrounding healthy tissue and are visible only if the percentage of blue / violet light transmission is high. Medical endoscopes use a grade of glass F2HT (made by SCHOTT) which has a light transmission percentage of >90% across the whole visible wavelength. The equivalent lead-free version transmits a relatively low percentage of light at lower wavelengths, as shown below (note that light is passed through 400mm thickness of glass unlike in Figure 12 where light passes through 25mm):

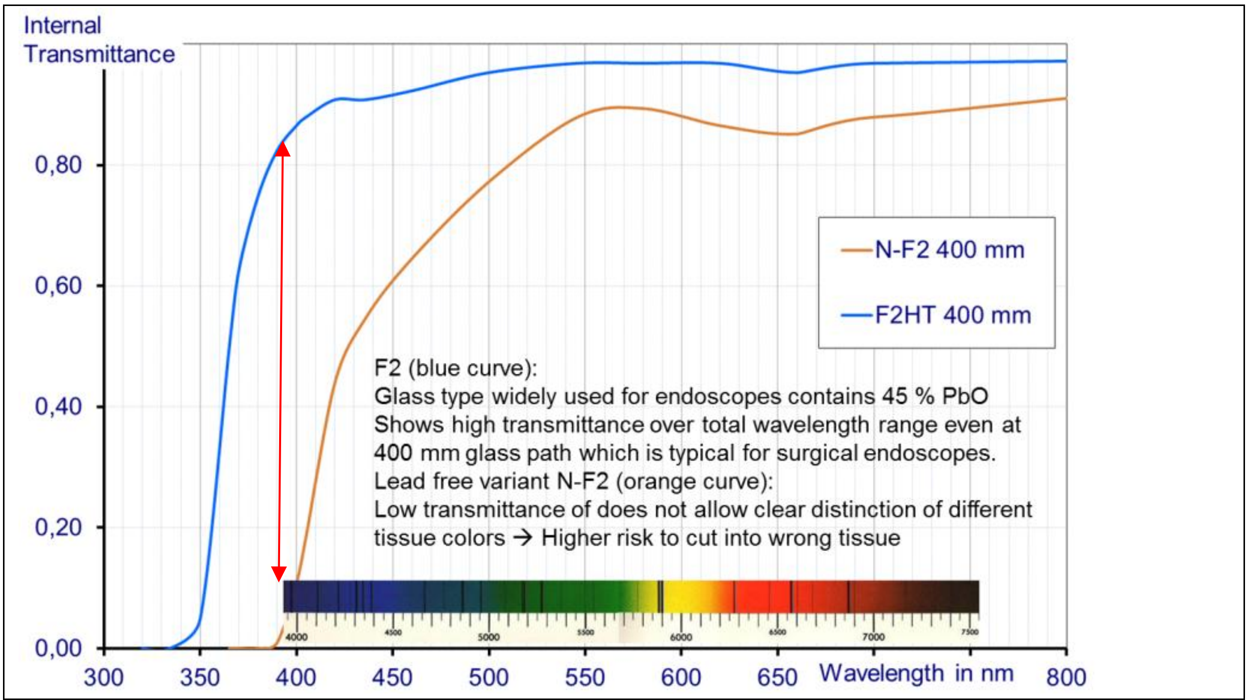



**Figure 20. Comparison of light transmission performance of lead-based glass (400 mm thickness) used for medical endoscopes with nearest lead-free equivalent. Arrow at 390nm indicates lower wavelength limit for light detection by a typical human eye**

F2 glass has a refractive index of 1.62 at 589nm and an Abbe Index of 36.37, which cannot be achieved by high transmission grades of lead-free glass.

Medical endoscopes are usually side-viewed and so the image is seen via a glass prism which must have very high optical transmission in all wavelengths and not distort the image and only lead glass is capable of achieving the required performance.

**LCOS (Liquid Crystal On Silicon) projectors** give the best optical performance of all types of projectors[16]. Figure 21 below illustrates the light pathways that are used to create a colour image.

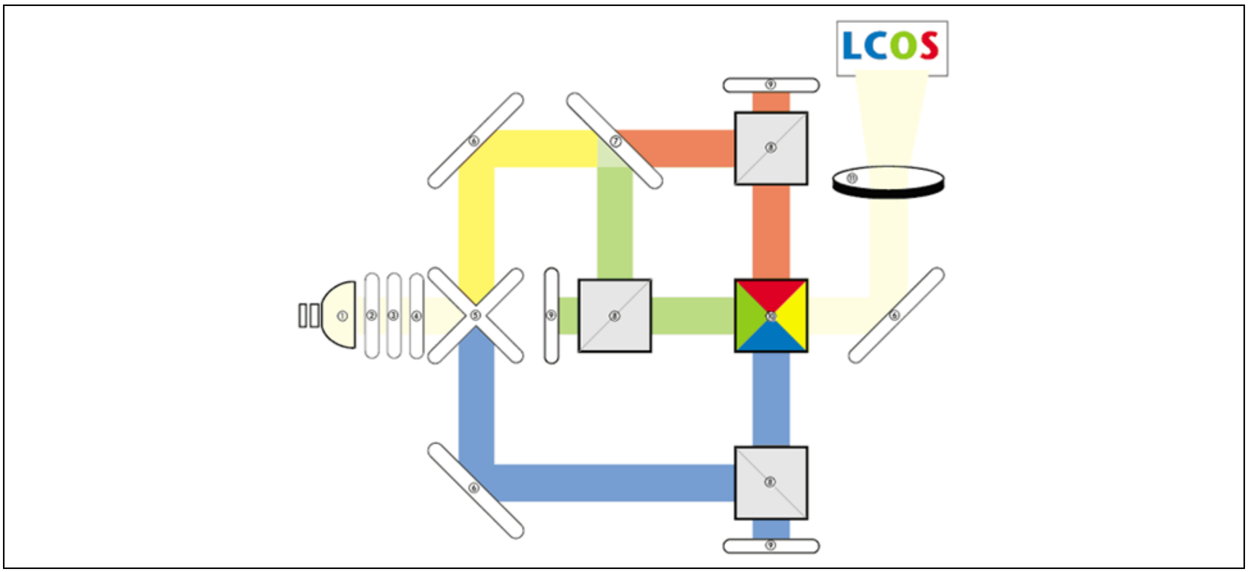



**Figure 21. Light pathways in LCOS projectors**

In LCOS projectors, white light from the lamp is split using three polarising glass beam splitters into the three primary colours, red, green and blue.

Each coloured light beam passes through different optical pathways to create red, green and blue images which are then recombined to generate the image. It is essential that the light transmission of each colour is equal to achieve accurate colours, but the percentage of blue light transmission through most lead-free glass types is significantly lower than the other colours and so accurate colours can be produced only by attenuating the red and green signals. As a result more energy (ca. double) is needed to obtain an accurate colour bright image with lead-free glass than with lead-based glass that have high blue light transmission efficiency. If more intense lamps are used, these generate more heat which potentially causes optical distortion due to heating of optical glass.

**Fluorescence spectroscopy** is an analytical technique that is used for analysis of some types of organic substances, molecular biology (e.g. cell and tissue analysis), medical research, cancer detection and other medical diagnostic procedures and industrial applications such as semiconductor analysis. All fluorescence techniques require optical glass with high percentage transmission at short wavelengths and fluorescence microscopes require many high quality lenses. Fluorescence spectroscopy operates by exposing the sample to light of a preselected wavelength which can be ultraviolet or visible light. Some materials absorb this light and then emit light of a longer wavelength by fluorescence in all directions. The emitted fluorescence is detected for quantitative analysis, imaging or mapping, depending on the type of instrument used. Medical diagnostics, for example often use near UV or blue/violet light to cause fluorescence and so a high percentage of light transmission at short wavelengths is essential.

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[16] http://www.projectorcentral.com/lcos.htm

## Binoculars and telescopes

Classical Binoculars and Spotting Scopes have been improved over the past decades, not only in terms of image quality, but also transmission and brightness. The incorporation of electronics, such as laser range finding or imaging capabilities, into these products is a challenge. Additional functionality has been incorporated without having a detrimental effect on the optical performance. To be able to observe those creatures that are active in the twilight hours, later in the evening or earlier in the morning, such as nightingales, bats, owls and other shy animals, one needs the highest possible transmission. Nature conservation and maintaining biodiversity is one of the UN sustainability goals and that it is of highest importance to have the best observation media for surveying and correctly identifying wildlife. Obtaining clear images in twilight conditions is particularly difficult, as many lead-free glass types absorb a significant proportion of the blue spectrum. Light levels at dusk and dawn are very much less than during the day, but the human eye is able to compensate so that scenery does not appear to the naked eye to be a lot less bright at dusk than at midday, even though light levels are much less. At twilight, the spectral component of the blue spectrum due to Raleigh scattering is particularly high, which is why high glass transmittance in the short-wave range makes observation much easier. In addition, there is the increased spectral sensitivity in the blue of scotopic vision (night vision) in comparison to photopic vision (daytime vision). When viewed through optical instruments such as binoculars and telescopes however, the optical performance is important to create a clear image from the very small amount of light received from small distant objects. Bright colour-accurate images are achieved only if as much light as possible of all visible wavelengths passes through the optical glass lenses of the instrument.

