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Materials & Treatments

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Introduction

Materials and treatments are the basic constituents of ophthalmic lenses: they provide optical correction and comfortable vision. More precisely, the materials create the optical function of the lens in combination with the surface geometry and treatments provide visual comfort by adding multiple properties to the lenses. Together their purpose is to allow the wearer to forget his/her corrective lenses.

In just a few decades, materials and treatments have seen profound changes: plastics have replaced glass lenses, the use of anti-scratch and anti-reflective treatments has become commonplace and numerous materials and treatments have appeared.

Ophthalmic lenses have a complex structure: they result from the interlayering of a material and a series of treatments, each of which is a response to a specific need: reduced thickness, light weight, transparency, durability, strength, protection, aesthetics, etc. An ophthalmic lens can have up to twenty of these thin layers deposited on the front and rear surfaces (figure 1).

Materials and treatments form an indivisible whole: if the material has the essential function of providing optical correction, it also has the purpose of being the carrier for the various treatments. The study of materials cannot be separated from that of treatments and, conversely, treatments cannot be studied independently of the materials with which they are associated. That is the reason why "Materials and Treatments" are dealt with jointly in a single Ophthalmic Optics File.

In order to give a structured summary, all the concepts presented in this file are first of all presented from the point of view of the needs of the lens wearer and technical elements are then considered as responses to these needs. That is why this file contains four sections :

I) Thinness and weight
II) Transparency and durability
III) Strength and protection
IV) Aesthetics and fashion

In each of these section the needs and expectations of the wearer are described first of all and the design and manufacturing techniques used are presented afterwards.

This volume "Materials and Treatments" in the collection "Ophthalmic Optics Files" aims to present in summary form the essential concepts used in the composition and internal design of lenses. It will take you on a fascinating journey through the very heart of ophthalmic lenses.

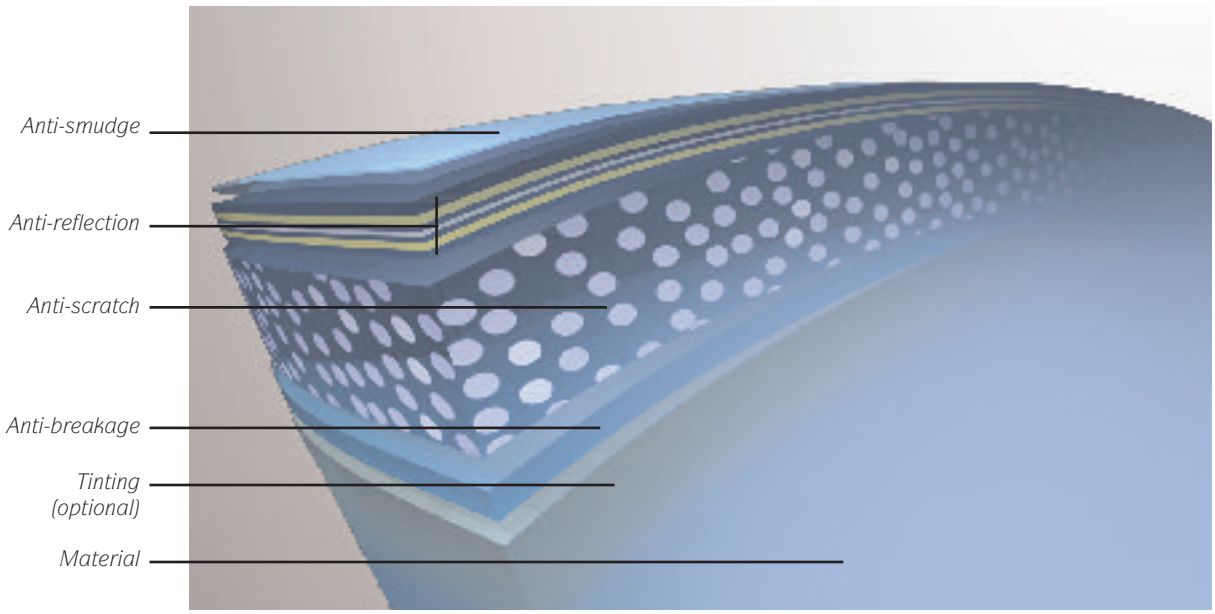

Figure 1 : *Structure of an ophthalmic lens.*

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1. Thinness and weight

For as long as spectacle lenses have existed, manufacturers have continued to try to make them thinner and lighter in response to the demands of wearers. So, refractive indices were increased, lens surfaces were aspherised, lenses were surfaced as thin as possible and heavy glass materials were replaced by extremely light plastic ones.
Actually, to produce lenses that are both aesthetic due to their reduced thickness and comfortable because they are light in weight, numerous parameters have to be combined. Let us examine closely those that reduce the thickness of lenses and, then, those that reduce their weight.

A Thinness

The reduced thickness of a lens results from a combination of three factors: the refractive index of the material, the aspherisation of the surfaces and working to minimum thickness when surfacing.

1. Effect of the material's refractive index

This is the main factor behind the reduction in thickness of the lens. For a given power, the higher the refractive index, the thinner the lens. More precisely, the higher the index, the greater the capacity of the material to deflect light rays, the flatter the curvatures required on the front and rear faces of the lens to produce a given optical power and, as a result, the thinner the lens.

Refractive index – definition

It characterises the speed of propagation of light through a transparent medium in relation to the speed of light in a vacuum. Thus it measures the capacity of a transparent medium to refract, that is to say deflect light at the surface between two media. It therefore gives an assessment of the capacity of the material to produce an optical effect.
The refractive index of a transparent medium is expressed in the relationship

$$n = c / v$$

between the speed of propagation of light in a vacuum (c) and the speed of propagation of light in this medium (v). This index is a number – dimensionless and always greater than 1 – which quantifies the refractive power of the medium: the higher the refractive index, the greater the deflection of a beam of light passing from air into the medium.
The refractive indices of the materials used in ophthalmic optics vary from 1.5 for the more traditional materials to 1.76 (in plastic) and 1.9 (in glass) for the latest materials (see table of materials).

2. Effect of the aspherisation of the surfaces

The aspherisation of surfaces is an indirect factor in reducing thickness: it enables the production of flatter and, as a result, thinner lenses. More precisely, aspherisation makes possible the use of flatter bases – or curvatures on the front face – without affecting the optical qualities of the lens.
For plus lenses, the sag of the front surface (i.e. its "height") is therefore less and the thickness at the centre of the lens can then be slightly reduced by bringing the rear surface closer; in addition, the overall flattening of the lens contributes to the impression of thinness. For minus lenses, naturally flat, the effect of aspherisation on the thickness is less but nonetheless significant.
This "optical" aspherisation must not be confused with "geometrical" aspherisation, a sort of peripheral flattening sometime added to the edge of high power lenses and which has more to do with geometry than optics.

3. Effect of surfacing on the thickness

An important factor in reducing the thickness of a lens is the ability for the manufacturer to surface it as thin as possible. Depending on the mechanical properties of the material – rigidity and solidity – the possibilities vary considerably: thus, the minimum thickness that can be produced at the centre of a minus lens can vary from 1.0 mm to more than 2.0 mm, depending on the material and the power; similarly, the minimum thickness at the edge of a plus lens at its thinnest point, can vary from less than 0.5 mm to more than 1.0 mm.

For a lens with a power of -6,00D and a diameter of 65 mm, using a 1.6 index material, allows, for an identical thickness at the centre, a reduction of the thickness at the edge by 1.5 mm compared to the same lens produced in 1.5 index material (7.5 mm as against 9.0). The aspherisation produces an additional reduction of 0.4 mm and makes the lens slightly flatter. Thin surfacing then enables an additional gain of 0.8 mm (1.2 mm as against 2.0). In total the reduction in thickness is 2.7 mm (6.3 mm as against 9.0), i.e. 30%.

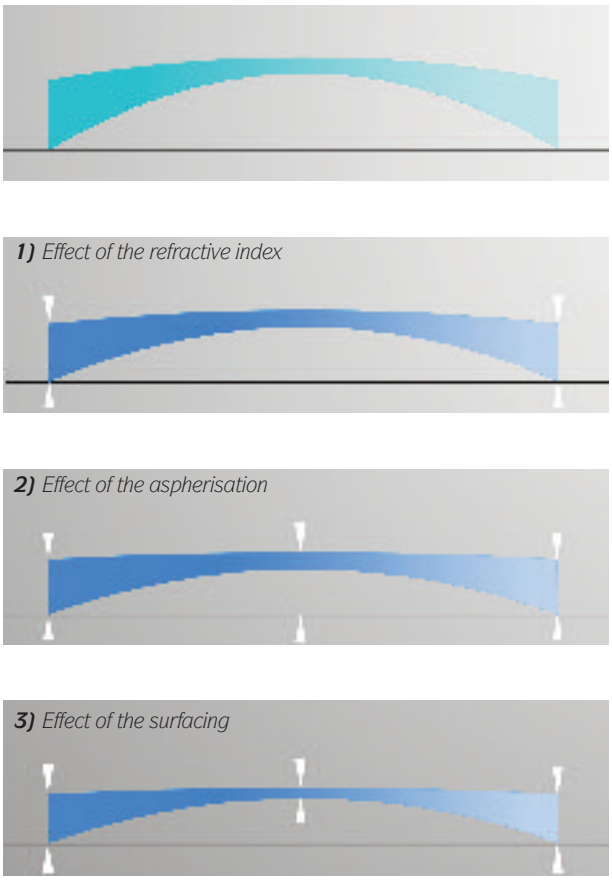

Figure 2a: *Effects of the refractive index (1), of aspherisation (2) and thickness of the surfacing (3) for a lens with a power of -6.00D.*

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Under the same conditions, the reduction in the thickness at the centre of a lens with a power of +4.00D and a diameter of 65 mm obtained using a material with a refractive index of 1.6 is 0.6 mm; the additional gain provided by aspherisation is 0.2 mm and is accompanied by a net flattening of the lens; finally a gain of 0.5 mm is provided by thin surfacing. In total the reduction in thickness is 1.3 mm (4.1 mm compared to 5.4) or close to 25%.

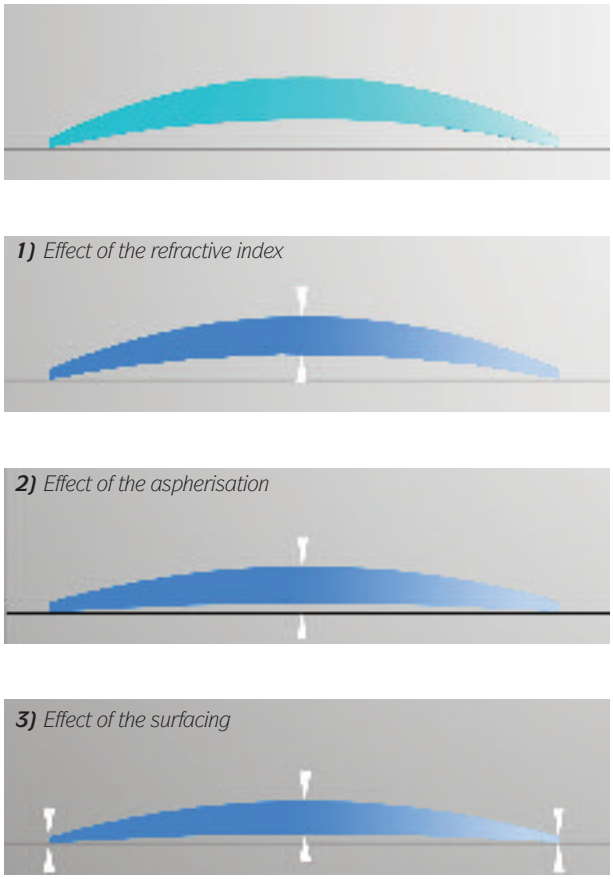

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Figure 2b: *Effects of the refractive index (1), of aspherisation (2) and thickness of the surfacing (3) for a lens with a power of +4.00D.*

It is self-evident that by using a higher refractive index and aspherised surfaces, the reduction in thickness would be even more significant: with an index of 1.74, it would be, compared to an index of 1.5, 3.8 mm (5.2 as against 9.0) for the -6.00D lens and 2.7 mm (2.7 as against 5.4) for the +4.00D lens, i.e. a reduction of nearly 50%. In addition, a judicious choice of frame and precalibration of the lenses enables the thickness to be reduced still further.

In addition, the thickness of the lens also varies with the type of fitting to be used:

- for a circular fitting a minimum edge thickness of 0.8 mm is recommended for the bevelling of the lens;
- for a "Nylor" type mounting, the thickness required at the edge for the grooving of the lens is a minimum of 1.6 mm for a nylon wire fitting and 2.2 mm for metal wire;
- for a drilled fitting, the minimum thickness required at the drilling point is 1.5 mm for a polycarbonate lens, 1.8 mm for a high index and 2.3 mm for traditional CR39.

Note that these are minimum values that have to be observed and that it is generally advisable to add 0.2 to 0.3 mm.

Finally, since the thickness which matters is that of the edged lenses, the choice of frame by the optician and the optimisation of the thickness of the lenses play important roles. In order to obtain the thinnest lenses, the frame must be chosen with a view to minimising the diameter of the lens necessary for centering, i.e. it must be small, symmetrical and of a size close to the wearer's pupillary distance. Also, the lenses must be "pre-calibrated", i.e. have a calculated, minimised thickness, related exactly to the shape of the lens and its centring; this technique is particularly effective in reducing the thickness of plus lenses.

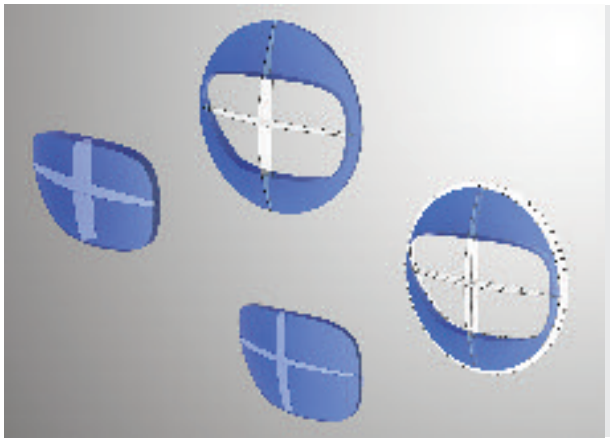

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Figure 3: *Effect of pre-calibration on lenses.*

In summary, the reduced thickness of a lens is the result of the combination of several factors: the choice of a high-index material makes it possible to gain several millimetres, the use of aspherisation gives an extra reduction of several tenths of a millimetre and a minimum thickness produced by surfacing can still save several tenths. In total, comparing a spherical lens with an index of 1.5 to an aspherical lens with an index of 1.74, the thickness is on average reduced by almost 50%.
In addition, the choice of frame and the precalibration of the lenses is added to the previous effects and provides a further saving of the order of a millimetre. Thus the combined skills of the manufacturer and the optician make it possible to offer wearers the thinnest and therefore most aesthetic edged lenses.

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B Weight

The weight of a lens comes from the combination of its thickness and the lightness of the material used in its manufacture. More precisely, it is the combination of the volume of the lens and the density of the material which determines its weight.
The volume of the lens depends on the geometry of its surfaces, its shape and the dimensions of the template of the lens and the thickness necessary to ensure its robustness and make fitting possible (minimum thickness at the centre of minus lenses or at the edge of plus lenses).
The density itself comes from the nature of the material and its chemical composition. It varies considerably from one material to another: from 1.1 for the lightest plastic materials to almost 4.0 for the heaviest glass materials (see materials table). Generally speaking, the higher the refractive index of a material, the higher its density, since the increase in the refractive index is obtained by introducing heavy atoms into the chemical structure of the material.
The lightest lenses are therefore obtained through the best combination of reducing the thickness of the lens and the lightness of the material, i.e. by the simultaneous optimisation of the thickness (index + aspherisation + surfacing) and the density.

Density and specific gravity of a material – definitions:

Density is a value which quantifies the mass of a material per unit of volume. It is defined as the relationship between a mass and its volume and is usually expressed in grammes per cubic centimetre.
Specific gravity, also called specific mass, is the relationship between the density of a substance and that of another substance chosen as a reference (water in the case of solids and liquids); it is expressed as a dimensionless number. Since the density of water, chosen as the reference substance, is 1 g/cm^3, its specific gravity has the same value as its density.
The density (or specific gravity) gives a precise measurement of the weight of the material but only gives an approximation of the weight of the lens. It cannot be used as the only reference when comparing lenses. Only the weight of the edged lens and the combination of the exact volume and the density of the material, can make an exact and relevant comparison possible.

a) Plastic materials:

Categories	Brand names	Refractive index (n_e / n_d)	Abbe number (v_e / v_d)	Density	UV cut-off
Normal index	Orma® (Essilor)	1,502 / 1,500	58 / 58	1,32	355 nm
Normal index	Trivex® (PPG)	1,533 / 1,530	43 / 44	1,11	395 nm
Mid-index	Airwear® (Essilor)	1,591 / 1,586	31 / 31	1,20	385 nm
Mid-index	Ormix®/ Thin & Lite 1,60 (Essilor)	1,596 / 1,592	41 / 42	1,31	400 nm
High index	Stylis®/ Thin & Lite 1,67 (Essilor)	1,665 / 1,660	32 / 32	1,36	400 nm
Very high index	Lineis®/ Thin & Lite 1,74 (Essilor)	1,734 / 1,728	33 / 33	1,47	400 nm

b) Glass materials:

Categories	Brand names	Refractive index (n_e / n_d)	Abbe number (v_e / v_d)	Density	UV cut-off
Normal index	Stigmal 15 (Essilor)	1.525 / 1,523	59 / 59	2,61	330 nm
Mid-index	Stigmal 16 (Essilor)	1,604 / 1,600	41 / 42	2,63	335 nm
High index	Fit 40 (Essilor)	1,705 / 1,701	41 / 42	3,21	335 nm
Very high index	Stigmal 18 (Essilor)	1,807 / 1,802	34 / 35	3,65	330 nm
Very high index	19 (BBGR)	1,892 / 1,885	30 / 30	3,99	340 nm

Figure 4 : *Table of the principal materials.*

In summary, these are materials which combine both a high refractive index, a low density and the ability to take thin surfacing which make it possible to produce the thinnest, lightest lenses. In this respect, these are high-index plastic materials and, more particularly polycarbonate, which are the most suitable materials available today.