The graph below shows a spectral distribution of a typical spotting telescope and the spectral sensitivity curves of the human eye:

- (1) with the glass types being of lead-containing glass (red spectral curve) and

- (2) the same device with the glass types being of lead-free glass (blue spectral curve).

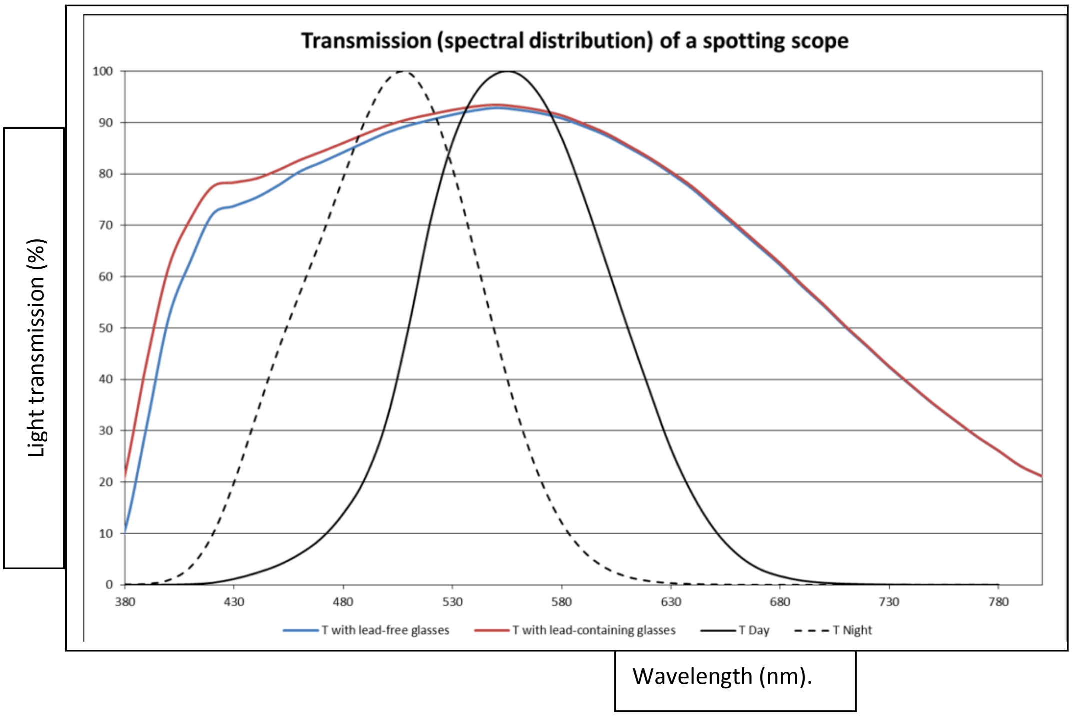


**Figure 22. Light transmission with lead and lead-free glass compared with day and night human vision behaviour**

In the example above the values $\tau_{Day}$ are 89% without lead and 90.0% with lead. A larger effect can be seen for the $\tau_{Night}$ value, where we calculate 86% without lead and 88% with lead. The difference between 86% and 88% may seem small but this is clearly noticeable to the human eye and can make the difference between seeing a creature or not.

The values $\tau_{Day}$ and $\tau_{Night}$ are calculated from these curves and give a sensitivity value for the human eye when using the device in daylight or at night. The value is always in the range from 0 to 1 (or 0% to 100%) and describes the perceived brightness of the image when watched through the device compared to the naked eye. The higher the value, the better the performance is for the user.

The calculation uses the eye sensitivity curves for day and nighttime watching as well as a standardized illumination source which corresponds to an overcast sky in the afternoon. Common values of $\tau_{Day}$ and $\tau_{Night}$ are around 85 to 95%.

High performance binoculars, monoculars and telescopes, etc., require that a very high proportion of all visible light wavelengths are transmitted through the glass (as well as other essential properties). These instruments have at least one optical element which is used to image an object and usually many are required. An optical element is, for example, understood to mean a lens unit, a prism, or a prism system composed of multiple prisms. A lens unit is, for example, understood to mean one single lens or a unit which is composed of at least two lenses. It is necessary to make the optical element of both leaded and lead-free types of glass to achieve the required optical performance and typically use at least several of the following types of glass: N-BK7HT, N-SK2HT, F2HT, N-LASF45HT, SF6HT, N-SF6HTultra, N-SF6HT, SF57HTultra, N-SF57HTultra, N-SF57HT, as well as N-LASF9HT.

The above-named glass types are glass made by the SCHOTT Corporation[17]. The high performance is achieved only if all of the listed glass types can be used.

Examples of the types of glass and their properties that could be used are as follows:

**Table 5. Refractive index, Abbe number and transmission of example types of glass.**

| Glass | $n_d$ (refractive index of the glass at Na-D-line (589nm) | $v_d$ (dispersion at 589nm) | $\tau_t$ ** (transmission, with $\tau_t$ = 1 is 100%) |
|---|---|---|---|
| N-BK7HT | 1.51680 | 64.17 | 0.998 |
| N-BAK4HT | 1.56883 | 55.98 | 0.993 |
| N-SK2HT | 1.60738 | 56.65 | 0.996 |
| N-KZFS4HT | 1.61336 | 44.49 | 0.985 |
| F2HT | 1.62004 | 36.37 | 0.996 |
| N-LASF45HT | 1.80107 | 34.97 | 0.886 |
| SF6HT | 1.80518 | 25.43 | 0.947 |
| N-SF6HTultra | 1.80518 | 25.36 | 0.887 |
| N-SF6HT | 1.80518 | 25.36 | 0.877 |
| SF57HTultra | 1.84666 | 23.83 | 0.924 |
| N-SF57HTultra | 1.84666 | 23.78 | 0.830 |
| N-SF57HT | 1.84666 | 23.78 | 0.793 |
| N-LASF9HT | 1.85025 | 32.17 | 0.843 |
| ** 10mm thickness, 400nm wavelength | | | |

The table shows that there are Pb-free HT-glass types as well as Pb-containing HT-glass types used. Example: For SF6HT the transmission at 400 nm is much better than for the Pb-free type N-SF6HT (94.1% instead of only 88.7%). The substitutes for SF6HT that are listed above have high $\tau_l$ values but have smaller refractive indices and different Abbe Indices and so cannot be used as alternatives.

Binoculars and spotting scopes increasingly contain electronic functionality. Information is being superposed onto the image which always means an incorporation of a display along with a beam splitter in the optical viewing path. These displays (e.g. transparent LCDs) absorb a fairly high amount of light which counteracts all efforts to increase the transmittance of the device. This is an additional reason to use lead-containing glass to maximize light transmission.

[17] US20130258161A1, downloaded from https://patents.google.com/patent/US20130258161?oq=US+2013-0258161


**Figure 23. Novel design of telescope with inbuilt CCD camera (image courtesy of Carl Zeiss).**

The image above shows a spotting scope with integrated CCD camera. Here it is of particular importance to realize a high percentage of light transmission, not only for the observation channel, but also for the camera path. Short exposure time for fast moving birds or animals require a large amount of light in the camera path.

### Low stress birefringence (low stress optical constant)

Low stress birefringence is essential for obtaining clear images without distortion and only lead-based glass types have both low stress optical constants and high refractive index. The graph below shows all types of optical glass produced by SCHOTT. Only a very few types, all lead based, have high refractive index (close to 1.8) and very low stress optical constants (<1.0).

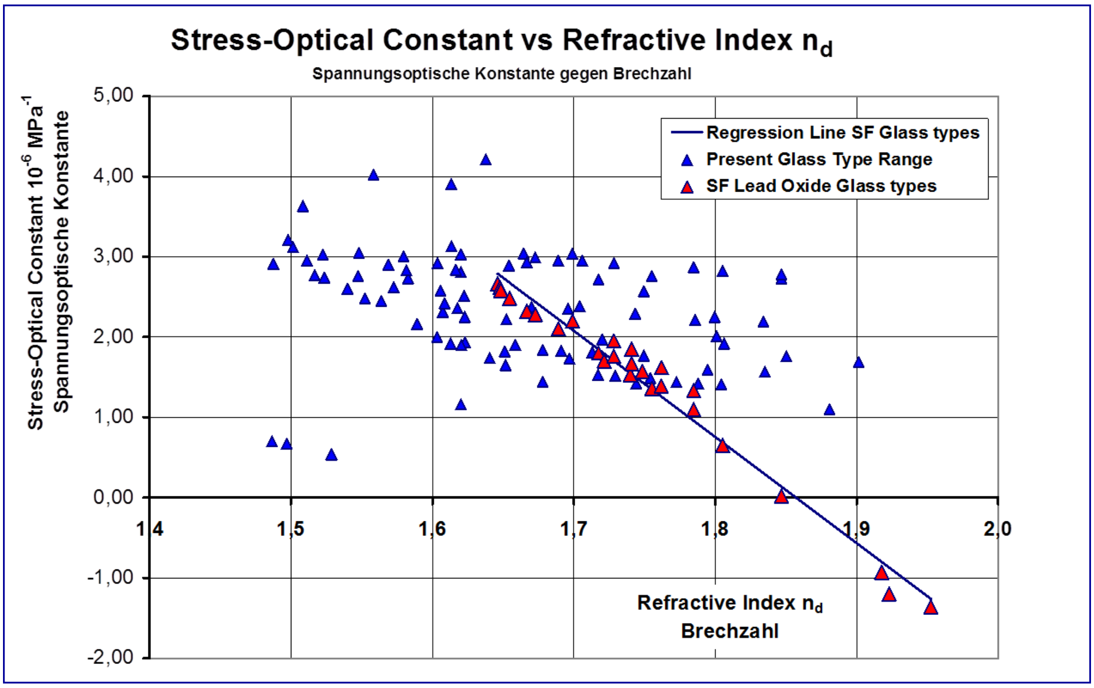


**Figure 24. Graph of stress optical constant and refractive index for optical glass.**

Stress birefringence causes a variety of optical effects that make images appear blurred and colours to be changed. The image below compares the light output from a LCOS projector with lead-free and lead-based glass beam splitters.