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Plastic and glass materials

In order to respond even better to the demand for thin, lightweight lenses, research into the chemistry of materials continues. This has enabled the use of new materials to be developed and, in the space of a few decades, has profoundly transformed the ophthalmic optics industry. Above all, it has brought wearers a reduction of almost half in the thickness of corrective lenses. The properties of these materials are considered below.

A Plastic materials

Used in ophthalmic optics since the 1960s, plastics have progressively replaced glass lenses and now make up 90% of the materials used. In addition to their natural qualities of light weight and impact-resistance, the curbs on their development have been gradually lifted: improvement in their resistance to scratching thanks to hardening varnishes, reduced thickness because of materials with a higher index, better reliability of anti-reflective treatments through new vacuum depositing technologies, the availability of photochromic versions by surface addition, etc. Today, they have become the benchmark materials in ophthalmic optics.

Plastic materials are traditionally divided into two groups:

- Thermosetting materials:

Thermosetting materials are products whose chemical transformation, under the effects of heat, produces hard, rigid, three-dimensional macro-molecular compounds. They are made of relatively short and highly reactive molecular chains which are chemically linked. Under the effects of heat, a chemical reaction occurs called "reticulation" or "firing", creating rigid links between all the molecules present to form a three-dimensional network; the structure is then said to be "reticulated" and gives the material particular chemical stability and mechanical strength properties.
The basic molecule or "monomer" occurs in liquid form and has the property of being able to be "polymerised" under the action of heat or ultraviolet light and/or a catalyst. This polymerisation reaction consists of chaining together the monomer's identical molecules. It creates a new molecule, the polymer, of a different nature, size and properties: the material changes from a liquid monomer to a solid polymer. This transformation is chemical and therefore irreversible: once the monomer is cast and polymerised, the material is hard, infusible, insoluble, resistant to impacts and chemicals and dimensionally stable.
Most of the materials used in ophthalmic optics belong to this group of thermosetting materials, and CR39® is the most popular.

- Thermoplastic materials:

Thermoplastic materials are formed by the agglomeration of long molecular chains, linear or slightly branched, that are intertwined but not joined. It is only their tangling and inter-molecular forces that give these materials the appearance of solidity; the chains are not chemically linked in any way. This free molecular structure gives them excellent impact resistance qualities, since the chains can move in relation to each other and so absorb the energy of impacts.

Thermoplastic materials have the property of softening under the action of heat and being able to be hot-formed or moulded by injection. The transformation being mechanical and not chemical, is reversible and makes materials recyclable.
While thermoplastic materials are widely used in industry, only polycarbonate has been used successfully in the manufacture of ophthalmic lenses.

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Figure 5: *"Thermosetting" and "Thermoplastic" materials.*

Certain more recent materials combine the characteristics of thermosetting and thermoplastic resins.

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1. Normal-index plastic materials (1,48 ≤ n < 1.54)

CR39®

After several unsuccessful attempts to develop lenses in thermoplastic material (Igard® in PMMA or Plexiglas®, around 1940) and in thermosetting material (Orma® 500 lenses, around 1950), it was CR39®(*) that proved to be the plastic material of choice in ophthalmic optics.

Diethylene glycol bis (allyl carbonate), known by the name of CR39®, is the basic material used in the manufacture of the majority of plastic lenses. Discovered during the Second World War by chemists at the Columbia Corporation (a division of the American manufacturing company PPG or Pittsburgh Plate Glass), its name came from that fact that it was Columbia Resin no. 39 in a series of monomers being studied by chemists for the US Air Force. It was used in the manufacture of corrective lenses between 1955 and 1960 (by LOR or Lentilles Ophtalmiques Rationnelles, one of the original companies behind Essilor) and enabled the introduction of the Orma® 1000 lens (from Organic Material, i.e. plastic, and today simply known as Orma®), the first lenses that were both light and impact-resistant.

CR39® is a thermosetting resin, i.e. it comes in the form of a liquid monomer that can be poured into moulds and hardened (i.e. polymerised) under the effect of heat and a catalyst. The refining and control of the manufacturing procedure required many years of research.

For ophthalmic optics, CR39® has several characteristics that make it successful at the expense of glass materials: a refractive index of 1.5 (close to that of the traditional glass lens), a density of 1.32 (virtually half that of glass), an Abbe number of 58-59 (therefore, low chromatism), strong resistance to impact, excellent transparency and multiple possibilities for colouring and treatments. Although it can be used uncoated, CR39® is sensitive to scratching and a surface-hardening treatment is recommended. Its anti-reflective treatment was the subject of very advanced technical developments (see part II of this file). Its use by opticians for grinding and mounting is very easy.

Trivex®

Introduced at the turn of the millenium, Trivex®(**), available from PPG Industries Inc. – and marketed under various lens names – is a material said to be "quasi-thermosetting", combining the qualities of thermosetting and thermoplastic resins. Originally developed for visors on army helmets, it comes as a thermosetting resin in the form of a polymerisable liquid resin. On the other hand, its special chemical structure allows control of the level of inter-connection of the molecules during polymerisation, giving it qualities close to those of a thermoplastic resin.

Trivex® combines three qualities demanded by wearers of ophthalmic lenses: optical quality, light weight and safety (hence the name Trivex®). The optical clarity comes from the purity of the monomer, the transparency and low chromatism of the material (Abbe number **V** = 43 to 45) and the ability of the material to be treated against scratches and reflections. The light weight comes from the material's very low density (d = 1.11), combined with a higher refractive index than CR39® (n_e = 1.533, n_d = 1.530) and an ability to be surfaced to a minimum thickness of 1.0 mm at the centre of minus lenses. Finally, safety is provided by the material's high resistance to impact and good natural protection against ultraviolet radiation (UV cut-off at 395 nm). Trivex® is a material that is vulnerable to scratching, so requiring systematic anti-scratch treatment on both faces. It can be coloured but, for this, requires the use of appropriate techniques. Its grinding and grooving is special and requires the use of specific functions on grinding machines. Its drilling and fitting are relatively simple.

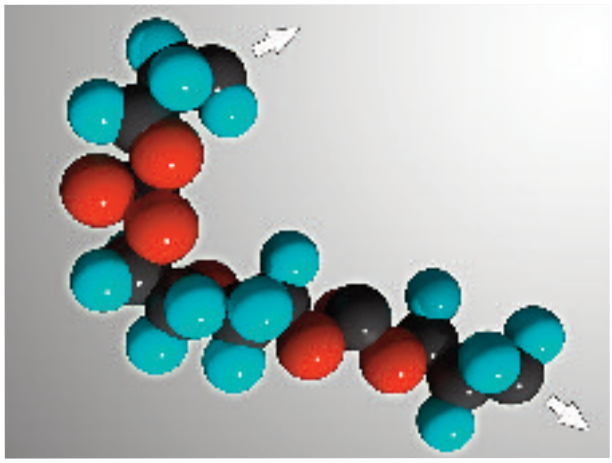

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Figure 6: *CR39® molecule.*

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Figure 7: *Chemical structure of Trivex® (Source PPG).*

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(**) Trivex is a registered trademark of PPG industries

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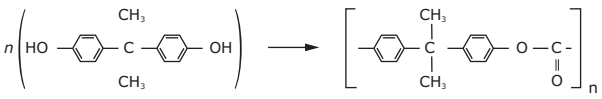
2. Mid-index plastic materials (1.54 ≤ n < 1.64)

Nowadays, mid-index plastics are enjoying great success. Compared with traditional CR39®, they make it possible to manufacture thinner, lighter lenses. Usually, they have a slightly lower density than CR39® (between 1.20 and 1.32), exhibit higher chromatism (Abbe number between 31 and 42) and a greater sensitivity to heat and they provide better protection against ultraviolet radiation. These materials are very vulnerabe to scratching and require systematic treatment and hardening of their surfaces. They can be coloured or made photochromic, most often by the deposition of a special layer. Anti-reflective treatment is especially recommended for them.
Most of these materials are "thermosetting"; only polycarbonate is a "thermoplastic". Let us first look at the latter and then at the family of high-index thermosetting materials.

Thermoplastic resins: polycarbonate

Used in the 1950s in the manufacture of the first plastic lenses, thermoplastic materials – like PMMA and Plexiglas® – proved to be insufficiently abrasion-resistant and were quickly replaced by CR39®. They saw renewed popularity between 1995 and 2000 with the development of polycarbonate, and Airwear® in particular.
Polycarbonate is a relatively old material – having first appeared around 1955 – but it was not really used in ophthalmic optics until the 1990s. Because of the numerous improvements which it underwent – in particular for use in the compact disc industry – it offers an optical quality quite comparable with that of other plastic materials. From a chemical point of view, polycarbonate belongs to the family of poly-(aromatic carbonates); it is an amorphously structured linear polymer, whose carbon skeleton is made up of a succession of carbonate (-O=C-O-) and phenol ($-C_6H_5OH$) units. It is most often manufactured by means of the following chemical reaction, called "polycondensation":



Polycarbonate has advantages that make it particularly interesting for ophthalmic optics: excellent impact-resistance (the highest of all ophthalmic materials), a high refractive index ($n_e = 1.591$ / $n_d = 1.586$), extremely light weight (density = 1.20), the ability to be surfaced to minimum thickness (as little as 1.0 mm at the centre of minus lenses), efficient protection against ultraviolet radiation (when using an additive giving a UV cut-off at 385 nm) and high resistance to heat (softening point – or vitreous transition Tg – higher than 140°C). As with all mid-index plastics, polycarbonate is a material that is vulnerable to scratching, making coating with an anti-scratch varnish absolutely essential. Its Abbe number is relatively low ($\mathbf{V}_e$ = 31, $\mathbf{V}_d$ = 31) but this has no effect on the majority of prescriptions. Today, its colouring and treatment possibilities are close to those of other plastic materials. Since polycarbonate is by nature difficult to surface tint, colouring is essentially obtained either by impregnating colour into a varnish which is deposited on the rear surface of the lens, or by UV attack on the surface, allowing the distribution of colorants into the material. Anti-reflective treatment is applied using a similar technique to that used on other plastic materials.
The cutting/fitting of polycarbonate lenses is special: it requires dry grinding, the use of suitable cycles and the polishing of the edge of the lenses.

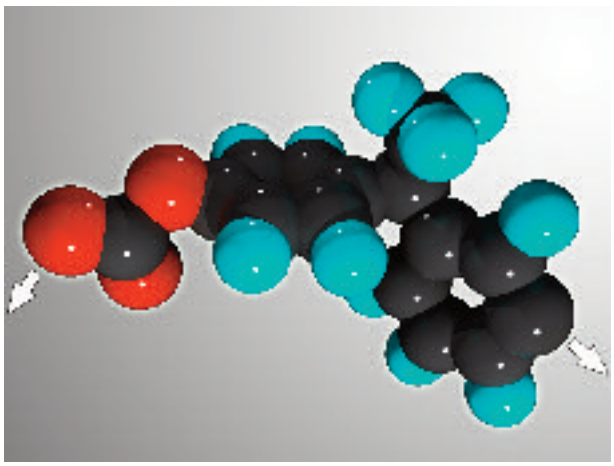

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Figure 8: *Thermoplastic resin: polycarbonate molecule.*

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Thermosetting resins

Most high-index plastics available today are thermosetting resins. When perfecting them, chemists come up against an unavoidable law of physics which links the refractive index, chromatic dispersion and density of the material: generally speaking, the higher the index, the stronger the chromatic dispersion and the heavier the material. When perfecting a new material, chemists always look for the best compromise between the three characteristics, in combination with other essential properties of the material such as sensitivity to heat, vulnerability to yellowing, treatment possibilities and suitability for grinding, grooving and drilling.

An increase in the refractive index of a plastic material can be obtained as follows:

- either by modifying the structure of the initial material, for example, by introducing aromatic structures
- or by introducing heavy atoms such as, sulphur into an initial molecule.

We should note that the introduction of metal and halogen atoms, which was used originally, was abandoned, since it was giving rise to excessive yellowing of the materials.

The first high-index plastic materials appeared between 1980 and 1990; they belonged to the allylic family. The increase in the index was obtained through the addition of cyclical functions – benzene-type aromatic groups – to the starting CR39® molecule. This process gave birth to a family of mid-index lenses, n = 1.54 to 1.57, with an Abbe value between 36 and 43 and a density in the order of 1.20. The material Ormex® ($n_e = 1.561$ / $n_d = 1.558$, $\mathbf{V}_e = 37$ / $\mathbf{V}_d = 37$, d = 1.23) belonged to this category.

Since this technique only allowed a limited increase in the refractive index, chemists then became interested in the thiourethanes family and the chemistry of sulphur. From the 1990s onwards, the association of the functions of thiols and isocyanates enabled the creation of materials with an index of between 1.58 and 1.61, with an Abbe value varying between 30 and 40 and a density between 1.30 and 1.40. Materials such as Ormil®, later replaced by Ormix® / Thin&Lite 1.60 are examples.

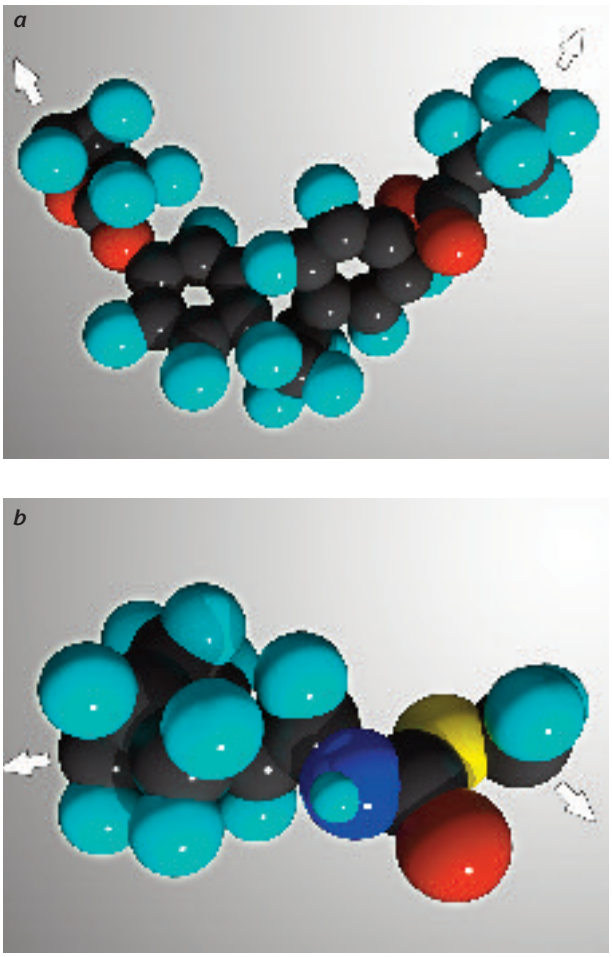

Figure 9: *Mid-index thermosetting resin: examples of the Ormex® (a) and Ormil® (b) molecules.*

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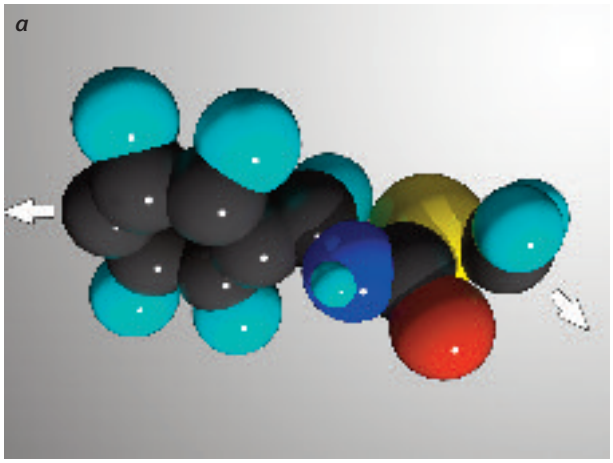
3. High- (1.64 ≤ n < 1.74) and very-high-index (n ≥ 1.74) plastic materials

To obtain a higher refractive index through the chemistry of thiourethanes, thiols richer in sulphur but still associated with isocyanate functions were used. It was therefore possible to raise the refractive index to n = 1.67 and the material Stylis® / Thin&Lite® 1.67 was produced.
We should note that, given their special chemical composition, materials resulting from the chemistry of thiourethanes (Ormix® / Thin&Lite® 1.60 and Stylis® / Thin&Lite® 1.67) proved particularly well suited to grooving and drilling.

Finally, to raise the refractive index still further, chemists began to explore the chemistry of episulphides, allowing the introduction of sulphur atoms in a greater concentration. So it was materials with a very high index n ≥ 1.74, such as Lineis® / Thin&Lite® 1.74, that made an appearance. However, it should be noted that, although these materials allowed extremely thin lenses to be manufactured, they also proved to be more sensitive to heat, easier to break and more difficult to tint.



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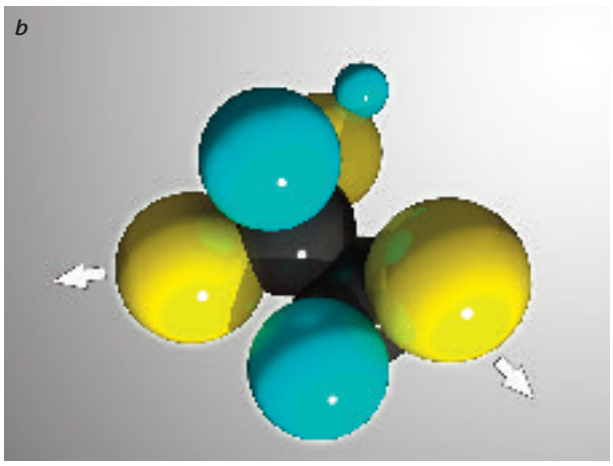

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Figure 10: *High- and very-high-index thermosetting resins:*
a) Stylis® / Thin&Lite® 1,67
b) Lineis® / Thin&Lite® 1,74.

To sum up, we note that it is essentially through the introduction of sulphur atoms into the different molecular families that an increase in the refractive index of plastic materials is obtained. So, as the materials chemical composition table below shows, the higher the proportion of sulphur, the higher is the material's refractive index.
We should note that it is the presence of sulphur in the composition of plastic materials with a high index that explains the particular smell released during lens grinding.

	Orma®	Ormix® / Thin&Lite® 1,6	Stylis® / Thin&Lite® 1,67	Lineis® / Thin&Lite® 1,74
Carbon %	65	54	48	36
Oxygen %	25	8	10	1
Nitrogen %	-	7	8	-
Sulphur %	-	24	29	58
Hydrogen %	10	7	5	5
Index	1,5	1,6	1,67	1,74
Abbe number	58	41	32	33
Density	1,32	1,31	1,36	1,47
Tg (Vitreous transition temperature)	80°C	115°C	85°C	80°C

Figure 11: *Chemical composition of plastic materials.*

The perfecting of a new material is a complex exercise since it must seek not only to optimise the basic characteristics – refractive index, Abbe number and density – but also to ensure that all their other physical and chemical properties are controlled, in particular the ease with which they can be surfaced (using traditional and digital surfacing technology), given photochromic, tinted, polarised, given anti-scratch and anti-reflective treatments and finally, edged, grooved, drilled and slotted for fitting. It goes without saying that with the increased knowledge and progress in chemistry, materials have seen constant changes and improvements. Thus research work in ophthalmic optics is, to a large extent, devoted to the chemistry of materials and ophthalmic lens manufacturers have become at least as much specialists in chemistry as they are in optics!

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B Glass materials

For several centuries, from the origins of optics to the middle of the 20th century, glasses were the only material used in lenses for ophthalmic optics. In just a few decades they were deposed and replaced by plastics.

The glass lens is a solid and amorphous material (i.e. of a non-periodic structure); it is hard and breakable at room temperature and takes on a viscous state at high temperature. It is obtained by the fusion at approximately 1500° of a mixture of oxides such as those of silicon (the main oxide used, as it makes up approximately 65% of the material), calcium, sodium, potassium, lead, barium, titanium, lanthanum, etc. The glass lens does not have a regular chemical structure and, as a result, has no clear melting point at which it suddenly changes from a solid to a liquid state. In addition, with a rise in temperature, glass becomes soft and changes gradually from a solid into a liquid via a state known as "vitreous", characterised by the absence of crystals. This exclusive special property enables it to be worked when hot and thus moulded. Two properties make it interesting for ophthalmic optics: it transmits visible light and its surface can be polished to make it transparent and non-diffusing.

1. Standard glass materials

Glass with an index of 1.5 is the traditional material, formerly used in ophthalmic optics. It is made up of 60-70% silicon oxide and the remainder of various components such as oxides of calcium, sodium or boron. Glass with an index of 1.6 is the standard glass material: its higher index is obtained by the addition to the mixture of a significant proportion of titanium oxide.
It is usual to separate glass into two categories depending on its chemical composition:

- "Sodiocalcic" materials containing significant proportions of sodium and calcium: these are the traditional materials used in optics. Their refractive index is a little higher (n_e = 1.525 / n_d = 1.523) and their chromatic dispersion low (Abbe number in the region of 60).
- "Borosilicate" materials with a high boron content: these are the materials used in the manufacture of photochromics and mid-index glass lenses (n_e = 1.604 / n_d = 1.600)

2. High-index glass materials

Glass specialists have always sought to increase the refractive index of materials, in order to reduce the thickness of lenses and to maintain chromatism at a low level. To do this, metal and rare earth atoms (lead, titanium, lanthanum, etc.) are introduced into the material's composition. So it was that in around 1975 titanium lenses with an index of 1.7 and an Abbe number of 41 appeared, then around 1990, lanthanum lenses with an index of 1.8 and an Abbe number of 34 and finally, around 1995, niobium lenses with an index of 1.9 and an Abbe number of 30. These materials enabled the production of thinner and thinner lenses but without a significant reduction in their weight.

Once again, the increase in the index was accompanied by an increase in the density of the material which cancelled out the expected weight saving from the reduced thickness of the lens. As a result, a glass lens, whatever its index, remains at least twice as heavy as a plastic one. As for thickness, the new very-high-index plastic materials enable the manufacture of lenses whose reduced thickness rivals that of traditional high-index glass lenses (n = 1.7). On the other hand, for high levels of correction, very-high-index glass (n = 1.8 or n = 1.9) undeniably retains a thickness advantage compared with plastic lenses.

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The principles of lens manufacturing

Ophthalmic lenses are manufactured in two ways (see figure 12):

- **"mass" production :** for the large volume production of the most commonly required finished lenses (spherical and aspherical single vision) and for the production of "semi-finished" lenses, thick lenses whose front face is finished and whose rear face will be surfaced as required;
- **"prescription" manufacture:**
  - either from a semi-finished lens: the operation consists of surfacing the rear face according to the patient's optical correction and subjecting the lens to various surface treatments (colouring, anti-scratch, anti-reflection, anti-smudge, etc.)
  - or by direct surfacing of the two lens faces or direct polymerisation, followed by various surface treatment operations.

Mass production is carried out on a large scale in manufacturing plants (approximately two thirds of lenses); "prescription" manufacturing is effected piece by piece in finishing laboratories (one third of lenses).
The number of possible combinations – of optical corrections, materials and treatments – is very high (usually estimated at more than five billion)! It makes the organisation of lens manufacturing very complicated. One of the great skills of the ophthalmic optics industry is the management of a highly complex production-logistics chain, which makes it possible to manufacture "custom" lenses on a large scale (approximately one billion lenses are produced worldwide every year).

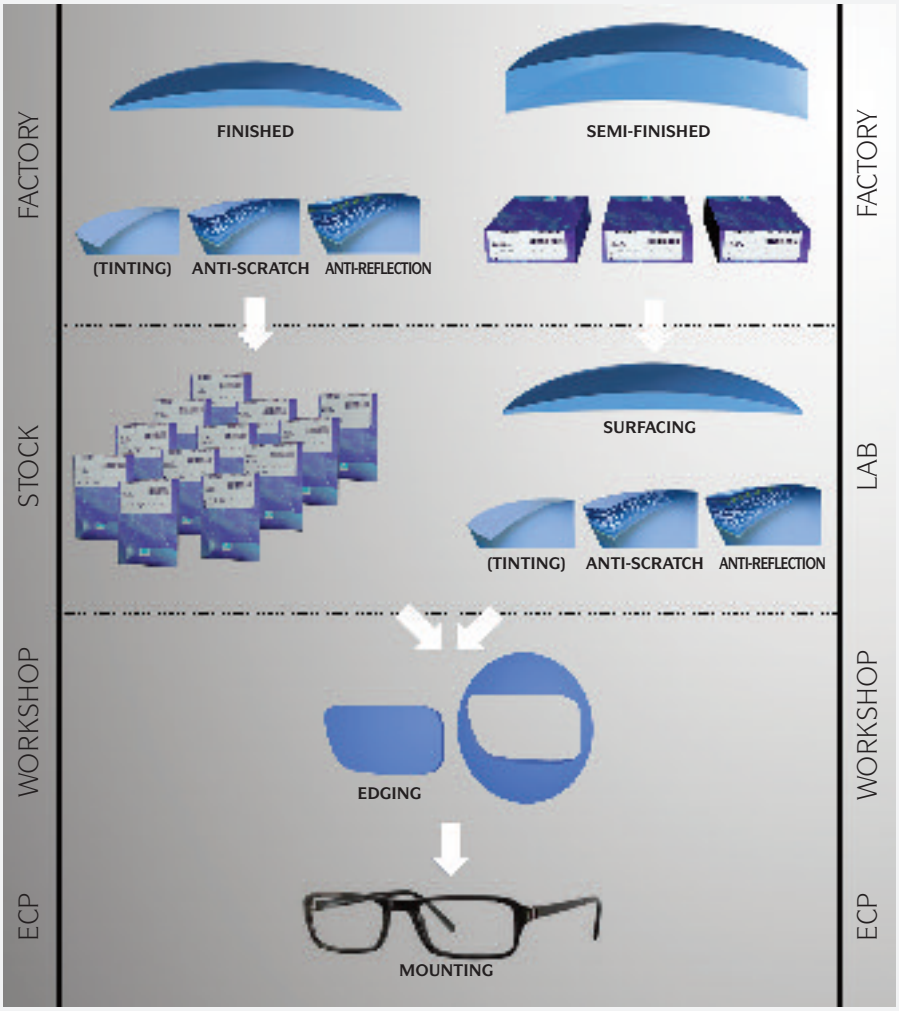

Figure 12: *General lens manufacturing principles.*

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Supplement

A) Plastic lens manufacturing principles

1. “Mass” production

Depending on whether the resin used is thermosetting or thermoplastic, the manufacturing method differs considerably. We will consider them in turn.

Thermosetting resins

Take, for example, the material CR39. The monomer is supplied by the chemical industry in liquid form and then goes through the following stages of manufacture:

- preparation of the monomer: filtration, degassing and addition of a catalyst and additives;
- assembly of the moulds: these comprise two glass or metal walls which are assembled, either by pressure on a circular gasket and clamping with a clip, or with adhesive tape;
- filling: the empty space between the two parts of the mould is filled with the liquid monomer;
- polymerisation: the filled moulds are placed in ovens and subjected to a temperature cycle over several hours – or, for certain materials, subjected to ultraviolet radiation for a few minutes – which causes a progressive hardening of the resin;
- demoulding: the gasket or tape and the walls of the mould are separated to release the lens.

This procedure is also used for the mass production of “finished” and “semi-finished” lenses; only the shape of the mould and the polymerisation time are different. The overall principle is the same for the majority of thermosetting plastic materials used in ophthalmic optics.

Thermoplastic resins

We will take polycarbonate as an example. The base material is already a polymer and comes in the form of granules, the purity of which has been adapted for use in the optical industry. These granules are softened and melted by heating for injection into the lens-shaped moulds. The technology consists in making the material fluid by heating it, so that it penetrates into the metal or glass moulds. An extrusion screw plasticises the material in the injection cylinder and simultaneously acts as a piston, pushing the hot material through several ducts into the mould cavity. After injection and a cooling time, the moulds are opened and the lenses released.

The various manufacturing operations are as follows:

- preparation of the material: de-dusting and drying of the granules by hot air and loading onto the press;
- setting up the press: positioning of the moulds, adjustment of the liquid pressure, mould temperature, injection and cooling time, heating of the material (to about 300 °C);
- injection: moulding under pressure of the molten material;
- cooling: solidification of the material by conduction through the moulds;
- demoulding: by opening the press and the mould support block.

This technology allows all lens geometries to be manufactured, depending on the shape of the moulds inserted in the injection press. These lenses are either “finished” and can undergo treatments as they are, or “semi-finished” and will be surfaced later on their rear face, before undergoing various surface treatments.

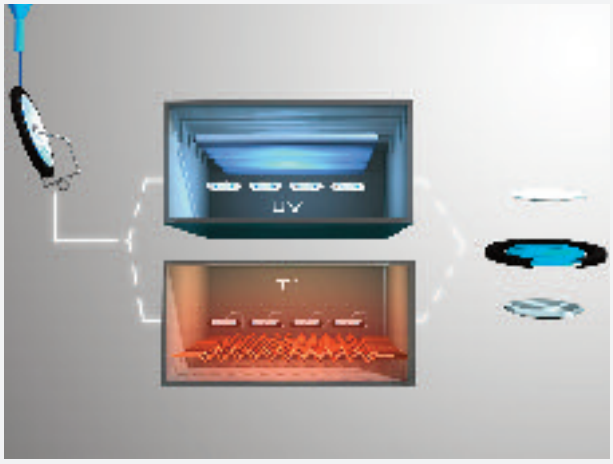

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Figure 13: *Mass production of plastic lenses in thermosetting resin.*

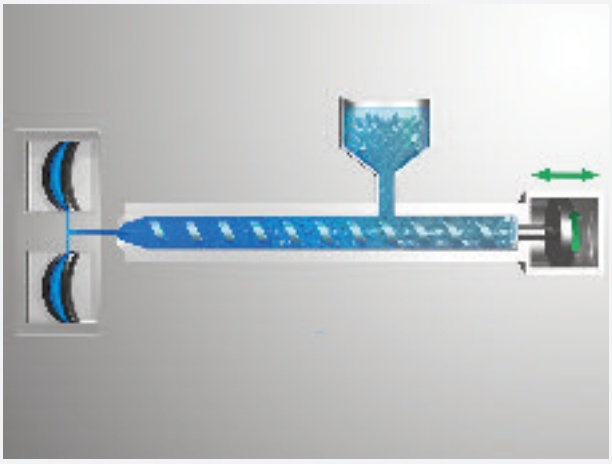
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Figure 14: *Mass production of plastic lenses in thermoplastic resin.*

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2. “Prescription” manufacture

Traditional surfacing

Carried out in prescription (i.e. lens finishing) laboratories, this consists of machining the rear face of a semi-finished lens (mass-produced previously), in order to give it the required power. It comprises the following steps:

- blocking of the semi-finished lens: protection of the face with a film and fitting of a fusible metal button (the pitch) which will be used for handling the lens during the following steps;

- trimming of the semi-finished lens to the finished diameter by milling;

- grinding: this consists of a spiral milling of the rear face of the lens; at the end of this operation the lens is almost in its final shape but the surface is still very rough;

- fining by generation: this consists of finely machining the surface by turning, using a knife tool (this operation was traditionally carried out by friction on a shaped tool covered with an abrasive pad). After smoothing, the lens has the exact thickness and the desired curvature radii; although it is smooth, its surface is still unpolished at this stage;

- polishing: by friction against a shaping tool, a duplicate of the rear face of the lens, covered with felt and sprayed with a polishing liquid containing a very fine abrasive. This operation gives the lens its final transparency.

Used for many years, traditional surfacing requires a large range of tools and only allows the generation of rear surfaces with simple geometry, either spherical or toroidal.

Figure 15 a: *Traditional surfacing - Grinding.*

Figure 15 b: *Traditional surfacing - Fining.*

Figure 15 c: *Traditional surfacing - Polishing.*

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Supplement

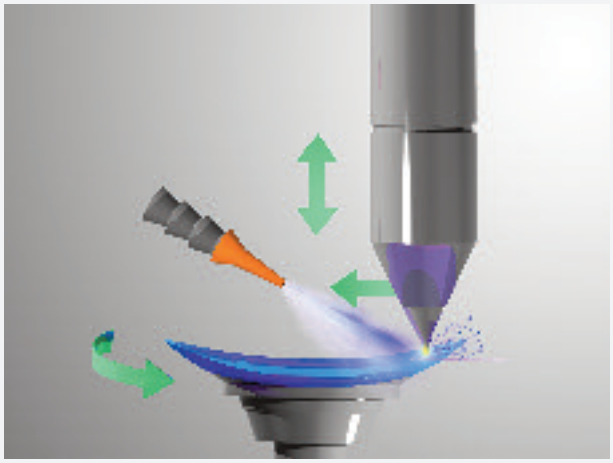

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Figure 16 a: *Digital surfacing - Machining (finishing).*

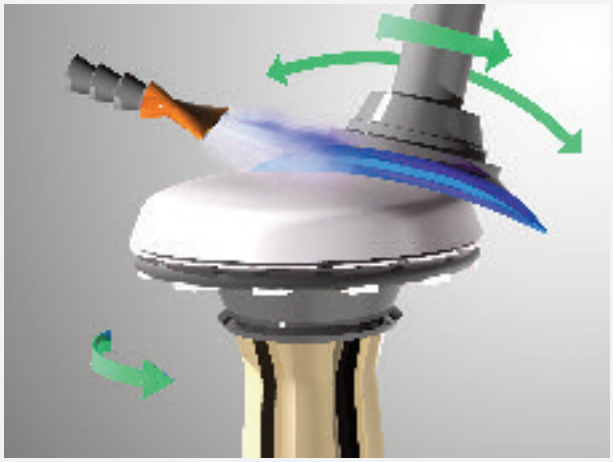

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Figure 16 b: *Digital surfacing - Polishing.*

Digital surfacing

A recent development, digital – or direct – surfacing is essentially used to produce complex rear surfaces but can also be used for any simple surface geometry. It consists of machining the rear surface of the lens using a "point by point" process and a numerically controlled machine managing the relative positions of the lens and the tool in three dimensions and with extreme precision.

In comparison with the traditional surfacing described previously:

- the blocking and trimming operations of the semi-finished lens are identical;
- machining is divided into two steps: grinding, achieved by milling in a similar way to traditional surfacing and finishing, effected by turning, using a special diamond tool (see figure 16a). These operations, performed by a single machine using two different tools, are very similar in principle to those carried out in traditional surfacing. On the other hand, the use for the finishing stage, of a clearly more accurate control of the position of the lens and of the tool, in conjunction with the cutting qualities of a diamond tool, enable both an excellent geometry on the rear face and an almost transparent surface to be guaranteed.
- polishing is done, as with traditional surfacing, by friction of the lens against a soft surface sprayed with a very fine abrasive liquid, but using both rigid and flexible tools specific to digital surfacing (see figure 16b); these tools allow the surface to be polished without deforming it, i.e. to make it perfectly transparent while maintaining the geometry imparted during the finishing operation.