**Figure 25. Images from lead-free (left) and lead-based (right) glass beam splitters viewed in real LCOS projectors. Users expect the high quality display image, as above, to be absolutely black as in the right image**

The lead-free N-BK7 glass beam splitter has a stress optical constant that is much larger ($2.77 \times 10^{-6}$ $mm^2/N$) than the SF57 leaded glass ($0.02 \times 10^{-6}$ $mm^2/N$) beam splitter so that the colours of white light are refracted unevenly resulting in the colour separation seen in the left image of Figure 25. Stresses are induced by thermal effects, which in projectors are caused by heat from the lamp. Birefringence causes poor quality images in cameras and many other types of optical instruments which appears as poor contrast and distorted colours.

### Colour aberration

The refractive index of all types of glass varies with wavelength so that blue light is refracted more than red light and this causes colour aberrations in images seen as coloured fringes. Lead-free glass types are typically inferior showing greater aberration than lead-based glass and this is because the difference between the refractive index of blue and red light is larger with lead-free glass than with lead-based glass. Examples are shown below.

**Figure 26. Colour photograph showing coloured fringes (arrowed)**

Contrast and image clarity can also be affected as is shown by the pair of images below.

**Figure 27. Photographs obtained with lead-based glass lens (left image) and lead-free glass lens (right image). Note colour fringes on right image which is also blurred.**

Chromatic aberration is removed by using combinations of lenses with different properties. Axial chromatic aberration is prevented by combining one concave (negative) and one convex (positive) lens either as:

A. the positive lens element is assigned a significantly higher Abbe number than the negative lens, while the negative lens element has to be allocated a higher refractive index.
B. the positive lens element is assigned both a higher Abbe number and higher refractive index than the negative lens element.

In both cases, the difference between the Abbe numbers should be as great as possible but to obtain a compact design (necessary for microscopes and photographic and video camera lenses) with smallest chromatic aberration, the second option "B" is preferred and the positive lens should have as high a possible refractive index as possible. In these designs, the negative lens must have a low Abbe number and this is provided by the SF range of leaded glass and their lead-free equivalents. However, only the leaded versions transmit a high percentage of blue light and so lead-free glass is not suitable.

Table 6 illustrates the combinations of essential properties required by several illustrative uses of lead in white optical glass e.g.: High % light transmission together with specific index of refraction and dispersion values.

**Table 6 Illustrative uses of lead in white optical glass with essential properties**

| | High refractive index | Special Dispersion charac-teristics | High change of refractive index with tempera-ture | High trans-mission in blue to UV range | Very low birefrin-gence at high tempera-ture gradients | Produci-bility in large sizes (> 250 mm) | Extremely high homo-geneity in large items | High Faraday effect (Verdet-constant) | High density | Thermal expansion coefficient |
|---|---|---|---|---|---|---|---|---|---|---|
| **Fluorescence microscopy** | x | x | | xx | | | | | | |
| **Surgical microscopes** | x | x | | xx | | | | | | |
| **Laserscanning microscopy** | x | x | | xx | | | | | | |
| **Digital projection** | x | | | xx | xx | | | | | |
| **Binoculars, telescopes** | x | x | | xx | | | | | | |
| **Temperature stabilized lenses (printing machines)** | x | x | x | xx | xx | xx | x | | | x |
| **Photographic lenses** | x | x | | xx | | | | | | |
| **Cinematographic lenses television lenses** | x | x | | xx | | | | | | |
| **Photolab equipment** | x | x | | xx | x | | | | | |
| **i-line microlithography** | x | xx | | xx | | xx | xx | | | |
| **x-ray imaging optics** | x | x | | xx | | | | | X | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Endoscopes medical and technical** | x | x | | xx | | | | | | |
| **Ophthalmic instruments** | x | x | | xx | | | | | | |
| **Microbiology optical instruments** | x | x | | xx | | | | | | |
| **Spectrometers for food watch and environment surveillance** | x | x | | xx | | | | | | |
| **Polarimeters** | x | x | | x | | | | xx | | |
| **Glass fibers for high quality illumination** | xx | | | xx | | | | | | |
| **Atmospheric dispersion correction (Astronomy)** | x | xx | | xx | | xx | xx | | | |
| **Astronomical telescopes transfer optics** | x | x | | xx | | xx | xx | | | |
| **Periscopes** | x | | | xx | | xx | xx | | | |
| **CNC video measuring systems (bright illumination)** | x | x | | xx | xx | | | | | |
| **Laser optics for commercial printers** | x | x | | xx | xx | xx | x | | | |

Removal of lead containing glass from EU products would mean severe restrictions in functionality and quality of the applications and in many of the above examples, these types of products could not be sold in the EU. This would have a devastating impact on a wide variety of research, technology, industrial production, medical research, diagnosis and therapy, food analysis, environment monitoring, air traffic control, facilities safety and defence, which all depend critically on equipment that contains lead optical glass.

In virtually for all applications of optical glass a combination of three or more technical parameters needs to be considered and optimized for best performance, so it is impossible to pick a single parameter as a criterion of distinction under RoHS.

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## 5. Information on Possible preparation for reuse or recycling of waste from EEE and on provisions for appropriate treatment of waste

**1) Please indicate if a closed loop system exist for EEE waste of application exists and provide information of its characteristics (method of collection to ensure closed loop, method of treatment, etc.)**

No closed loop exists

**2) Please indicate where relevant:**

☒ Article is collected and sent without dismantling for recycling: Based on WEEE EUROSTAT data for categories 8 and 9 (the categories that have most uses for this exemption), data for Germany indicates about 86% of collected WEEE is recycled.

☒ Article is collected and completely refurbished for reuse: Eurostat data[18] is available for only a few EU States and only for a few WEEE categories. Based on categories 8 and 9 data for France and Germany, reuse is typically 0.1 to 1%

☐ Article is collected and dismantled:

☐ The following parts are refurbished for use as spare parts:

☐ The following parts are subsequently recycled:

☒ Article cannot be recycled and is therefore:

☒ Sent for energy return: Based on WEEE EUROSTAT data for categories 8 and 9 (the categories that have most uses for this exemption), data for Germany indicates about 11% of collected WEEE is incinerated

☒ Landfilled: Based on WEEE EUROSTAT data for categories 8 and 9 (the categories that have most uses for this exemption), data for Germany indicates about 2% is not recovered (6 – 8% France), so is probably landfilled, but this does not include unreported WEEE.

**3) Please provide information concerning the amount (weight) of RoHS substance present in EEE waste accumulates per annum:**

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[18] Via links from https://ec.europa.eu/eurostat/web/waste/key-waste-streams/weee

The quantities of lead in each waste stream are not measured. As the quantity of lead optical glass used annually has not changed for many years, the total amount is likely to be the same as the amount used (from section 4.4) of 275 tonnes.

☐ In articles which are refurbished
☐ In articles which are recycled
☐ In articles which are sent for energy return
☐ In articles which are landfilled

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## 6. Analysis of possible alternative substances

**(A) Please provide information if possible alternative applications or alternatives for use of RoHS substances in application exist. Please elaborate analysis on a life-cycle basis, including where available information about independent research, peer-review studies development activities undertaken**

Three options are considered here as potential alternative substances or designs.

- Lead-free optical glass.
- Plastic lenses.
- Alternative equipment designs.

**Alternative lead-free optical glass** is compared with lead-based glass in the answer to Section 4 above. In the following example, we consider professional camera lenses for photography and for cinematography which have superior performance to camera lenses used on cameras sold to consumers. This is because, images frequently need to be magnified by large amounts and any errors become very obvious at high magnifications. Therefore, the best quality is essential. To achieve the best performance, professional cameras consist of many different lens shapes which are made from different types of glass. Two example lenses are shown to illustrate the need for lead-based glass:

i. A typical professional lens is shown below. The version that uses lead-based glass requires 12 individual lenses whereas to achieve similar image quality, 14 lead-free glass lenses are needed.