Recently applied to prescription manufacturing, digital surfacing offers immense possibilities for producing complex optical surfaces. It allows the optical optimisation of lenses for each prescription and an ever greater customisation of lenses to the needs of the individual wearer: for example, by taking into account the characteristics of the frame, of the position of the centre of rotation of the eye, of eye/head behaviour, etc. For ophthalmic optics, this represents an immense field of investigation and opens broad horizons for new developments.

In this respect we should state that it is not the simple use of digital surfacing technology that makes the lens more efficient but the relevance and precision of the use that is made of this new technology. In other words, it is not sufficient that a lens is manufactured by digital surfacing for it to be of the best quality; on the contrary, a badly controlled optical design or process can result in inefficient optical designs, despite the use of this new technology.

Once the surfacing operation has been carried out, the lens can then undergo surface treatment operations. These will be dealt with later.

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B) Glass lens manufacturing principles

Whatever the type of material, the manufacture of a glass lens consists of the surfacing of the front and rear faces of a glass lens blank supplied by the glass industry. This blank is manufactured by moulding the still glowing glass on exit from the furnace in which its various constituents were melted. It has the appearance of a very thick lens with irregular surfaces and a perfectly homogeneous internal composition. Its front and rear faces are then surfaced to produce the final lens.

The surfacing of each of the two faces of the glass comprises three distinct phases:

- Phase 1: grinding consists of machining the lens with a diamond-tipped tool to give it its thickness and curvature radii. After grinding the lens already has its final shape but the surface is rough and only translucent.
- Phase 2: fining consists of refining the grain of the lens surface without modifying the curvature radii. For this the lens is held firmly and brought into contact with a forming tool, covered with an abrasive pad, the radius of which is exactly that of the lens to be produced. The lens and tool are sprayed with an abrasive and lubricating mixture. At the end of the operation which lasts several minutes, the lens is exactly at the thickness and curvature radii desired but the surface is not yet transparent.
- Phase 3: polishing is the finishing operation that gives the glass its final transparency. This is a similar operation to the previous one and uses a flexible polisher covered with felt and an abrasive solution with a very fine grit.

Industrially, the surfacing of the front surface of a glass lens (of all types: spherical, aspherical, bifocal or varifocal) is carried out in mass production while the surfacing of the rear surface is carried out batchwise or individually, depending on the frequency of use.

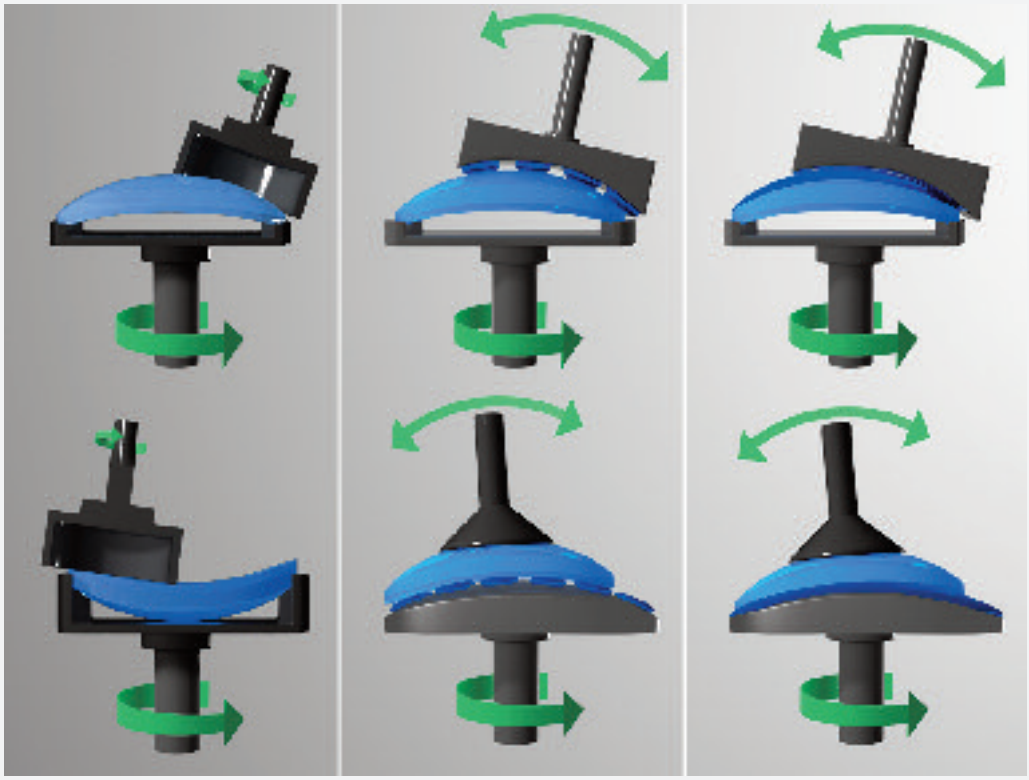

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Figure 17: *Manufacture of glass lenses: grinding, fining, polishing.*

Once the geometry of the lens had been produced, treatments are then applied; we will discuss them later.

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2. Transparency and durability

In order to ensure good optical correction, every ophthalmic lens must be perfectly transparent and remain so over time. There are two types of enemies opposing this: on the one hand, natural optical enemies, such as reflection, absorption, dispersion, diffraction and the diffusion of light and, on the other hand, the effects of wear and time: scratching, dirt, dust and the ageing of the material. To assist in the fight against these natural or encountered enemies, numerous technical solutions are sought and implemented in the form of the intrinsic characteristics of the material and special treatments. These will be dealt with in the second section of this file.

A Apparent colour of the material

The apparent colour of a lens is determined by the chromatic composition of the light which it transmits. If all the colours of the visible spectrum are fully transmitted, the glass is white. When this not the case, the lens takes on a particular colour, the complementary colour of the light not transmitted. For example, when blue radiation is absorbed by glass, the material takes on a yellow tint. This is exactly what happens when we try to make a material a better absorber of ultraviolet radiation. To remedy this, either a slight colour tint (brown in the UVX® treatment) is added, or brighteners are added to the material's chemical composition; these are bluish colorants intended to compensate for the yellow tint (the case with high-index plastics).

All plastics are light-sensitive and have the tendency to yellow over time. Depending on the chemical structure, the material interacts with ultraviolet and visible radiation and with oxygen and undergoes "photo-oxidation": the structure of the material is modified, chemical groupings absorbing more and more blue light so that the material yellows. Thus, the more a lens is exposed to sunlight and receives a significant dose of ultraviolet radiation, the more quickly it is likely to yellow. High-index materials are particularly sensitive to this phenomenon, and since they are products of sulphur chemistry, they have a marked affinity for oxygen and a greater tendency to oxidise. Brighteners added to the composition of the materials also play a role in delaying this natural ageing phenomenon.

It should be noted that anti-scratch treatment, deposited onto the surface of a plastic lens, has no particular influence on the apparent colour of the material. Very thin, it does not yellow, but nor does it protect the material from a change in colour. On the other hand, anti-reflective treatment is a protective factor against yellowing, not by eliminating ultraviolet radiation but by acting as a diffusion barrier for oxygen in the material. An anti-reflective treated lens therefore has a lower tendency to yellow than an untreated one.

To correctly assess the apparent colour...

In order to assess the apparent colour of a lens, it is usual to observe it by transmission in front of a sheet of white paper. This demonstration can be misleading. Papers often contain fluorescent brighteners – i.e. absorbing ultraviolet radiation and re-emitting it in the visible spectrum – intended to emphasise blues and give the paper a perfectly white appearance. Placing the lens in contact with the sheet eliminates the whitening stimulation provided by the ultraviolet light and the lens, or more precisely the paper, is rendered inescapably yellowish. This serves only to demonstrate the UV-absorptive qualities of the material and there is a risk of misinterpreting filtering qualities as lack of transparency. To confirm this, it is sufficient to move the lens away from the paper and observe that the latter returns to full whiteness.
In practice, the best method for judging the apparent colour of a lens is to observe, by transmission, a sheet of white paper that contains no brighteners. The observation is made through the central part of the lens at a distance of 10 to 20 cm and under white light. Also, remember to replace the sheet of paper regularly, to ensure that it does not itself yellow...

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B Chromatism of the material

1. Chromatism in ophthalmic lenses

The variation in the refractive index with the wavelength of the light is responsible for the phenomenon of chromatic dispersion of white light during refraction. As the refractive index is higher for shorter wavelengths, there is a change in the degree of refraction of the visible light from red towards blue.
Chromatic dispersion is an important characteristic for ophthalmic optics but of less consequence than for instrumental optics: the human eye is itself strongly affected by chromatism. Chromatism occurs in all lenses; it is always considered as negligible at the centre because the longitudinal chromatic aberration of the lens is low compared with that of the eye. On the other hand, chromatism can prove to be perceptible when the eye looks through the outer areas of the lens, because the Transverse Chromatic Aberration (TCA) of the lens creates multiple offset coloured images there; these can be perceived by the wearer in the form of coloured fringes surrounding the image of a high contrast object (see figure 18).

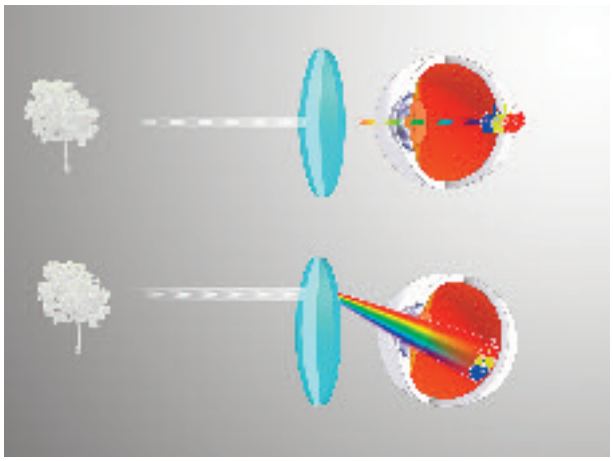

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Figure 18: *Longitudinal and transverse chromatic aberration.*

To quantify the transverse chromatism at any point on the lens, the equation TCA = P / **V** is used, of the deflection P of the rays at this point (expressed in prism dioptres) and the Abbe number, **V**, of the material used. The deflection P of a single vision lens being, according to the Prentice approximation, equal to h x F, where h is the distance separating the optical centre from the point on the lens and F is the power of the lens, it is therefore the case that TCA = h x F / **V**. Thus, it can be seen that transverse chromatism depends on three factors: the eccentricity of the gaze of the wearer, the power of the lens and the Abbe number of the material.

Abbe value (or Constringence) – definition:

To characterise the dispersive power of a material, a value called the Abbe number or the constringence is used (defined by Ernst Abbe, a German physicist and industrialist, 1840-1905) and symbolised by the Greek letter **V**. It is a number inversely proportional to the chromatic dispersion of the material and its definition varies slightly from country to country, depending on the wavelengths on which the definitions are based.

in Europe and Japan: V_e

$$V_e = \frac{n_e - 1}{n_{F'} - n_{C'}}$$

where
n_e : is the index for λ_e = 546.07 nm (mercury green line)
$n_{F'}$: is the index for $\lambda_{F'}$ = 479.99 nm (cadmium blue line)
$n_{C'}$: is the index for $\lambda_{C'}$ = 643.85 nm (cadmium red line)

in the English-speaking countries: V_d

$$V_d = \frac{n_d - 1}{n_F - n_C}$$

where
n_d : is the index for λ_d = 587.56 nm (helium yellow line)
n_F : is the index for λ_F = 486.13 nm (hydrogen blue line)
n_C : is the index for λ_C = 656.27 nm (hydrogen red line)

In practice, Abbe values V_e and V_d do not differ greatly, only the first decimal being affected. The Abbe number varies in ophthalmic optics between 60 for the least dispersive materials and 30 for the most dispersive. Generally speaking, the higher the refractive index of a material, the stronger its chromatic dispersion and therefore the lower its Abbe number (see materials table).

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2. Effects of chromatism on vision

Among the effects of chromatism on vision, it is important to distinguish between the two types: on one hand, the perception by the wearer and, on the other hand, its effect on visual acuity.

- The perception of chromatism is very subjective and variable from one subject to another: It is produced on average for a level of chromatism of 2.5 minutes of arc, i.e. that produced by a prismatic effect in CR39® (**V** = 58-59) of approximately 4 prism dioptres (**Δ**) (*).

- The effect of chromatism on visual acuity - for example the loss of readability of one line on a scale of acuity by not 0.1 Log MAR – necessitates a chromatism three times greater, i.e. approximately 7.5 minutes of arc or even the chromatism produced by a prismatic effect in CR39® of approximately 12.5 **Δ**(*).

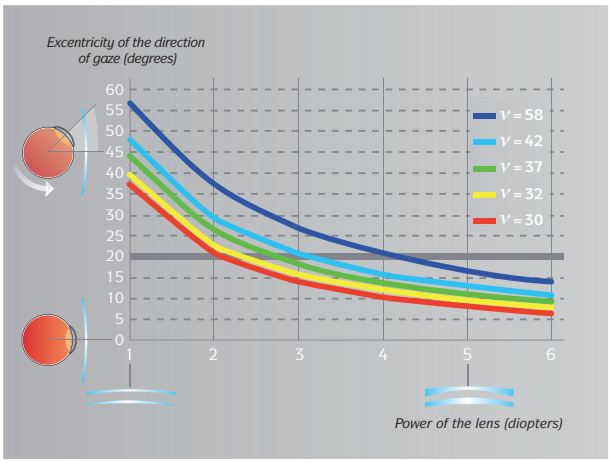
In addition, since the chromatism is only perceptible from an off-centre viewing position, it is important to consider the portion of the lens that the eye is effectively using for foveal vision. In this regard, the coordination of eye movements and of the wearer's head plays an essential role as it defines the direction of gaze in the lens at any particular moment. Any movement of the head generally causes the eye to re-centre and reduces the area of lens that the eye actually sees through. Measurements* have shown that 80% of ocular fixations occur at an angle of ± 15° to 20° and that 100% are within an angle of ± 30°. Therefore, in practice, it is only in this central zone of the lens – in a radius approximately 15 mm around the optical centre – that chromatism can have an influence on vision.

According to Prentice's Rule, it is possible to translate the values of thresholds shown below, into eccentricities of sight as a function of the power of the lens and for different Abbe values:

- In figure 19a) relative to the perception of colour fringing, we read, for example, that for a lens of 4.00 D power made from classic material with an Abbe number of 58, chromatism starts to be observed from a 20° rotation of the eye. We see, on one hand, that chromatism is not perceptible in the central part of the lens, and on the other hand, that with a material of low Abbe number, a lens with a power of over 2.50 D is necessary before the wearer perceives colour fringing by turning the eye 20°. Note that at this level of chromatism, visual acuity is not significantly affected.

- In figure 19b) relative to the effect on visual acuity, we see that with eye rotation of an angle of ± 20°, the power of the lens has to exceed 7.00 D with a material of low Abbe number (the most critical case) for the visual acuity to be affected. Consequently, it appears that in the case of foveal vision, the effects of chromatism manifest themselves most often outside the areas through which the eye sees and that therefore it has no significant repercussion on visual acuity most of the time.

We see, therefore, that chromatism has a limited influence on visual performance and has no consequence for the majority of wearers. It has no real effect except at the periphery of high-powered lenses made from very dispersive materials. Due to natural optical deviations, this effect may be more noticeable in cases of hypermetropia than with myopia, because the line of sight can vary over a wider range. It is also more noticeable in presbyopic wearers of progressive lenses when they lower their eyes for closer viewing.



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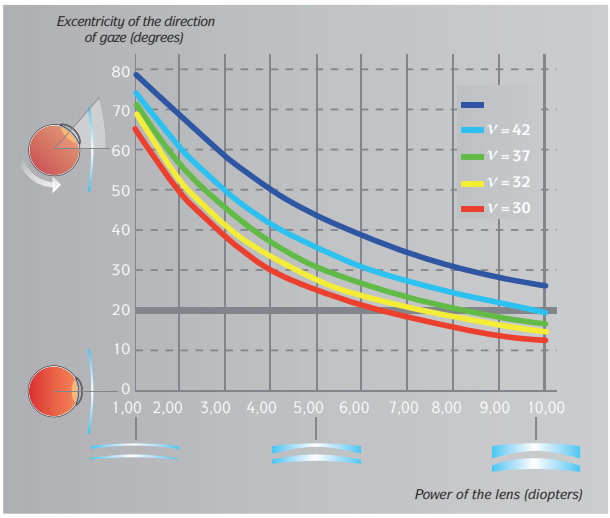

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Figure 19: *The effect of chromatism on vision:*
a) Threshold of perception of colour fringing
b) Threshold effect on visual acuity.

To remedy this problem of chromatism, chemists are trying to develop materials with low chromatism and therefore, with higher Abbe values. Unfortunately, their leeway is relatively limited and any increase in a material's refractive index generally leads to an increase in its chromatism. In practice, the effect can only be partially attenuated and the wearer must inevitably get used to a certain level of chromatism in his lenses.
Finally, it should be noted that chromatism exists in all lenses and is part of various optical imperfections that exist, like the aberrations of faults in power or astigmatism of oblique light rays or intrusive reflections. Therefore, care has to be taken to avoid any accumulation of optical defects by ensuring perfect aspherisation of the lens surfaces and by systematic use of anti-reflective coating.

(*) According to an Essilor Research and Development study.