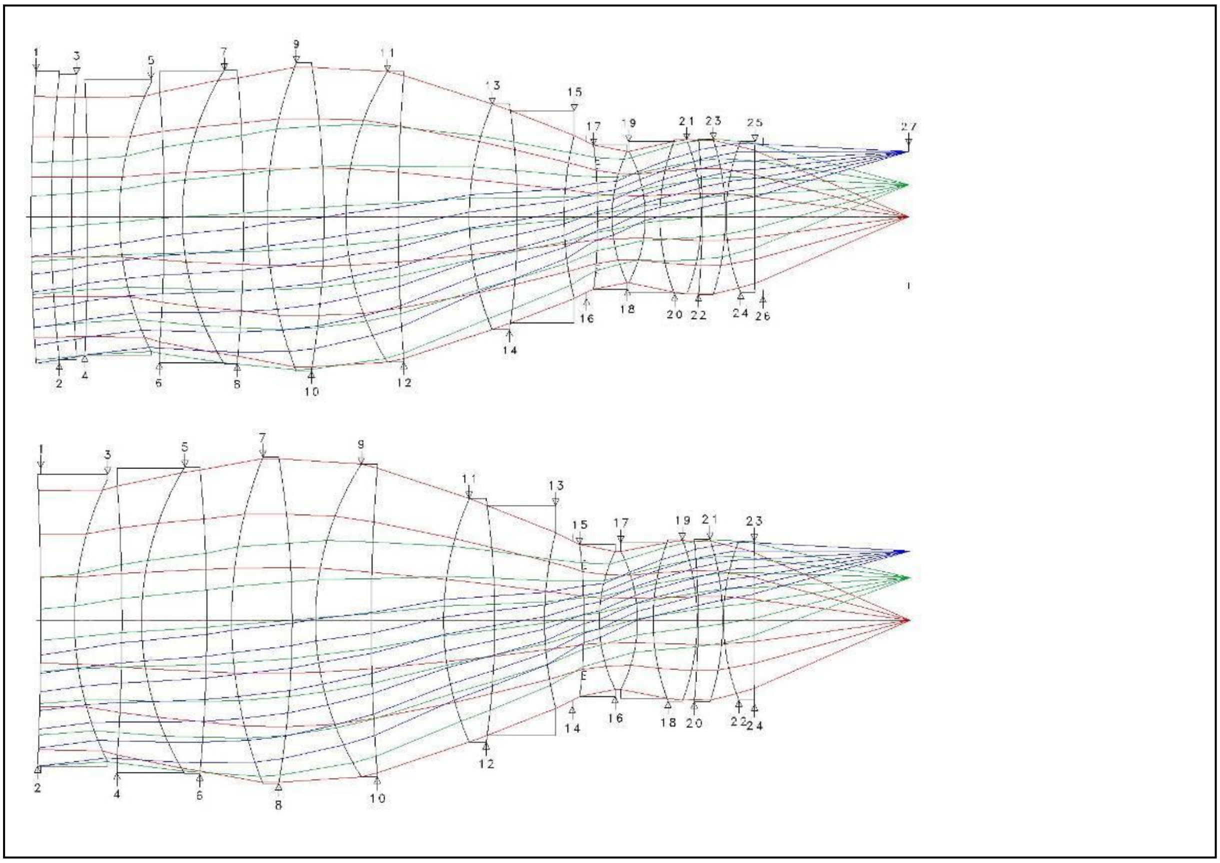

**Figure 28. Comparison of lens designs, showing that lead-free designs need more glass material – upper diagram Lead-based glass lenses with 12 components, lower diagram Lead-free glass lens with 14 components**

The effect of increasing the number of lenses from 12 to 14 has a significant negative effect. There will be more transmitted light absorbed through 14 lenses than through 12, especially at shorter wavelengths. Also, at every lens surface, some light is reflected which degrades image quality and two additional lenses means four more surfaces for reflections to occur. It is not possible to quantitatively measure this difference as inferior quality lead-free lenses are not made but the difference in image quality between these two lenses would be obvious to a professional photographer.

ii. “Fish-eye” lenses are used with cameras for photography, cinematography and television cameras. These use relatively thick lenses such as the example shown below.

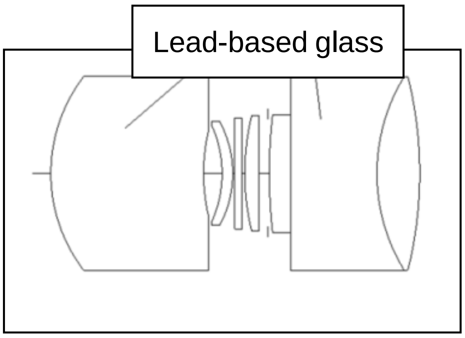


**Figure 29. Design of a “Fish-eye”-lens structure for a professional camera**

The two very thick lenses must have low light absorption to obtain clear bright images with good colour accuracy. The table below shows the difference in light transmission losses for the same lens made with lead-free glass and with lead-based glass:

**Table 7. Light transmission through lead and lead-free glass between 404 and 656nm**

| Wavelength (nm) | 656 | 622 | 587 | 566 | 546 | 516 | 486 | 460 | 435 | 420 | 404 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| With lead | 0.985 | 0.985 | 0.985 | 0.985 | 0.984 | 0.977 | 0.963 | 0.941 | 0.901 | 0.828 | 0.657 |
| Lead-free | 0.947 | 0.954 | 0.961 | 0.960 | 0.956 | 0.928 | 0.892 | 0.854 | 0.782 | 0.699 | 0.464 |
| Difference | 0.038 | 0.031 | 0.024 | 0.024 | 0.028 | 0.050 | 0.071 | 0.087 | 0.119 | 0.129 | 0.193 |
| Difference in % transmission loss | 3.83 | 3.15 | 2.47 | 2.47 | 2.85 | 5.08 | 7.34 | 9.21 | 13.23 | 15.53 | 29.35 |

At blue wavelengths, such as 420nm, only 70% of blue light is transmitted with the lead-free version whereas 83% of blue light is transmitted by the lead-based glass lens. As a result, the lead-free fish-eye lens will give a redder coloured image.

### Laser optics

A laser manufacturer has evaluated a lead-free optical glass to replace the lead-based glass that is currently used. The currently used optimal glass is type SF10 (made by SCHOTT AG) and the most similar lead-free glass is N-SF10 (developed by SCHOTT as a potential substitute with similar, but not identical properties). The laser manufacture has compared internal transmission of these two materials and found the following:

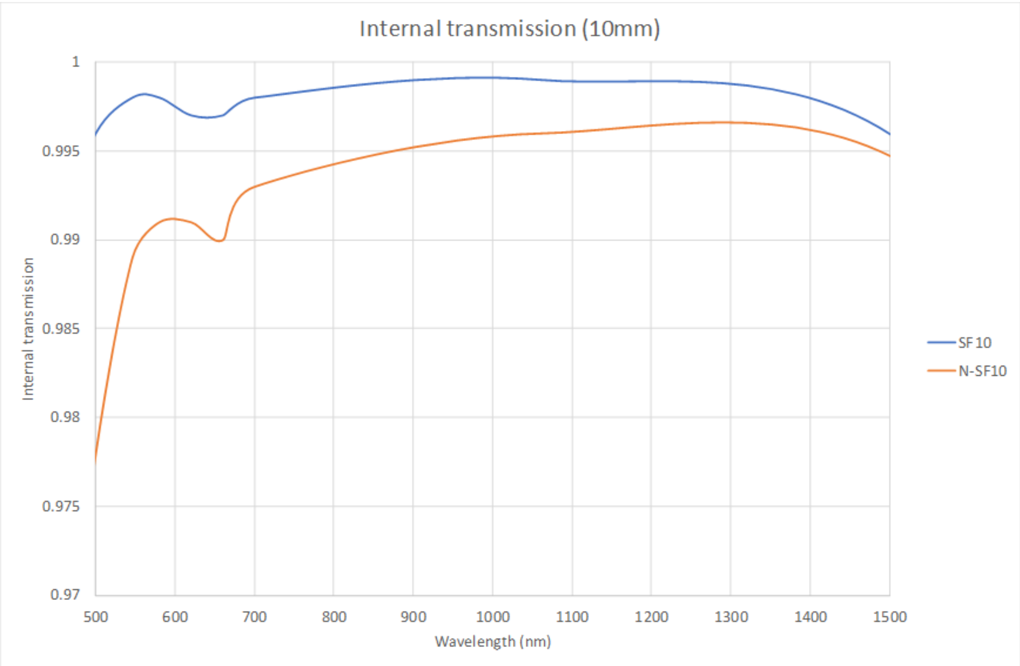


**Figure 30. Comparison of internal transmission of SF10 with N-SF10 glass**

Laser manufacturers find that the increased absorption of the lead-free glass is unacceptable because this causes a loss of laser power and more importantly localised heating. This heating causes a change of refractive index and therefore a power dependent distortion of the beam shape. This distortion can be quantified as the “beam quality” or $M^2$ which should ideally be equal to 1.0. Any degradation of beam quality increases $M^2$. Laser manufacturers have measured $M^2$ for SF10 glass in the wavelength range 650 to 1350nm and found that it is close to or below 1.1. See below.