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C Anti-scratch treatments

Among the daily hazards of ophthalmic lenses, scratches are surely the most formidable. They can be separated into two types:

- "fine" scratches (sleeks) resulting from abrasion by small particles rubbing on the two surfaces of the lens. They are caused, for example, by wiping. They tend to increase the diffusion of light through the lens surfaces and cause the perception of diffused blurring.
- "large" scratches caused by rubbing large particles or by damage caused by contact with various objects. They are really a breakdown of the surface and cause streaking by diffracting light. To the wearer, they look like a marked, localised blurring at the site of the scratch and are both visible and annoying.

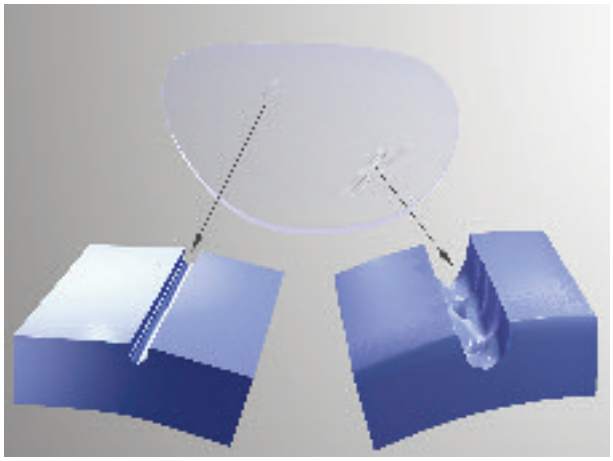

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Figure 20: *Different types of scratches: "Fine" and "Large" scratches.*

To prevent the appearance of scratches and to maintain the lens's original quality, the aim is to increase the abrasion-resistance of polymer lenses by using a specific coating to harden their surfaces. This coating consists of a very thin layer of a substance that is harder and more resistant to damage than the substrate itself. Although the primary purpose of this coating is to improve resistance to abrasion, it also has a role in assisting later application of high-quality anti-reflective coating.

Below are the details of the principle of how this anti-abrasion coating works.

Diffusion and diffraction of light – definitions:

Diffusion of light:

Diffusion is a phenomenon in which light is scattered in all directions with the same intensity. It occurs at the surface of any body and within transparent materials. It allows the eye to see objects and define their colour.
In an ophthalmic lens, surface diffusion theoretically does not exist, because the surface of the lens, and especially its coating, is designed to eliminate it. On the other hand, it appears as soon as extreme external pollution or grease-staining spreads on the surfaces or as soon as the surface becomes finely scratched.
Diffusion within the body of the lens is also very limited: it can, in some cases, give the lens a yellowish or milky appearance. The amount of light diffused by an ophthalmic lens remains very small; it is generally considered negligible.

Diffraction of light:

Diffraction is the phenomenon of a change in the direction of propagation of light waves produced when they meet small obstacles (in the order of several wavelengths of light). The light is re-emitted in one or more particular directions with an intensity that makes it visible.
Diffraction takes on a certain importance in ophthalmic optics because it acts as a sign of possible irregularities in the lens surface, and more particularly, abrasions due to wear and tear.

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1. Principle of anti-scratch coating

Anti-abrasion coating of ophthalmic lens surfaces consists of effectively combating both fine scratches from wiping and the large scratches caused by physical damage. The solution is therefore two-fold: greater surface hardness to counter the effect of fine particles and greater flexibility to increase resistance to large particles.

An effective solution to the problem of abrasion has been found by applying a nanocomposite coating to the surface of the lens (see "historic evolution of anti-scratch treatments" below), so-called because they are composed of both organic and mineral materials, and contain nanometric-sized mineral particles in an organic matrix. These varnishes solve the problem of abrasion due to their two-fold properties: resistance to fine scratches due to the hardness of their mineral component and resistance to large scratches due to the suppleness of their organic component.

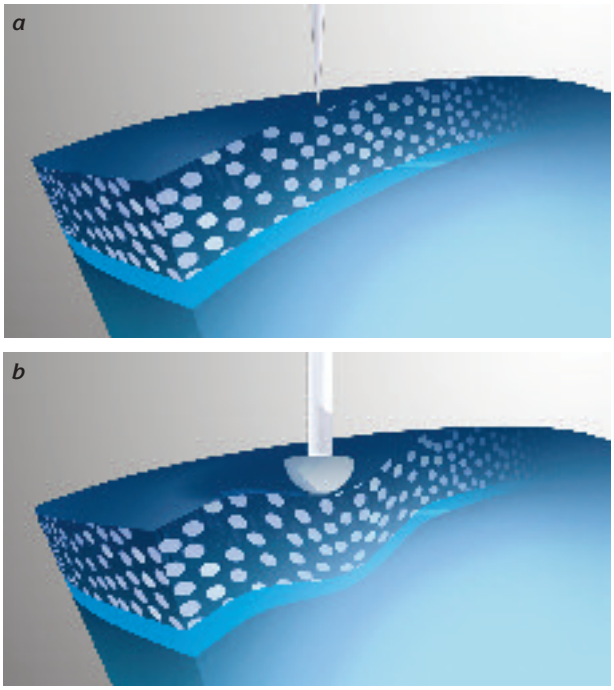

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Figure 21: *Principle of anti-scratch coating:*
a) Fine scratches
b) Large scratches.

In addition, this type of coating has become necessary to solve the particular problem of treating lenses with anti-reflective coatings, which consists in depositing onto the anti-scratch varnish several fine layers of materials that are purely mineral and therefore very hard and brittle. The role of the anti-abrasion coating is then to fill the gap between the mechanical properties of the plastic-based materials and those of the fine anti-reflective mineral by sandwiching an intermediate layer between the two. The original structure of the nanocomposite varnishes, which are both organic and mineral in nature, provides a mechanical transition – a sort of "dampening" effect – between the anti-reflective coating and the base material. It is one of the essential characteristics of Crizal® coating.

To reinforce the dampening effect even more, an extra layer with intermediate mechanical properties is sandwiched between the anti-abrasion varnish and the anti-reflective coating. Called a "Scratch Resistance Booster", this layer ensures perfect continuity of the lens structure, from its soft organic core to the fine, hard mineral shell of its anti-reflective coating. Thus, through the effect of continuity and inter-penetration of the different layers, the lens's resistance to scratching is considerably improved. This extra layer is one of the specifics of Crizal Forte® (or Crizal Avancē™ with Scotchgard™ protector) coating.

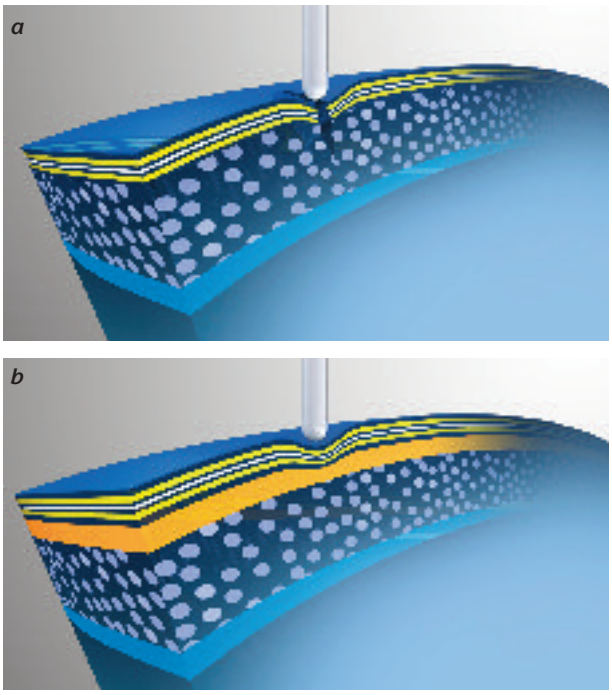

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Figure 22: *Anti-scratch coating and anti-reflective coating:*
a) Classical coating
b) Coating with "Scratch Resistance Booster".

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2. The anti-scratch coating process

Anti-scratch coating of polymer lenses consists of applying a layer of varnish, in the order of 3 to 5 microns thick, on both surfaces of the lens. It can be applied by two methods: dipping or centrifugation.

Dip-coating

In this procedure, the lenses receive a coat of varnish on both surfaces simultaneously. The lenses are first cleaned and prepared for the varnish to adhere in different ultrasonic baths, then immersed in a viscous liquid varnish bath from which they are extracted at a constant speed for perfect control of the thickness of material deposited (see figure 23). The varnish is then polymerised i.e. hardened, by baking at a temperature close to 100°C. It is then transformed into a sturdy, hard layer that gives the lens scratch-resistant properties that are a function of its composition and thickness.
All these operations are carried out in a clean atmosphere (a clean-room) with controlled temperature and hygrometry.

Spin-coating

This procedure consists in placing the lens on a support that spins at a controlled speed, and depositing a drop of liquid varnish in the centre to create, by centrifugal spreading, a uniform coating on the lens. The varnish is then polymerised either by baking in an oven, or by exposure to ultraviolet radiation.
This procedure, in which the lens surfaces are coated individually, is particularly suitable for small batches. The anti-abrasion performance of such coatings, when polymerised by UV, is often mediocre.

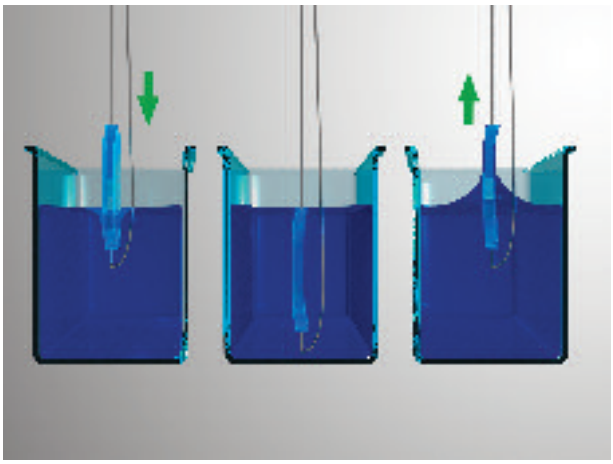

Figure 23: *Principle of dip-coating.*

Figure 24: *Principle of spin-coating.*

The use of anti-scratch coatings on polymer lenses is widespread: over 2/3 of plastic lenses are treated in this way. The growing desire of wearers to protect their investment in lenses and the growing use of high-index materials – for which this type of coating is imperative and systematic – can only increase its use. Anti-scratch coatings will no longer be an option, but will become an integral part of all plastic lenses.

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Supplement

Characterisation of the phenomenon of scratch-abrasion

For a better appreciation of the coatings used to improve a lens's resistance, it helps to understand the phenomenon of scratch-abrasion. This can be described by considering an abrasive particle as a point which exerts local pressure – called stress – on the lens surface. The surface then reacts as a function of its mechanical properties. When the stress is removed, an imprint remains, the shape of which varies. This is the result of the interaction between the abrasive particle and the lens surface. This imprint reflects the material's two properties of hardness and deformation. As an illustration, if an abrasive point is applied with identical stress on different materials, they will each react differently:

- a block of rubber will deform in a completely elastic fashion and will return to its original shape when the point is removed, with no imprint remaining;
- a block of glass will deform very little but will fracture if the stress exceeds a certain threshold, leaving a very visible imprint;
- a block of aluminium will deform by flow of the material, and the imprint will retain the shape acquired at the moment of maximum deformation.

Thus, there is a "law of behaviour" for each material. Technicians usually show the percentage of deformation on a graph as the x-axis and the value of stress as the y-axis (pressure "σ" in Pascals). For any material, its law of behaviour is a curve which originates at 0 and terminates at a point R where rupture occurs; σ_R is the rupture pressure and X_R the deformation at the fracture point. The figure shows typical rules of behaviour of a glass lens and a polymer lens (CR39®). We can see that:

- the glass lens fractures under the effect of relatively high stress but without a lot of deformation, and conversely,
- the polymer, is deformed, in the form of a scratch, by a considerably weaker stress than those withstood by the glass lens. Before reaching its fracture threshold, it may display substantial permanent deformation, without any rupture or splintering.

Knowing the behaviour of each material is essential to determine which "scratch-resistant" protection should be used.

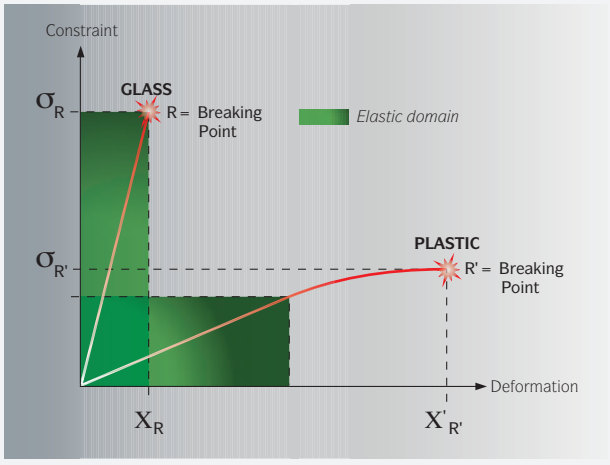

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Figure 25 : *Law of behaviour of glass lenses and plastic lenses.*

Historic evolution of anti-scratch treatments

Ever since the introduction of polymer lenses, resistance to scratching has been a problem. Various solutions have been studied in turn, removing one of the major obstacles to the development of plastic lenses and allowing the introduction of high-index materials. They are described in this brief history.

The first generation of anti-scratch coatings (which appeared around 1970) was based on the single notion of hardness, and consisted of applying a mineral coating of silica on the polymer lens surfaces by evaporation under vacuum. Although this coating, often called "quartzing" was effective against fine scratches, it broke down under stronger damage and did not solve the problem of large particles.

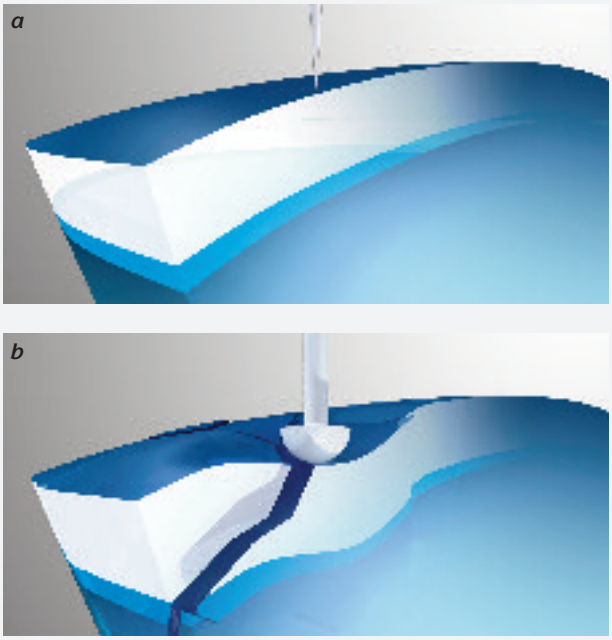

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Figure 26: *Principle of "quartzing":*
a) Fine scratches
b) Large scratches.

This first generation was followed (in 1975) by applying a layer of harder organic material that would follow the deformation without fracturing. This was the beginning of the first hardening varnishes, polysiloxane or acrylic composites that made up the second generation of coatings. A product of silicone chemistry – in which the carbon atoms are replaced by silicon atoms – polysiloxane varnishes constituted a bridge between organic and mineral matter: the presence of silicon gave the surface a hardness that resisted fine scratches, and the existence of long-chain hydrocarbon molecules gave it the elasticity necessary to stand up to heavy wear and tear. But these varnishes proved insufficiently rigid to act as a base for the application of an anti-reflective coating.

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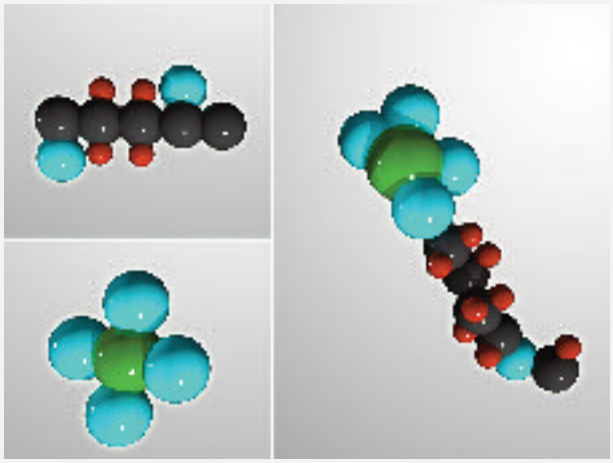

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Figure 27 : *Principle of classic varnishes: organo-silica structure.*

A decade later, a solution to the particular problem posed by anti-reflective lenses gave birth to a third generation of hardening coatings: nano-composite varnishes. It was necessary to bridge the gap between the mechanical properties of organic polymers and those of fine mineral layers of anti-reflective materials in order to constitute a combination that was both cohesive and flexible. Nano-composite varnishes, consisting of an organic matrix in which mineral nano-particulates were dispersed, could contain up to 50% silica, and offered superior rigidity to that of polysiloxane varnishes. Moreover, the nanometric dimensions of these particles – 10 to 20 nm – eliminated any risk of light diffusion and ensured perfect transparency. In solving the problem of anti-reflectivity, they also provided a real solution to the problem of scratching, due to their resistance to fine scratches resulting from their mineral composition, and to large scratches due to their organic composition.

"Quartzing" then made a market come-back (around the 1990s), as a further response to the particular challenge of protecting anti-reflective coated lenses. The principle involved the deposition of a thick, hard mineral layer as a base for anti-reflective coating. Resistance to minor scratches was good, but the coating broke down under heavy wear and tear and the overall performance proved unsatisfactory.

Of a quite different nature, "plasma-polymerisation" was also tried in response to the problem of abrasion. The technology consisted in creating a plasma, i.e. an electrical discharge, in a gas under low pressure in a vacuum chamber, and introducing a gaseous monomer rich in siloxanes. The latter polymerises under the effect of the energy of the plasma and condenses to form a solid film on the lenses in the chamber. The high cost, the complexity of production control and a tendency to amplify irregularities in the lens surface have limited the development of this process.