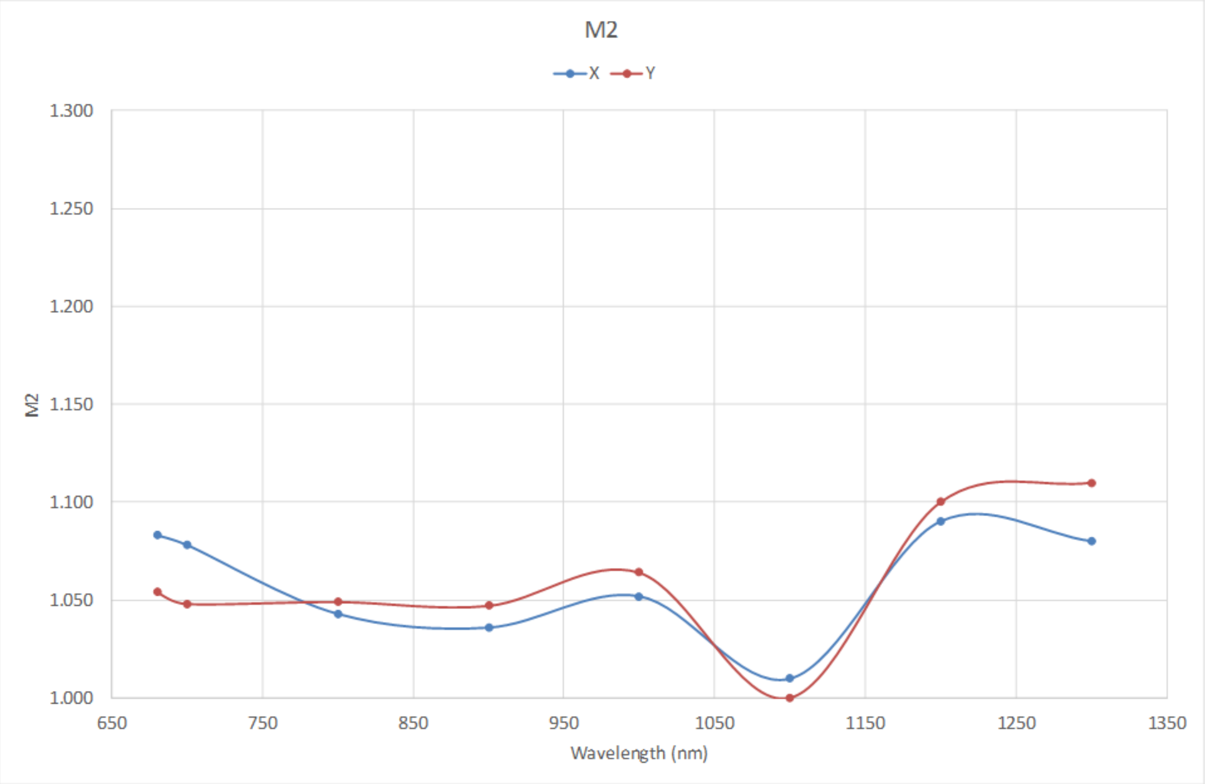


**Figure 31. $M^2$ parameter for SF10 glass dependence on wavelength in X and Y orientations**

The graph below shows the beam quality (as $M^2$) for the lead-free N-SF10 glass in the same wavelength range:

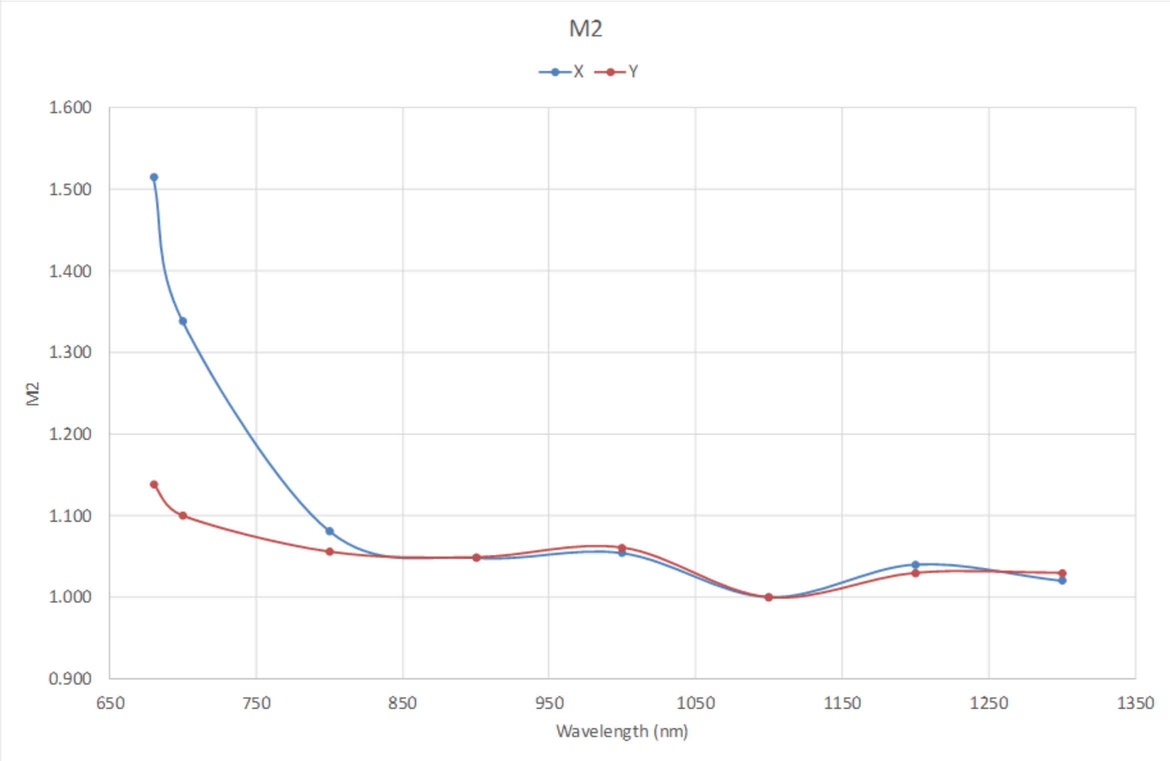


**Figure 32. Beam quality measurements for N-SF10 optical glass**

The $M^2$ parameter of N-SF10 is significantly increased at the lower wavelengths where the larger light absorption occurs with the lead-free N-SF10 glass compared with SF10.

A laser manufacturer has measured $M^2$ at various power levels and wavelength as shown below and this shows that the lead-free glass has increasingly inferior performance as power levels increase and especially at lower wavelengths.

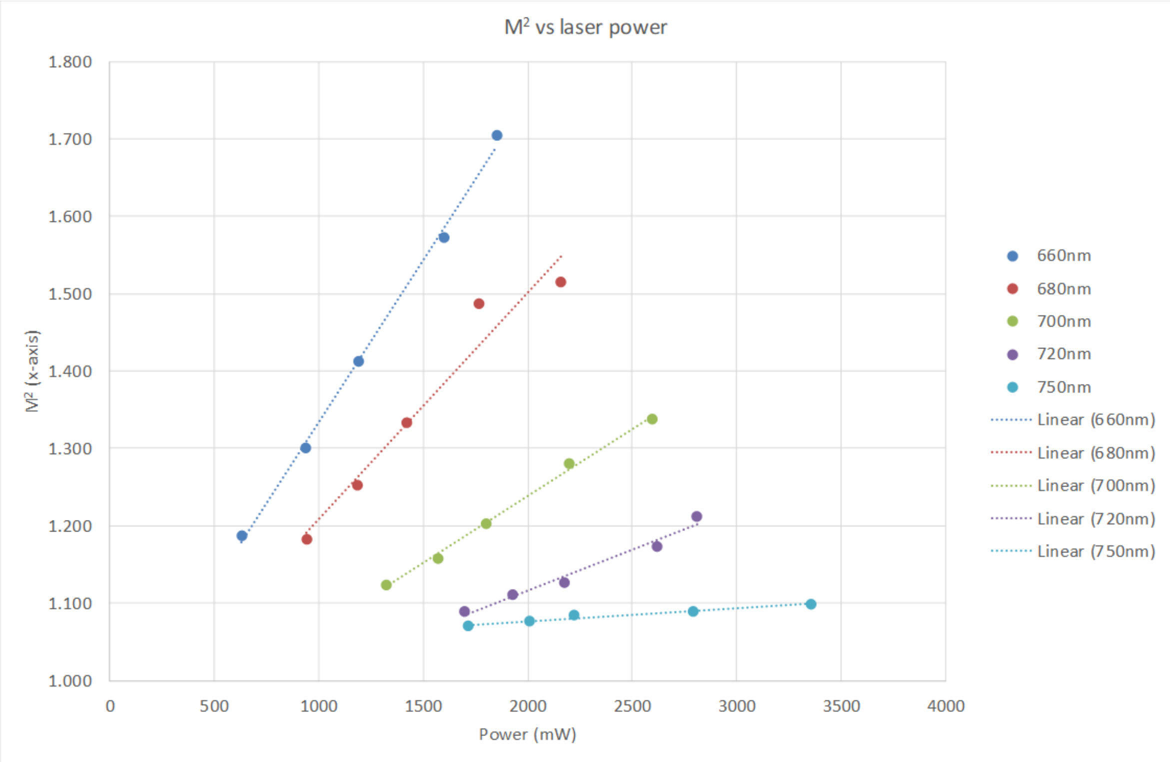


**Figure 33. Dependence of M$^2$ for N-SF10 glass on laser power and wavelength**

In conclusion, lead-free glass cannot be used with laser applications due to the poor beam quality that is achieved.