Nano-composite varnishes have finally proved to be the best response to the question of improving the resistance of polymer lenses to scratches, and their use is now generally widespread.

Measurement and control of anti-abrasion performance

The ability to measure a lens's resistance to abrasion is essential for assessing its performance. Testing must be rapid, easy to implement and simple to interpret. Producers have developed test methods that consist in subjecting sample lenses from production batches to simulated abrasion and scratching. The following are some of the most frequently used tests:

- Bayer test: the lens is moved back and forth in a frame containing an abrasive powder (sand or aluminium oxide) with a defined grain-size distribution. Measuring the diffusion of light of the lens tested compared with that of a control sample gives an evaluation of the abrasion produced.
- Abrasimeter test: a tape encrusted with fine abrasive particles (e.g. carborundum) is rubbed over a sample lens a certain number of times under a given load; the diffusion of the light transmitted through the lens is compared with that of a control lens.
- Steel-wool test: there are several methods of rubbing a lens with a fine steel-wool pad, using a mechanical device for reproducibility, or manually for demonstration. The test lens is compared with the control sample either visually or using a standard diffusion-measuring device.

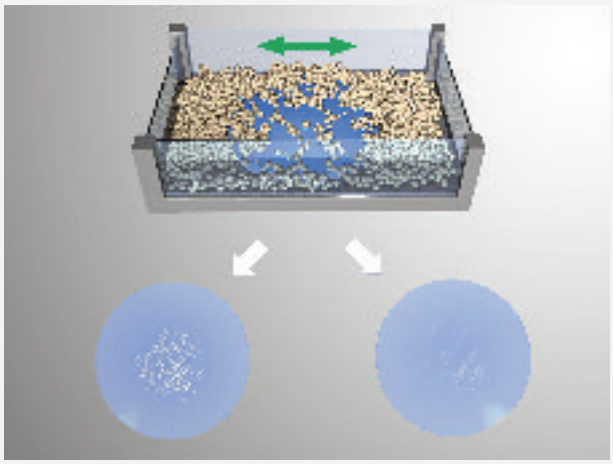

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Figure 28: *Measuring abrasion-resistance performance: the Bayer test.*

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D Anti-reflective treatments

Intrusive reflections of light from lens surfaces can be of various types: reflections from the front surface, reflections from the rear surface and internal reflections. They result in reduced transmission of light through the lens and cause undesirable reflections that are both distracting for the wearer and unsightly to the observer.
The different types of reflection are described below, together with the solutions offered by anti-reflective coatings.

1. Different types of reflections and their effect

a. Reflection from the front surface and internal reflection from the rear surface

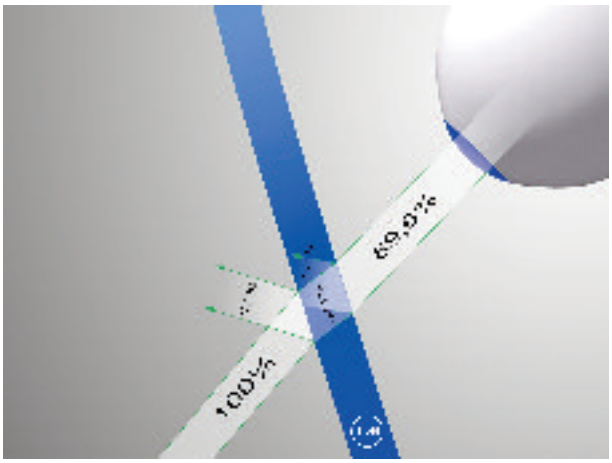
Together with the phenomenon of refraction of light through each lens (which provides the lens's corrective effect), a phenomenon is produced that reflects the light from each surface: firstly on the front surface of the lens, but also on the rear, after passing through the thickness of the lens. These reflections result in a reduction in the intensity of light transmitted by the lens.
The higher the refractive index of the material, the greater the intensity of the reflected light. It can be quantified for each surface by the coefficient of reflection.

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

Therefore, the total quantity of light lost by reflection on passing through the two surfaces of the lens is:

Refractive index	1,5	1,6	1,7	1,8	1,9
Total light reflected	7,8 %	10,4 %	12,3 %	15,7 %	18,3 %

Considering that the refractive index of the most commonly used lenses is 1.6, a rule of thumb is that on average, the amount of light lost by reflection is about 10% of the incident light. From this, we can see the importance of anti-reflective coatings on lenses of high refractive indices, as the loss of light can reach 15 to 20% for lenses of very high indexes.
With anti-reflective coatings, it is possible to reduce the proportion of light lost by reflection to less than 1% (see below).



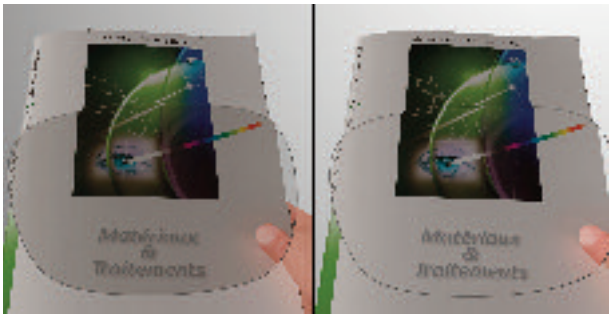


Figure 29: *Reduction in the intensity of light transmitted caused by reflections from the lens surfaces.*

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b. Reflection from the rear surface

A significant phenomenon is the reflection from the rear surface of the lens of light coming from a source situated behind the wearer. Visually, this can be very annoying, particularly in conditions of low light, for example when driving at night. This undesirable reflected light can be superimposed over the light from the scene being observed and cause a reduction in contrast and thus in the quality of vision. It can also cause glare. For more details, go to the following page headed “Supplement: visual benefits of anti-reflective coatings”.
With anti-reflective coating, it is possible to reduce considerably these disruptive effects i.e. to maintain the wearer’s visual contrast and minimise the consequences of glare.

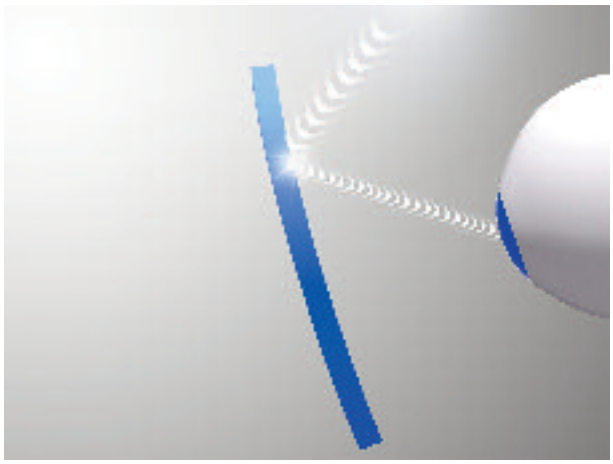
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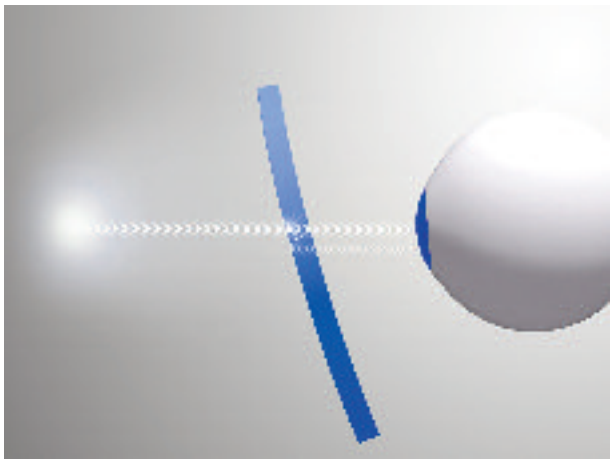
Figure 30: *Alteration of the visual contrast caused by reflection from the rear surface of the lens.*

c. Double internal reflection

A particular phenomenon of double images is also produced by internal reflection within the lens which occurs as follows: after refraction at the first surface of the lens, the light beam reaches the second surface where, in addition to refraction, a second reflection of light occurs. The reflected light is then reflected again at the front surface of the lens and after refraction at the rear face, gives rise to a second image of lower intensity than the main high-intensity refracted image and slightly displaced from it. For the wearer this results in the perception of a double image, a second image of lower intensity “echoing” the main, high-intensity image.
This phenomenon can prove annoying, particularly in low light conditions (such as driving at night), and may be considerably reduced by applying an anti-reflective coating to the two surfaces of the lens.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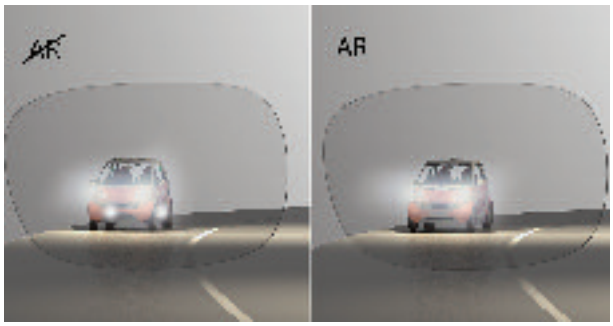

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Figure 31: *Double images, caused by internal reflection within the lens.*

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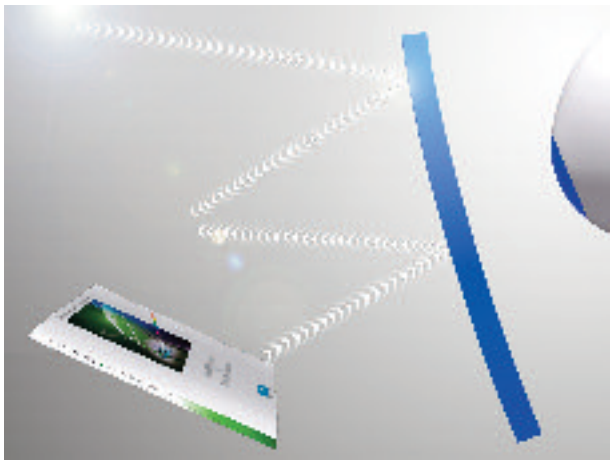
d. Reflection from the front surface

The most obvious and best known phenomenon of reflection of light is the "mirror effect". This is the reflection of light from the front surface of the lens and is easily seen by an observer situated in front, who sees a mirror image of the source of ambient light (sun, indoor or outdoor lighting). It does not affect the wearer at all but simply the observer, who cannot see the eyes of the person to whom he/she is talking. It is essentially aesthetic and does not affect the lens-wearer. Often cited to promote the use of anti-reflective coatings, this argument has probably proved a disservice to the use of anti-reflective coatings: this purely aesthetic aspect is often insufficiently convincing to motivate wearers to adopt this type of coating.
With an anti-reflective coating, it is possible to reduce the "mirror effect" considerably.



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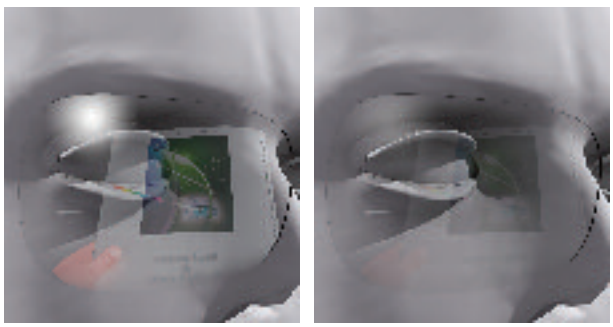

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Figure 32: *"Mirror Effect" caused by reflection from the front surface of the lens.*

Visual benefits of anti-refl

The benefits of anti-reflective coatings are primarily visual and secondarily aesthetic. Above all, they make the lens wearer's vision more comfortable and, moreover, contribute to the aesthetic appearance of the lenses. These benefits are not always fully understood by eyecare professionals themselves, and even less, therefore, by the general public. It is shown here in detail, supported by the results of experimental studies, the two most significant visual benefits: improvement in visual contrast and reduction of the effects of glare.

A) Improvement in contrast

To describe the improvement in contrast provided by anti-reflective coating, the visual task of a subject trying to distinguish two object points can be analysed and, to do this, we must examine the formation of images on the retina. Like any optical device, the eye has imperfections and the image that the eye forms of an object on the retina is not a point but a luminous spot. Thus a view of two points is seen as the juxtaposition of two luminous spots that overlap to some extent. As long as the distance separating the two points is sufficient, the image formed on the retina allows them to be distinguished. When the points approach each other, the two spots tend to merge and the subject sees only one point.
This phenomenon may be quantified, starting with minimum and maximum intensities of the luminous spot, in the form of contrast of the image formed, according to the formula: $C = (a - b) / (a + b)$, with "a" being the maximum intensity, and "b" the minimum intensity of the luminous spot on the retina (see figure). For the two points to appear separate, C must be higher than a value corresponding to the eye's detection threshold.

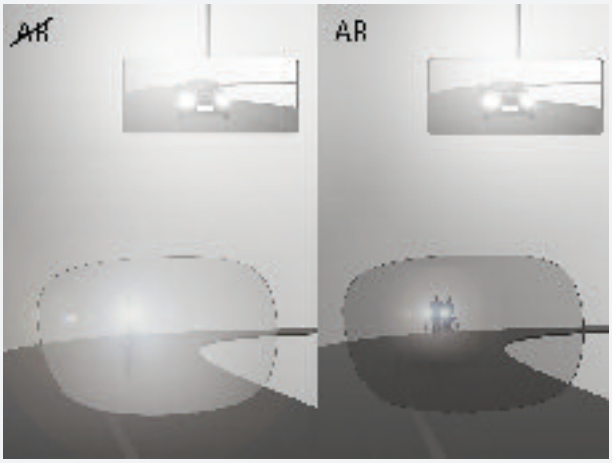

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Figure 33a : *Formation of retinal images of separate points.*

(1) Stuart G. Coupland, Trevor H. Kirkham: Increased contrast sensitivity with antireflective coated lenses in the presence of glare, Canadian Journal of Ophthalmology, 1981; 16: 137-140
(2) Trevor H. Kirkham, Stuart G. Coupland: Increased visual field area with antireflective coated lenses in the presence of glare, Canadian Journal of Ophthalmology, 1981; 16: 141-144
(3) Catherine Eastell: The effectiveness of AR-Multireflection coatings on night driving, Cardiff College of Optometry, University of Wales, 1991
(4) Study conducted in the United States by an independent vision research centre, 2004/2005

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ective treatments

Suppose that the subject is driving at night, trying to distinguish clearly from a distance the lights of two cyclists coming towards him. Then, a car approaches from behind whose headlights are reflected at the rear surface of his glasses: the distracting reflections create a luminous spot of uniform intensity on the retina that is added to the intensity of the two points observed (the headlights of the cyclists). The result is a net decrease in contrast that becomes C′ = (a′ – b′) / (a′ + b′). This can blend the sight of the two cyclists together into one image where they were previously seen separately, or even cause the driver to lose sight of them completely.

By reducing reflections of light on the rear surface of the lens, anti-reflective coating can minimise or even eliminate this effect altogether.

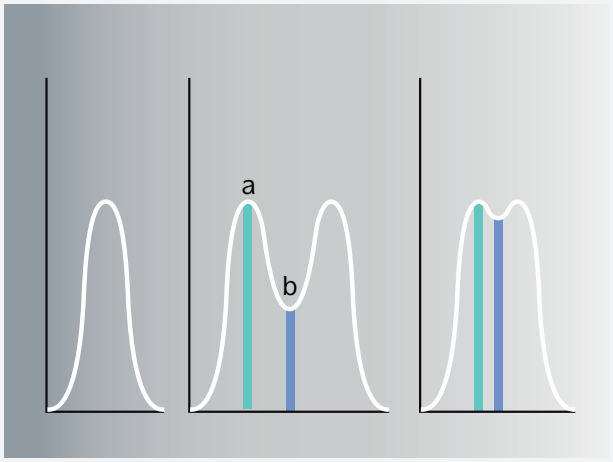

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Figure 33b : *Effect of a parasite reflection.*

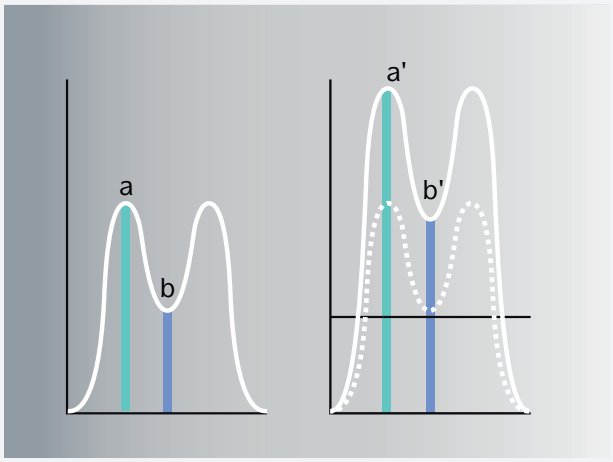

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Figure 33c : *Improvement in contrast with anti-reflective coatings.*

B) Reduction of glare

Studies[1] have shown that in the presence of a disruptive light source, anti-reflective coatings can considerably improve sensitivity to contrast. These studies involved subjects who were alternately supplied with anti-reflective coated and uncoated lenses to observe standard test patterns. Some of the wearers were then subjected to glare from behind (see figure). The results in the figure below show:

- the normal contrast sensitivity curve for these subjects, in the absence of glare;
- the reduction in contrast sensitivity caused by glare with lenses that are not anti-reflective coated;
- the restoration of contrast sensitivity as a result of anti-reflective coating under identical conditions of glare.

In the same way, it could be established that, under predetermined conditions of glare, a spectacle wearer's field of vision is considerably wider with anti-reflective coated lenses than with uncoated lenses[2].