**Plastic lenses** have very different optical and physical properties to lead-based glass. One of their limitations for many applications is their inferior heat stability when compared to glass; for example, the temperature inside projectors can reach well over 100˚C and many polymers will distort or melt at these use temperatures. High refractive index (R.I.) spectacle lenses are stable at up to 120˚C although the plastic lens material with the highest refractive index is MR174 (made by Mitsui) with R.I. of 1.74 which has a heat distortion temperature of 78˚C[19].

Polymers also have much higher coefficients of thermal expansion (CTE) than glass so that temperature changes can cause dimensional changes which alter the optical characteristics. Typical linear CTE values are:

- Glass SF57HT Ultra 9.2 x $10^{-6}$/K
- Polycarbonate 70 x $10^{-6}$/K

Most clear transparent polymers such as polycarbonate and acrylics have relatively low refractive indices (<1.6) making them unsuitable for high performance magnification applications.

[19] http://www.mitsuichem.com/special/mr/resources/img/MR_Brochure_en.pdf

Table 8 summarises the main differences between lenses made of glass with plastic lenses.

**Table 8. Comparison of properties of glass and plastic lenses**

| Property | Glass | Plastics |
|---|---|---|
| Refractive index | 1.44 to 2.1 achievable (highest for lead is 2.1) | 1.49 to 1.74 |
| Tolerance (i.e. variation in characteristics of commercial lenses) | Low (±0.0001) can be achieved, so variation is very small | Estimated at ±0.001 |
| Abbe number | Broader range (20 to >80) especially to low dispersion values | 23 – 58 is possible |
| Transmittance (through 3mm) | >99% achievable | 85 – 91% typically |
| Birefringence | 2 to 10 nm/cm | 2 to >40 nm/cm |
| Density | Lead-based are ca. 5 $g/cm^3$. This offers advantages and disadvantages | 1 – 1.2 |
| Water absorption | Zero (so moisture has no effect on performance) | All plastics absorb water causing changes to optical properties (as they swell) and also potentially degradation can occur. From 0.01% to 0.3% |
| Thermal expansion | SF57HT Ultra is $9.2 \times 10^{-6}$/K, all glass 4.5 to $13 \times 10^{-6}$/K. | Range is 47 to $80 \times 10^{-6}$/K. This causes optical changes with temperature and thermal degradation |
| Refractive index thermal dependence | Smaller range of - 0.7 to + 1.2 $10^{-5}$/˚C | -8 to -14 $10^{-5}$/˚C |
| Resistance to damage | Relatively hard so not easily damaged. | Soft so easily scratched |
| Exposure to UV light | No effect | Discolours and degraded |
| Heat resistance | Resistant to temperatures created by lamps and laser light sources | Lamps and lasers can easily cause deformation or even make holes |
| Medical sterilisation | Completely resistant | May be damaged at sterilisation temperature. Viruses and bacteria can survive within scratches which plastics are more prone to than glass |
| Thermal conductivity | Lead-glass is relatively high so equilibrates faster than lead-free glass and plastics | Slow to equilibrate so can distort due to uneven heating |

Figure 34 shows the Abbe numbers and refractive indices of optical plastics that are available and all types of optical glass.

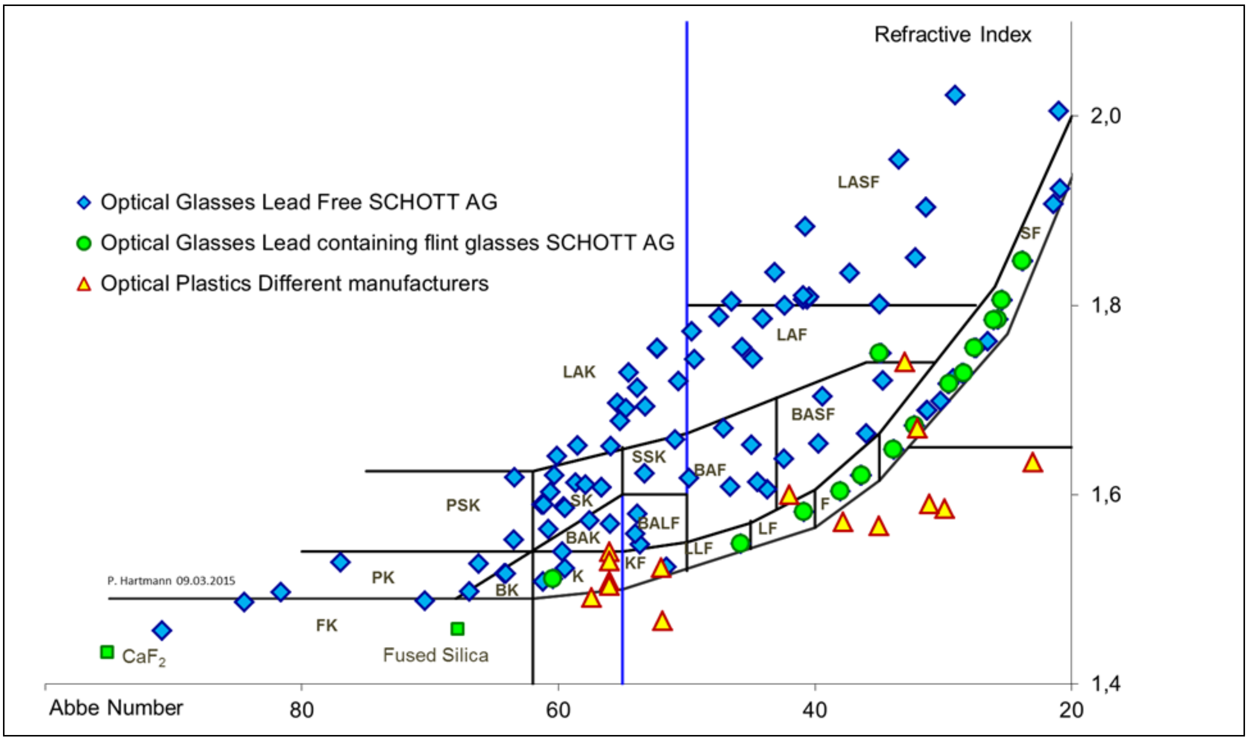


**Figure 34. Comparison of characteristics of optical plastics and optical glass**

Another significant disadvantage of plastic lenses is that they are much softer than lead-based glass and so are easily scratched and as a result become useless as this distorts images. Although lead-based glass is softer than lead-free glass, it is much harder than plastic and is not easily scratched except by very hard materials whereas plastic lenses are scratched by much softer materials. The methods usually used to measure the hardness of glass and plastic materials are not the same and so comparative data is not published.

However, Spectaris has arranged for three plastics that are used for lenses to be measured for "Knoop hardness" (0.1kg weight and 20 sec indentation, 5 measurements per sample), which is the standard method used for brittle materials such as optical glass. These measured values are compared with the values for glass published by SCHOTT outlined in below.

**Table 9** below.

**Table 9 SCHOTT Material hardness**

| Material | Knoop hardness (Pascals) |
|---|---|
| Polycarbonate | Measured at 13.2 ± 0.2 |
| PMMA | Measured at 22.4 ± 0.1 |
| Polydithiourethane (used for spectacle lenses) | Measured at 14.0 ± 0.1 |
| Lead-based glass SF57 | 350 |

| Material | Knoop hardness (Pascals) |
|---|---|
| Lead-based glass SF11 | 450 |
| Lead-free N-SF57 | 520 |
| Lead-free N-SF11 | 615 |

The larger the Knoop hardness value, the harder the material. Lead-based glass is more than 10 times harder than the hardest plastics.

**Alternative equipment design**

Different designs of equipment that provides the same function and performance, but without leaded glass would be, if available, viewed as an alternative. However, leaded glass is used in a very wide variety of applications as described here and no alternative designs have been or are likely to be developed with equivalent performance for a very large variety of applications. One example described above is of LCOS projectors. Alternative designs of projector are widely used but it is acknowledged that LCOS designs give the best optical performance.

Digital compensation software is now available and is used to modify poor quality images. This cannot, however, be used as an alternative to good quality images obtained using lead-based optical glass. This technology can only convert poor or medium optical quality to acceptable limits for amateur users. High end optics such as diffractive limited microscope objectives need the best direct optical imaging. If an image is distorted due to the properties of an inadequate optical system, digital processing software will not make the image better or clearer.

**(B) Please provide information and data to establish reliability of possible substitutes of application and of RoHS materials in application**

Reliability is not an issue as lead-free alternatives are not able to provide all of the essential characteristics needed for the many diverse applications of lead-based optical glass.

---

## 7. Proposed actions to develop possible substitutes

### (A) Please provide information if actions have been taken to develop further possible alternatives for the application or alternatives for RoHS substances in the application.

In the last 25 years not one single lead-containing glass type had been developed. Lead-containing glass types had been reduced by 88% by number within this time-frame and now have a share of 12% on the melted tonnage of all optical glass types.

There are about 90 naturally occurring elements in the periodic table. Those that are toxic such as mercury cannot be used and radioactive elements are also unsuitable. In the last 100+ years, glass types of every conceivable combination of elements have been made and evaluated.

One of the main reasons for use of lead in optical glass is to achieve high refractive index, low Abbe number and good blue wavelengths transmission. These characteristics are generally obtained by use of a high concentration of elements with a high atomic number and lead is one of the heaviest metals that is not radioactive. Table 10 describes the behaviour of the metallic elements in the periodic table from atomic number 56 (barium) to 83 (bismuth) in glass, based on past research.

**Table 10. Properties of optical glass based on heavy elements with atomic number of 56 and greater**

| Heavy elements | Atomic number | Properties in glass |
|---|---|---|
| Barium | 56 | Used in glass, with refractive index typically 1.57 and Abbe number of typically 55 to 60[20] so properties are very different to lead-glass |
| Rare earths (Lanthanum to Lutetium) | 57 to 71 | Most colour glass. Lanthanum crown glass used as commercial glass types, but have high Abbe number (typically 55 – 60) with refractive index of 1.53 – 1.57[21] and so are very different to lead-glass. |
| Hafnium | 72 | Only suitable as a dopant in glass as tends to cause crystallisation. Used in polycrystalline ceramics. |
| Tantalum | 73 | Additive in some special glass types, but only small amounts can be added to avoid crystallisation |
| Tungsten | 74 | Additive in some special glass types, but only small amounts can be added to avoid crystallisation. Can also give a blue colour. |
| Rhenium | 75 | Inert, does not form glass. US research found that solubility of Re in borosilicate glass is only 0.3%[22] . |
| Osmium | 76 | Inert, does not form glass. |
| Iridium | 77 | Inert, does not form glass. |
| Platinum | 78 | Inert, does not form glass. |
| Gold | 79 | Stable only as metal particles. Colloidal gold particles are used to colour glass red. |
| Mercury | 80 | Toxic. |
| Thallium | 81 | High refractive index glass can be made, but no commercial products exist due to its severe toxicity (<1 gram is fatal). |
| Lead | 82 | Stable, ideal combination of properties. |
| Bismuth | 83 | High refractive index, but reduction of $Bi^{3+}$ to lower valency states can occur and causes brown / black colouration. |

20 https://shop.SCHOTT.com/advanced_optics/Products/Optical-Materials/Optical-Glass/Barium-Crown/c/optical-glass/glass-BAK

21 https://shop.SCHOTT.com/advanced_optics/Products/Optical-Materials/Optical-Glass/Lanthanum-Crown/c/optical-glass/glass-LAK

22 https://www.osti.gov/servlets/purl/1050037

| | | |
|---|---|---|
| Atomic number higher than Bi | ≥84 | Radioactive, so unsuitable. |

There are a limited number of elements in the periodic table available that can be combined to form optical glasss. Also, many of the combinations of elements that form optical glass do so within relatively small composition ranges as crystallisation occurs outside of these compositions. A publication on Ba, Ti silicate glass showed that glass without crystalline inclusions is possible only within relatively narrow concentration ranges of each element[23]. After many decades of research, practically all possible combinations of elements have been prepared and evaluated and this has shown that for the types of applications described in this renewal request, there are no alternatives to the compositions that contain lead.

A Spectaris member has carried out a keyword-based review of scientific publications since 1990 resulted in 225 hits with a detailed review resulted in 40 hits publications on glass compositions. However, not a single publication referred to substitution of lead, including none of the 23 found hits with date since 2014. While many referred to lead-free glass types with typical lead crystal glass properties and naming typically Barium oxide, Zinc oxide, Bismuth oxide and Titanium oxide and similar substances as ingredients, the published optical properties are analogous to known lead-free optical glass, in some cases for low Tg glass types. None of these publications are applicable for the combination of high index, low refraction and high transmission at short wavelengths, so no content explains new approaches of lead-free optical glass types.

Recent research has included the evaluated of glass combinations with 10 or more constituents and has also evaluated production method variable such as cooling rate. One recent publication describes glass types with up to ten constituent oxides[24]. There are only a few recent patents on complex lead-free glass formulations, but these glass

[23] https://nvlpubs.nist.gov/nistpubs/jres/057/jresv57n6p317_A1b.pdf

[24] US patent application US 2017/0137317A1 describes glass types with high % transmission at low wavelengths, refractive index of ca. 1.6 and Abbe number 43 to 45, so have different properties to lead glass.

types are not intended to be replacements for lead-containing glass (as compared with Figure 10 and Figure 34). For example:

**Table 11. Refractive index and Abbe number of recently patented optical glass**

| Patent and date | Typical component elements | Refractive index | Abbe Number |
|---|---|---|---|
| US1024369B2 2016 | Si, Ti, Zr, La, Nb and Ba | 1.7 | 39 |
| US9284216B2 2016 | Si, La, B, Ge, Hf and In | 1.75 to 1.9 | 42 to 53 |

It therefore appears that the only feasible alternative for substitution is to search for alternative designs, but this has not been possible for the types of applications described here, mainly as high-quality imaging requires lenses with suitable performance.

For all applications, research has already been carried out and when lead-free substitutes were found, they are used. Further research into alternative designs is uncertain and may never be successful due to the demanding combinations of essential characteristics. Therefore, it is not possible to predict how long this type of R&D will take or whether substitutes can be found for all of the diverse applications. It is entirely probable that it will never be possible to replace leaded glass in all applications.

In the 1990s all large optical manufacturers introduced lead free glass types with optical properties as close as possible to those of the preceding lead containing glass types. The lead-free glass types were required by the consumer optics market, which asked for eco-friendly cameras. By the end of the 1990s there was very little lead containing glass used for consumer optics, which has the largest share of glass usage by far. Many companies, which could not afford to develop lead-free glass went out of business. Today, lead-containing glass types are used only for cases, where there are no alternatives to achieve the optical performance. This restricts their use to special high- end applications. The production of lead-free glass since the 1990s is much larger than that of lead containing glass.

In the last 20 plus years, all newly developed glass types are lead-free. Before 1998 SCHOTT AG (glass manufacturer in Germany) had a global market share of 35% of lead containing glass, now it is 15%. However, the total number of glass types made by SCHOTT has been reduced by half since then. Related to the original number of types made before 1998 (202 glass types) the present number means a share of only 8%. For the world-wide production SCHOTT estimate the present ratio between lead-free to lead containing optical glass is about 20:1. It appears that the RoHS Directive has not contributed towards the reduction in lead use because most replacement had been achieved before RoHS was adopted in 2002 and further substitution has not been technically feasible (hence the need for exemption 13a). There is a contribution to the reduction due to RoHS to be expected, since optical equipment manufacturers have tried to remove lead glass wherever possible form their designs. However, this contribution is small compared with the yearly fluctuations in total volume and in ratio between lead free to lead containing glass. Consumer cameras no longer use lead-based glass and pocket cameras have been replaced by smartphones with built-in cameras, but this has occurred irrespective of RoHS.

**(B) Please elaborate what stages are necessary for establishment of possible substitute and respective timeframe needed for completion of such stages.**

Lead-based glass manufacturers constantly review the published literature for papers on new glass formulations but in recent years, no new glass types have been discovered that could replace lead-based optical glass. Unless a new formulation is discovered, it is difficult to see what else glass manufacturers can do to replace lead.
Equipment manufacturers also regularly review their designs to determine if lead-free glass can be used, but for the reasons explained in sections 4 and 6, this has not been possible. Where substitution was possible, this has already been carried out as lead-free glass is both cheaper and lighter in weight than lead-based glass. Only those applications (examples are described in section 4 (B)) where lead-glass is essential for technical performance reasons remain and as lenses are essential for these applications it is difficult to foresee any alternatives.

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## 8. Justification according to Article 5(1)(a):

**(A) Links to REACH: (substance + substitute)**

1) Do any of the following provisions apply to the application described under (A) and (C)?

☐ Authorisation

- ☐ SVHC
- ☐ Candidate list
- ☐ Proposal inclusion Annex XIV
- ☐ Annex XIV

☐ Restriction

- ☐ Annex XVII
- ☐ Registry of intentions

☒ Registration: Lead containing glass (>30% w/w of lead) and $SiO_2$ < 10% w/w. has been registered and has a REACH registration number: 01-2119990048-30-0000.

2) Provide REACH-relevant information received through the supply chain.
Name of document:

*Based on the current status of Annexes XIV and XVII of the REACH Regulation, the requested exemptions would not weaken the environmental and health protection afforded by the REACH Regulation. The requested exemptions are therefore justified as other criteria of Art. 5(1)(a) apply.*

**(B) Elimination/substitution:**

1. Can the substance named under 4.(A)1 be eliminated?

   ☐ Yes. Consequences?