Moreover, it has already been shown[3] that an anti-reflective coated lens, in night driving conditions, allowed a reduction of 2 to 5 seconds in recovery time to normal vision after being dazzled, compared with uncoated lenses. This corresponds to a distance of 28 to 70 metres at a speed of 50 kilometres per hour.

Finally, a study[4] conducted on approximately a hundred patients showed a net preference of wearers for anti-reflective coated lenses compared with uncoated lenses for different evaluation criteria (overall vision, at the computer, in night driving, visual comfort, reflections). The study also demonstrated that wearing anti-reflective lenses brought about a significant reduction in eye fatigue.

Anti-reflective coated lenses significantly limit the undesirable effects of light reflections: they eliminate ghost images, improve visual contrast, reduce the effects of glare (especially in low light conditions) and provide wearers with markedly superior visual comfort.

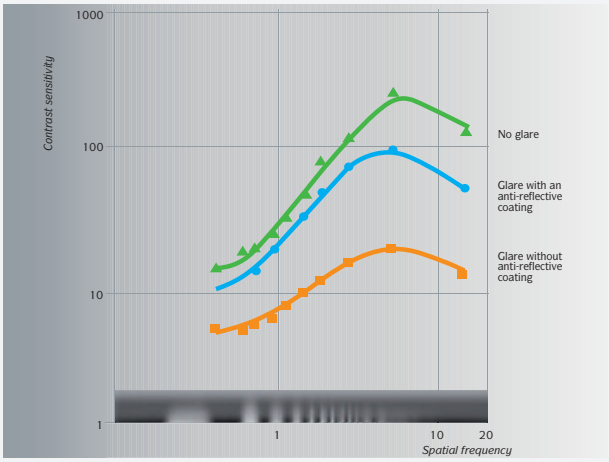

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Figure 34 : *Reduction of the effect of glare as a result of anti-reflective coating.*

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2. Principle of anti-reflective coatings

Anti-reflective coating consists in building up on the surfaces of the lens a number of fine layers that together interfere with the reflected rays of light and cancel them out. To do this, light is considered as a wave motion and the effects of interference of light waves taken into account.

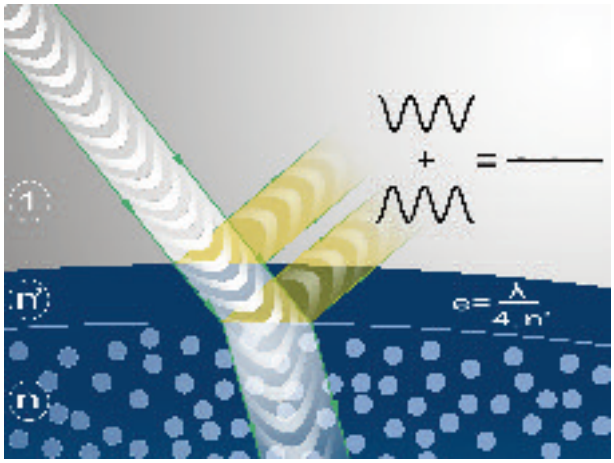

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Figure 35: *Principle of anti-reflective coating.*

Consider the phenomenon that occurs for an isolated layer of coating (figure 35). The light that reaches this layer breaks down into light reflected by the layer and refracted light that enters the coating. The latter then reaches the lens surface and divides in turn into reflected light and refracted light. If the thickness and the refractive index of the layer deposited on the lens are carefully chosen, the reflected light is cancelled out. For this to occur, the reflected light must be superimposed and be "out-of-phase", i.e. the crest of one wave must coincide with the trough of another, and conversely. The reflected light is thus suppressed. Any light that is not reflected is then added to the transmitted light, and the transmission of light through the lens is markedly improved.

Calculation shows that in order to cancel out the reflected light, the thin coating on the lens must:

- have a refractive index n' equal to the square root of the index of the material n;
- have a thickness that is an odd multiple of $\lambda / 4.n'$, λ being the wavelength of the light to be suppressed.

With a "single layer" coating, it is possible to obtain suppression of the reflection for a given wavelength of light, but it is impossible to suppress reflections for every wavelength in the visible spectrum. It is chosen more especially to suppress reflection in the part of the spectrum to which the eye is most sensitive, i.e. green-yellow light (λ = 555 nm). In this case the residual reflection will be blue or purple in colour.

In order to obtain overall attenuation over the whole spectrum, "multilayer" coatings are employed, which eliminate the residual reflection by enabling multiple suppression of reflected waves using several layers. Each of these layers produces a reflected lightwave, and these various lightwaves are out of phase with each other. Together, they suppress multiple wavelengths of reflected light. A complicated calculation is used to determine how to obtain almost complete suppression of reflected light. If a single-layer coating gives residual reflection in the order of 2% per surface, it is less than 1% for multilayer coating. Moreover, the chromatic effect (i.e. the colour of the residual reflection), which is significant for a single layer, is reduced to a very low intensity in multi-layer coatings.
It is important to state that the effectiveness of an anti-reflective coating is not directly proportional to the number of layers, but to the way they are stacked and the interaction of the different light waves reflected between them. According to the manufacturer, multilayer anti-reflective coatings may consist of between 3 to 8 layers.

Finally, we should note that, in principle, anti-reflective coating acts at the interface between the lens and the air, so it is always applied as the final phase of fabrication of the lens.

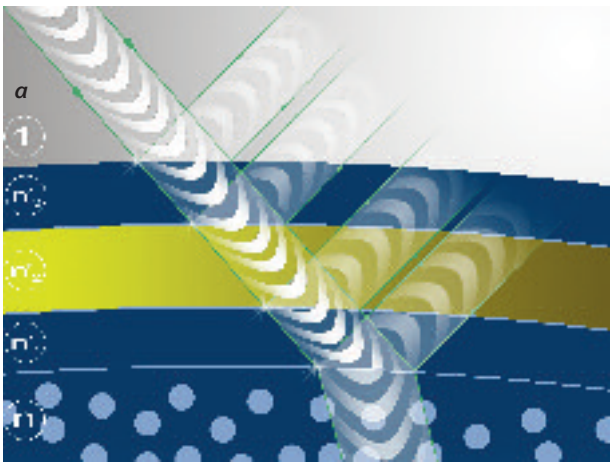

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Figure 36a : *Principle of "multilayer" anti-reflective coating: Multiple interferences.*

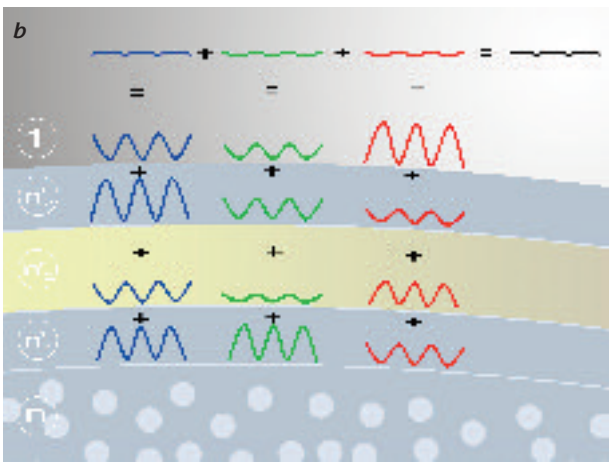

Figure 36b : *Principle of "multilayer" anti-reflective coating: Cancellation of reflected waves.*

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3. Specification and performances of anti-reflective coatings

a. Effectiveness of the anti-reflective effect

The effectiveness of an anti-reflective coating is measured by its "reflection spectrum", a graph which shows, after coating, the intensity of reflected light as a function of the wavelength (see figure 37). The area under the curve represents the quantity of reflected light remaining.
The anti-reflective efficiency may be categorised, in a very general fashion, into the three following categories:

Efficiency	Reflection per surface (ρ)	Transmission (τ)
High	0,3 à 1,0 %	97,5 à 99,0 %
Medium	1,0 à 1,8 %	96,0 à 97,5 %
Standard	1,8 à 2,5 %	94,5 à 96,0 %

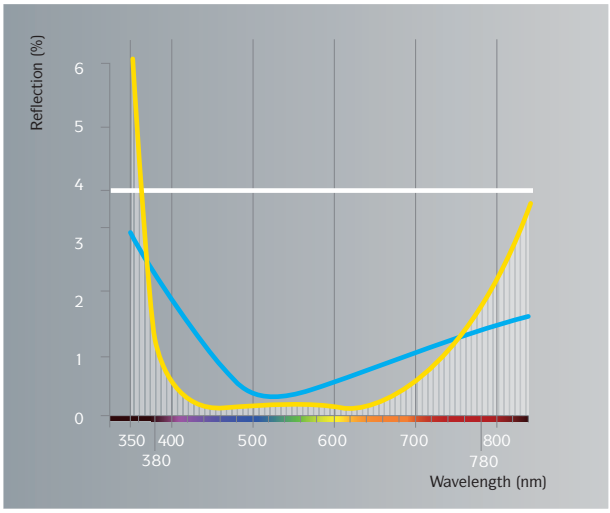

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Figure 37: *Reflection spectrum of anti-reflective coating.*

b. Residual colour

The residual colour of an anti-reflective coating is defined by the part of the spectrum of the light that it reflects. Depending on the type of coating, residual reflection may be of various colours. Thus, in figure 37, which represents the reflective spectrum of the surface of a lens of index 1.5:

- the white line represents the reflection with no coating: we see that all wavelengths are reflected in a uniform manner at a level of 4%;
- the blue curve represents the reflection of a single layer anti-reflective coating: the intensity of the reflected light is higher in the blue and red, giving a purple colour
- the yellow curve represents the reflection of a multilayer, Crizal®-type coating, with a yellow-green residual reflection.

Note that controlling the colour of the residual reflection is a difficult technical exercise because the slightest variation in the refractive index or the thickness of the layers has an immediate visible effect on the colour of the reflection. This is why, in prescription laboratories, both lenses in a pair of spectacles are usually anti-reflective-coated in the same production run. On the other hand, for mass production lenses, strict control is necessary to ensure that lenses manufactured at different times and with different equipment, match up when mounted in the same frame. That is why, in every production run, control lenses are included to ensure that the specified reflection and colorimetry of anti-reflective coatings are adhered to.

Moreover, beyond the question of aesthetics, the choice of residual colour of an anti-reflective coating may also be based on technical criteria, in particular as a function of absolute or differential sensitivity of the eye to different colours. That is how the yellow-green reflection of Crizal® coating was chosen.

Finally, it is possible to produce so-called "achromatic" coatings, i.e. coatings with a uniform residual reflection of different colours of the spectrum so that no specific colour can be observed... but this often impedes their recognition and identification!

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Supplement

The L*, a*, b* colorimetric system

In order to characterise the residual reflection of an anti-reflective coating, the L*a*b* colorimetric system is used (proposed in 1976 by the Commission Internationale de l'Eclairage. This system is a "map" of colours shown by a green-red plane along the x-axis and a blue-yellow plane along the y-axis. A colour P is defined by its co-ordinates a* on the green-red axis and b* on the blue-yellow axis, and may be quantified by its two essential characteristics:

- its angle of hue h* which defines the colour, represented by the angle formed by the segment OP with the green-red axis (the a* axis);
- its saturation C*, or Chroma, which expresses the intensity of colour, represented by the length of segment OP, from the absence of tonality ("achromatic") at the centre of the system, to pure tonality ("monochromatic") at the edge.

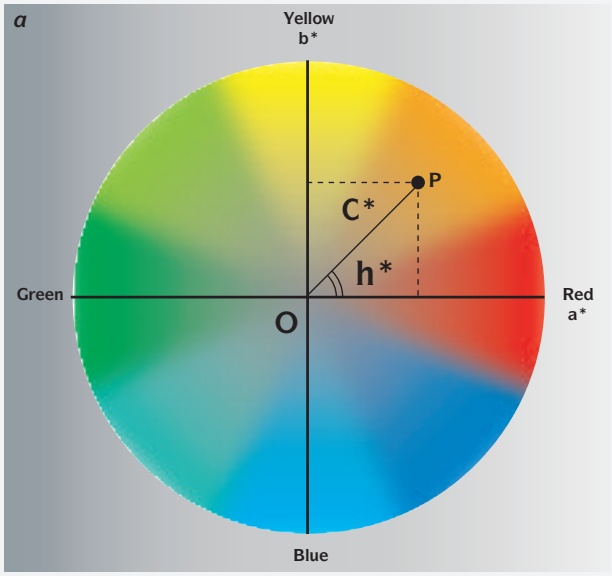

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Figure 38a: *L*, a*, b* Colorimetric System.*
This colorimetric system enables the different colours of reflections to be positioned as represented in the figure below.

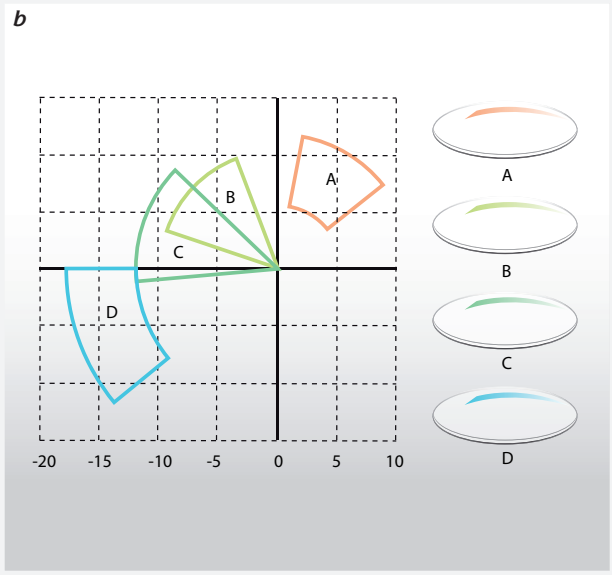

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Figure 38b : *Different residual reflects.*

Bands of interference on the surfaces of high-index plastic lenses

An unsightly phenomenon of optical interference is sometimes produced at the surface of high-index lenses that are coated with an anti-scratch varnish with a classic refractive index and also coated with anti-reflective coating.
It manifests itself in the form of bands of interference – alternating clear and dark bands – that can be seen on the surface of the lens. These bands result from the interference of light waves reflected by the anti-abrasion varnish, on one hand, and the substrate, on the other, and are accentuated by the anti-reflective coating.
This phenomenon only appears in the very special case where the following three conditions occur together:

- a significant difference between the index of the lens and the index of the anti-abrasion varnish: for example material of index 1.74 and a varnish of index 1.5;
- monochromatic lighting: for example from a fluorescent tube (polychromatic light with monochromatic peaks), therefore the bands do not appear in natural white light;
- variation in thickness of the varnish applied on the lens surface.

Although this phenomenon may alter the aesthetic appearance of the lens somewhat, it is of no visual consequence to the wearer who cannot see it.

The technical solution to this problem is twofold:

- either the use of a high-refractive-index anti-abrasion varnish which attenuates the phenomenon of interference by reducing the difference between the indices of the varnish and substrate (a technique called "index matching")
- or introducing another layer between the substrate and the varnish to suppress the wave reflected by the substrate by means of interference (a technique called "quarter-wave layering").

The use of these techniques tends to be widespread in manufacturing high-refractive-index polymer lenses (n > 1.7).

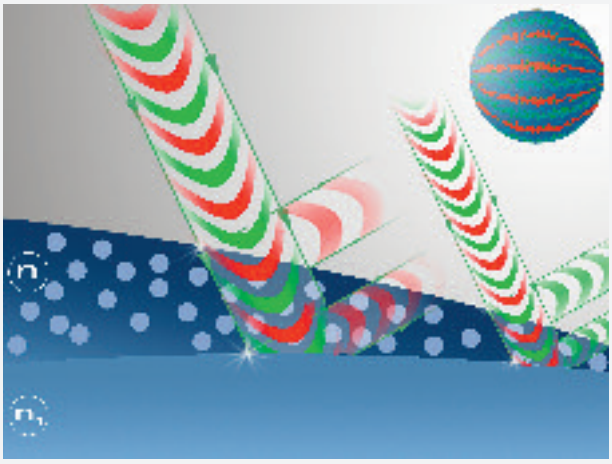

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Figure 39: *Principle of appearance of bands of interference on the lens surface.*

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Anti-reflective coating on the rear surface of sunglass lenses

In the case of sunglass lenses, anti-reflective coating has a particular goal: to eliminate reflection occurring on the back surface of the lens.
As much as anti-reflective coating of the front surface of a sunglass lens may be of little interest, so that of the rear surface may prove essential for the wearer's vision comfort. In fact, anti-reflective coating of the front surface of the lens to improve transmission of light is in direct contradiction with the purpose of the lens, which is to reduce the intensity of light reaching the eye. On the contrary, the lack of anti-reflective coating on the front surface of the lens may contribute to eliminating some 4% of light (for a 1.5 index lens) before it can penetrate into the lens. Moreover, this is the reason why, apart from aesthetic considerations, a number of sunglass lenses have mirrored front surfaces. Unlike the rear surface, anti-reflective coating has a totally different purpose: to eliminate reflections of light originating from sources behind the wearer.