☒ No. Justification: Performance and characteristics would be significantly inferior if lead-free glass were to be used. The following examples illustrate why substitution is not possible:

**Example 1**: Endoscopy: Without lead-based glass types, some surgical procedures will not be possible as tumours and other features will not be visible. Endoscopes for engineering applications such as the examination of turbine blades inside aero engines will be much more difficult or impossible so that small cracks may not be seen at an early stage. This will pose a safety risk to aircraft users.

**Example 2**: High-end camera lenses rely on several types of lead-based glass. Without these, image quality will be inferior.

**Example 3**: Surgical microscope: Surgeons use these to see very small features inside people’s bodies. Image quality without lead-based glass will be inferior which will result in a loss of precision. It is necessary to cut out small tumours without healthy tissue or leaving tumour fragments. Some procedures may be impossible as obtaining the same level of magnification, may require larger lenses with the objective needing to be closer (due to lower refractive index of equivalent lead-free glass) to the parts being viewed so that there may be insufficient space to operate.

2. Can the substance named under 4.(A)1 be substituted?

   ☐ Yes.

   ☐ Design changes:

   ☐ Other materials:

   ☐ Other substance:

   ☒ No.

   Justification: No alternatives exist

3. Give details on the reliability of substitutes (technical data + information): Not applicable

4. Describe environmental assessment of substance from 4.(A)1 and possible substitutes with regard to
    1) Environmental impacts:
    2) Health impacts:
    3) Consumer safety impacts:

This is not used to justify this exemption but not renewing this exemption would negatively affect all three impacts as described here:

1) Environmental impacts: Lead glass lenses are used in chemical analysis equipment that is used to monitor environmental pollutants. This would be less accurate without lead in optical glass so that pollution is more likely to remain undetected.

Optical glass containing lead is also used for spare parts to repair and refurbish equipment. The availability of these types of glass depends on a healthy market for new products that contain lead glass because optical glass production cannot be scaled-down.

Manufacture of lead-based optical glass on a small scale is technically impractical as it is too difficult to precisely control the glass composition and the optical properties of the glass. Glass production needs minimum production quantity to achieve the very high quality required. The first part of the melting run, when essential properties are still varied to reach the tolerance ranges, cannot be used. The last part while emptying the melting tank cannot be used also because refining, stirring and casting require a minimum glass level in the system. Only the glass that is molten in between, when all properties remain in tolerance and sufficiently stable, is usable. Depending on the glass type the melting tanks and pots need a minimum size to achieve the required glass quality. For lead flint glass the minimum production amount is 2 tonnes. This means that even if only 100kg is required (e.g. to make spare parts), two tons would have to be produced to achieve suitable quality but for sales of only 100kg, this would be uneconomic as the price of the spare parts would be too high as to prevent equipment being repaired and so it will become waste. Making a small amount and discarding the rest as waste would also be very non-ecological.

2) Health impacts: Several types of medical device require lead in optical glass in order to provide the optimum diagnostic and treatment performance. This is explained in the answer to Section 4 and 8 (B).1. Human health would be negatively affected if lead in optical glass could not be used.

3) Consumer safety impacts: None known to Spectaris

⇨ Do impacts of substitution outweigh benefits thereof?
Please provide third-party verified assessment on this:

**(C) Availability of substitutes:**

a) Describe supply sources for substitutes: Substitutes do not exist

b) Have you encountered problems with the availability? Describe: Not applicable

c) Do you consider the price of the substitute to be a problem for the availability?

☐ Yes ☒ No

d) What conditions need to be fulfilled to ensure the availability? Discovery of new glass formulations

**(D) Socio-economic impact of substitution:**

⇨ What kind of economic effects do you consider related to substitution?

☐ Increase in direct production costs

☐ Increase in fixed costs

☐ Increase in overhead

☒ Possible social impacts within the EU – see below

☐ Possible social impacts external to the EU

☐ Other:

⇨ Provide sufficient evidence (third-party verified) to support your statement: Data below was from a market research study in 2017 by Optech Consulting.

Without this exemption, all current optical designs would, in theory, have to be redesigned, but in practice, suitable alternative glass types do not currently exist and so redesign is impossible. This option therefore cannot be envisaged from current technology. Glass and optical equipment manufacturers have already phased out leaded glass types wherever this has been possible.

As most equipment manufacturers have already attempted to switch to lead-free optical glass wherever possible because lead-free glass has a lower price and is lighter weight than lead-based glass. This would mean that many types of products could not be sold in the EU, making EU industries such as film production and R&D uncompetitive or impossible and the health of EU patients would be negatively affected.

There would also be a competitive disadvantage to EU glass manufacturers that manufacture lead-based optical glass if this exemption were not renewed because only a very few global manufacturers produce lead-based glass as well as lead-free glass. Several EU glass manufacturers stopped making lead-based glass due to the declining market size resulting partly from the restrictions on lead by RoHS as well as due to consumer demand. Also, optical designs without Pb-containing glass will require more lens elements which increases lens size and reduces light transmission; both are unacceptable to users.

In the EU, there is no real disadvantage to EU manufacturers of lead-based optical glass as all manufacturers and importers must comply with RoHS in the EU. However, EU glass manufacturers may be at a disadvantage when competing outside of the EU with non-EU competitors that do not operate within the EU. This would not only be applicable to lead-glass manufacturers, but also manufacturers of products made with glass if the EU (lead-free) versions were to have inferior performance. EU glass manufacturers are subject to the EU Industrial Emissions Directive (IED), and therefore emissions are strictly controlled in the EU, however this Directive is only relevant to manufacturing sites located in the EU.

In the EU, there is only one lead-based optical glass manufacturer left. Emissions from lead containing glass types are very small and controlled. In Japan, almost all glass manufacturers have stopped production of lead containing glass since consumer optics, which is their by far largest market, does not require the special performance of these glass types. Only one Japanese manufacturer produces glass for microlithography, of which some glass types must be lead containing ones but they do not disclose details of their production. Due to cost reasons Japanese glass manufacturers shifted a large proportion of glass production to China many years ago. China is the only country with a significant production of lead glass but on a lower quality level. Details about Chinese production are not published.

There are an estimated 5000 manufacturers in the EU that rely on optical glass (most are SMEs), worth €69Bn per annum. The European Photonics industry has a 50% global market share for Production Technology, 35% global market share for Optical Measurement & Image Processing and a 32% global market share for Optical Components and Systems[25]. The European Photonics Production Growth rate is more than 3.5 times higher than the EU's GDP growth rate and has grown with an average CAGR of 5% since 2005.

If exemption 13a were not renewed, this would have a devastating impact on EU industry affecting up to 5,000 companies in the photonic sector alone with many billions of lost income to the EU and many lost jobs. 300,000 people work directly in the EU photonics sector, but many more in EU industries that rely on photonic equipment.

Without this exemption, hospitals could not replace optical instruments such as endoscopes and surgical microscopes and this would severely harm many thousands of EU patients per year. Also, EU manufacturers of a very wide variety of products ranging from aerospace automotive, IT/telecom, etc. could not buy the optical instruments they rely on so that many industries would not be able to continue operating in the EU. EU researchers in research establishments would become uncompetitive or be unable to continue in many fields without high performance optical instruments. Many manufacturers and researchers rely on equipment that needs exemption 13a to remain highly competitive.

All of the research methods and equipment described in page 11 above as well as many others rely on lead-glass optics and so not renewing 13a would have a severe and highly detrimental impact on the European research landscape covering research on cancer, AIDS, Alzheimer, etc., as well as routine diagnostics like fluorescence-in-situ-hybridization, pathology and digital slides. Deleting exemption 13a for lead-containing glass would hence severely harm EU academic research as well as pharmaceutical R&D in the European Union. Furthermore clinical analytics would become equally hindered with unpredictable consequences to the EU health system.

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[25] From Optech Consulting, data at https://www.photonics21.org/ppp-services/photonics-downloads.php

The EU is continuing to fund research in the photonics sector (€85 million awarded in 2018[25]) with the HORIZON 2020 Framework program which has funded research into optics technology for many years. Recently, the European Commission highlighted the importance of this sector to the EU by announcing that this will continue as Horizon Europe (2021-2027), once the current Horizon 2020 period is completed. This funding will encourage research into new optical solutions as substitute materials for lead is unlikely to be successful, as explained above. This funding would support the long-term EU aim to stay ahead of other competing economies, which currently do not have the same substance prohibitions as EU industry without this exemption.

## 9. Other relevant information

**Please provide additional relevant information to further establish the necessity of your request:**

See attached documents:

9.1 “Additional technical information for exemption 13a renewal request”.

9.2. Annex: Microscopic devices for UV-Light, important tools in biological and medical research

9.2.1 Appendix 1, examples of publications on cancer research.

9.2.2 Appendix 2, recent publications on laser capture microdissection

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## 10. Information that should be regarded as proprietary

**Please state clearly whether any of the above information should be regarded to as proprietary information. If so, please provide verifiable justification:**

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