To explain this phenomenon, consider the situation of a spectacle-wearer looking at an object with an intensity of 100 with the sun, with an intensity of 500, behind him. For a lens with a refractive index of 1.5, the reflection by each surface is 4% with no anti-reflective coating and 0.4% with the coating. The reflection of the light from the sun by the rear surface of the lens generates a parasitic image with an intensity of 500 x 4% = 20. Let us look at the intensity of light received by the wearer's eye and, more precisely, at the relationship between the intensity of the light interference received from the sun by reflection at the rear surface and the intensity of the light coming from the object being viewed and transmitted by the lens. This relationship could be described as the "discomfort index". Four scenarios may occur:

- If the lens is clear and without an anti-reflective coating, the light transmitted is 100 x 0.96 x 0.96 = 92 and the discomfort index is 20/92 = 22% (figure 40a).
- If the lens is clear and has an anti-reflective coating on each surface, the light transmitted is 100 x 0.996 x 0.996 = 99 and the light reflected is 500 x 0.004 = 2; the discomfort index is 2/99 = 2% (figure 40b).
- If it is a filter lens and has an internal absorption of 67%, the light transmitted is 100 x 0.96 x 0.33 x 0.96 = 30. The parasitic light reflected by the rear surface remains at 20 giving a discomfort index of 20/30 = 67% (figure 40c). Note that if the solar filter were stronger, the parasitic light could equal or even surpass the light received from the object!
- If this same lens has an anti-reflective coating on its rear surface, the light transmitted is 100 x 0.96 x 0.33 x 0.996 = 32 and the parasite light is 500 x 0.004 = 2, giving a discomfort index of 2/32 = 6% (figure 40d).

It can be seen that the value of an anti-reflective coating on the rear surface of sunglass lenses is to improve wearers' visual comfort. One can only regret that its use has been so limited until now.

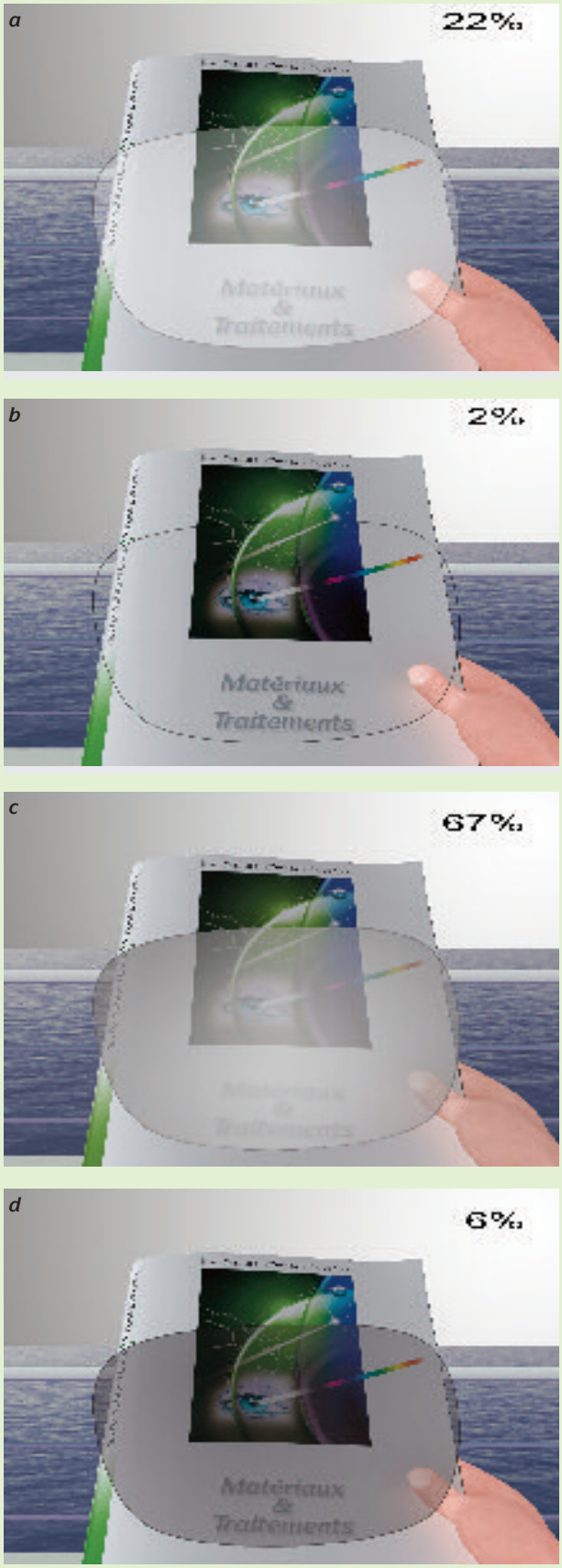

Figure 40: *Transmission and reflection of light in a sunglass lens (of index 1.5 and 67% absorption)*
a) Clear lens without anti-reflective coating (discomfort index = 22%)
b) Clear lens with anti-reflective coating (discomfort index = 2%)
c) Sunglass lens without anti-reflective coating (discomfort index = 67%)
d) Sunglass lens with anti-reflective coating (discomfort index = 6%)

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4. Manufacture of anti-reflective coatings

Anti-reflective coating requires a highly technical process and very sophisticated material. If lens manufacture is high technology, manufacture of anti-reflective coated lenses is very high technology. The manufacturing technology of anti-reflective coatings consists in stacking onto each surface of the lens, thin layers with specific refractive indices, and absolute transparency, to a thickness controlled to a tenth of a nanometre (i.e. an accuracy of $\pm 10^{-10}$ m). Only the technology of vacuum evaporation will satisfy these requirements and transfer onto the lenses, by condensation, a very pure material, of a rigorously regulated chemical composition, and a perfectly controlled, appropriate thickness. Vacuum evaporation – or sublimation – consists in converting the mineral substances comprising the anti-reflective coating to a gaseous state by heating to very high temperatures in a high-vacuum atmosphere. The substances thus evaporated in the vacuum chamber are deposited onto the surface of the lens; their thickness being controlled in real time by means of a piezoelectric quartz microbalance. The different substances that make up the various layers are evaporated successively and, in this way, the layers of anti-reflective coating are stacked.
For more detailed information on the manufacturing technology, refer to the pages headed "Supplement: Manufacturing technology of anti-reflective coating".

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Figure 41: *Diagram of a vacuum evaporation chamber.*

Anti-reflective coatings bring about an undeniable improvement in vision comfort to users. Their use has been growing steadily for several decades, but their market penetration varies greatly from one country to another, from systematic integration, as in Japan, to being a rarely-used option, as in the developing countries. Worldwide, about 50% of lenses presently have anti-reflective coatings. No doubt these coatings will continue their market growth in future years.

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E Anti-smudge and anti-dust treatments

1. Anti-smudge treatment

Anti-reflective coating, at microscopic level, provides an irregular surface in which dirt – composed of aqueous or lipidic molecules – can lodge. In fact, these thin layers of coating are relatively porous and greasy pollutants and impurities can become encrusted in the pores of the top layer. To overcome this inconvenience, techniques borrowed from the manufacture of electronic components are used: these consist in coating the surface with an extra layer, giving it oil- and water-resistant properties. These coatings work in 3 ways:

- they repel molecules of oily matter and reduce their adherence by creating a very weak surface force;
- they act against migration of the molecules of oily matter into the microscopic pores of the anti-reflective coating by closing the interstitial gaps;
- they facilitate their removal by making the lens surface very slippery.

This anti-smudge coating is extremely thin – in the order of only a few nanometres – and so has no effect on the anti-reflective performance itself. It consists of chemical components containing fluorinated or hydrocarbonated chains. Fluorinated polysilazanes, for example, which have quite a complex molecular structure: on one hand, they possess radicals that act as hooks on the silica (which makes up the top layer of the anti-reflective coating) and so have very good adherence to the coating; on the other hand, they possess rich patterns of fluorine and have a strong chemical repulsion of water and greases.

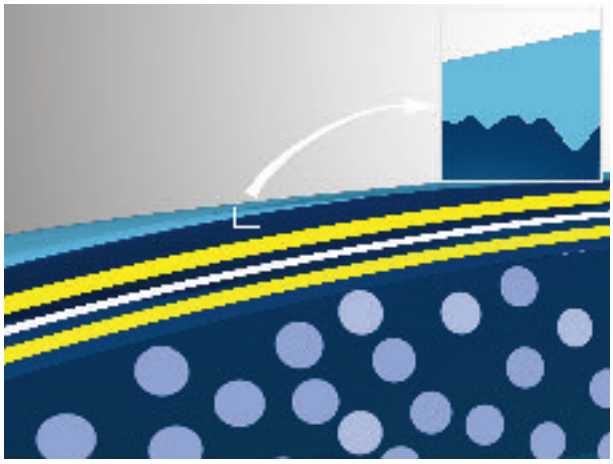

Figure 42: *Principle of anti-smudge coating:*
a) Blocking of the interstitial gaps in the anti-reflective coating.

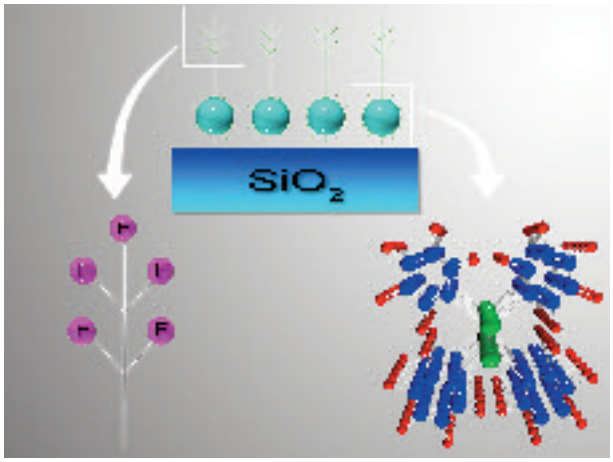

Figure 42: *Principle of anti-smudge coating:*
b) Chemical structure of the anti-smudge coating.

The efficiency of the anti-smudge coating can be quantified by the "contact angle" of a drop of water on the surface of the lens. This angle is the one between the lens surface and the tangent at the edge of the drop. It increases as the contact surface of the drop on the lens is reduced and therefore its adherence becomes weak.
The efficiency of anti-smudge coating may also be measured by the "slide angle": the measurement consists in placing a calibrated drop of water on the surface of a lens that is horizontal, and tilting the latter progressively until the drop of water slides on the surface. The angle of slide is the angle of inclination of the lens at the instant the drop starts to slide. The smaller the angle, the more slippery the surface, and therefore, the more efficient is the anti-smudge coating.

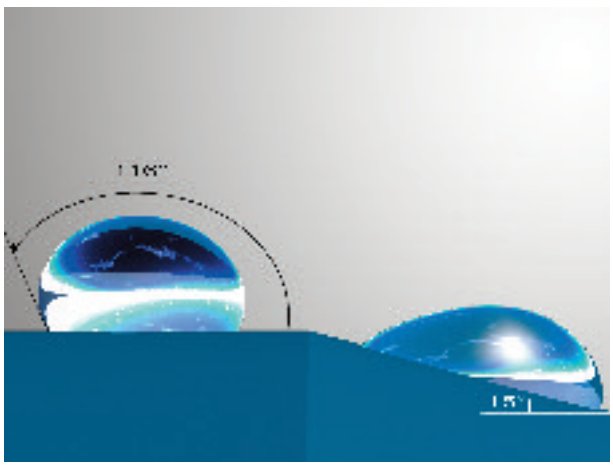

Figure 43: *Efficiency of anti-smudge coating:*
a) Contact angle
b) Slide angle.

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Although the first generation of anti-smudge coatings achieved only partial smoothing of the surface (1st generation Crizal®, for example), the new molecular structures applied to following generations have enabled true lacquering of the lens surfaces to be achieved, and they are now easily cleaned with a wipe (Crizal Alizé®). This property has been reinforced even more in Crizal Forte® (or Crizal Avancé™ with Scotchgard™ protector) by densification of the fluorine molecules thanks to the HSD (High Surface Density) anti-smudge process (see more details in "Supplement: Manufacturing technology of anti-smudge coatings").

Performance of these anti-smudge coatings is such that they are very slippery and this creates another problem: in fact, it has become necessary to add an extra, temporary layer after applying the anti-smudge coating in order to temporarily attenuate the slippery effect and allow the optician to block the lenses without the risk of seeing them skew or become loose during edging. This extra, provisional layer, blue in colour, is simply wiped off by the optician when mounting is completed; the lens's full anti-reflective effect is then revealed.

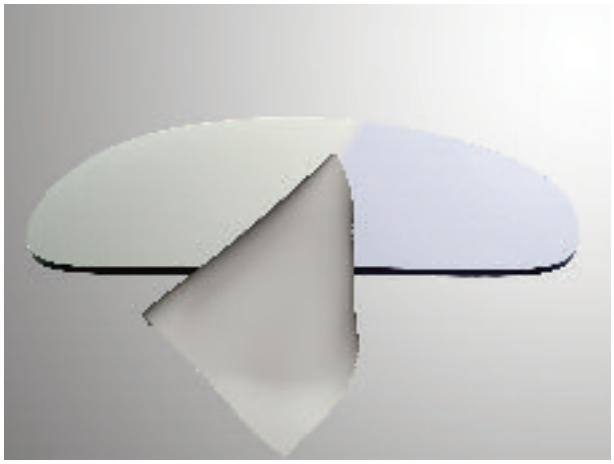

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Figure 44: *"Blue" layer.*

Anti-smudge coatings have enabled major obstacles in the development of anti-reflective coatings to be overcome. This was the major achievement that led spectacle-wearers to accept these coatings.

2. Anti-dust treatment

As well as becoming soiled, the lens surface can also attract dust through the phenomenon of electrostatic charge. In fact, organic material is an insulator and does not conduct electricity: as soon as the surface is rubbed, especially when wiping, it generates electrostatic charges that are not rapidly conducted away from the lens surface. As the surface charge is negative, it attracts positively charged dust particles. Therefore, the lens is never entirely clean and dust-free.

To avoid this phenomenon, the principle of anti-static coatings consists in adding, as part of the anti-reflective stacking process, a transparent conductive layer that enables the charges to flow away. They are then eliminated in a few milliseconds and, since they no longer remain on the surface, they no longer attract dust particles. The lenses are therefore perfectly clean and totally free of dust.

This technique, first applied in Crizal® A2 / Crizal® AST coatings, is also part of the Crizal Forte® (or Crizal Avancé™ with Scotchgard™ protector) process. It is now one of the characteristics of the Crizal® range of coatings.

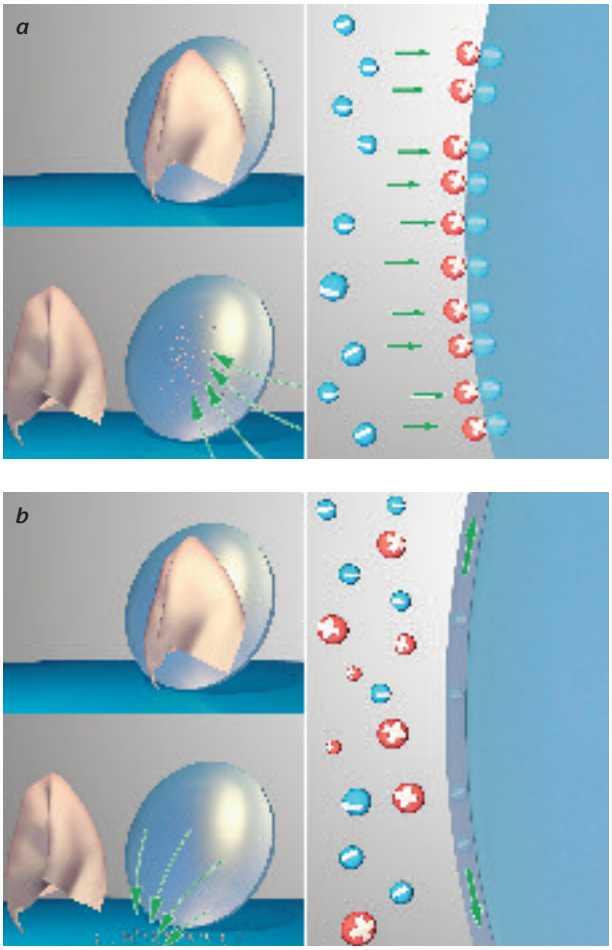

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Figure 45: *Principle of anti-dust coating:*
a) Principle of electrostatic attraction of dust
b) Repulsion of dust by a coated lens.

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Manufacturing technology of anti-reflective coatings

The technology of manufacturing anti-reflective coatings is very sophisticated and requires highly technical equipment. It consists in stacking ultra-thin transparent layers with perfectly controlled thickness on lens surfaces. The coating is applied on completely prepared lenses i.e. lenses that have first been previously surfaced, possibly coloured and, in the case of polymer lenses, already varnished. The lenses are placed in a vacuum chamber where the various coating layers are deposited by successive evaporation of their components.
The following are the details of the various steps of manufacture of these coatings.

A) Preparation of the lenses before coating

Before applying the various anti-reflective coatings, the surface of the lenses must be cleaned in order to eliminate any residue from previous manufacturing steps and to obtain near-perfect purity at molecular level. This cleaning is carried out in tanks of detergent products activated by ultrasound (their action is based on the phenomenon of cavitation, which consists in inducing powerful, high pressure variations of the liquid, and this has an effect similar to that of vigorous brushing).
These ultra-clean lenses are the loaded into the chamber in "clean-room conditions" – i.e. under controlled conditions of dust, hygrometry, temperature and pressure – to eliminate any dust deposit that could cause the coating to flake off and give rise to shiny dots on the lens surface.
Finally, the lens receives a final cleaning in a vacuum, immediately before the anti-reflective coatings are applied:

- either by "ion spallation", i.e. by electrical discharge in a gas under low pressure,
- or by ionic bombardment, a sort of blasting of the lens surface using an ion gun (a little like blasting a wall with a high-pressure hose); this technique is called "Ion Pre-Cleaning" or IPC.

B) Vacuum evaporation

Vacuum evaporation consists in bringing a material to a gaseous state by heating in a vacuum (sublimation). In the case of materials used for anti-reflective coating, they must be heated to temperatures between 1000° and 2200°C to obtain good quality coatings.

To reach these temperatures, the materials are placed in a crucible where heat can be created by one of the two following processes:

- heating by the Joule effect: a crucible of refractory metal (tungsten or tantalum) or of carbon is filled with solid material which reaches a high temperature when a strong electrical current is passed through it. The material melts and then vaporises in the chamber in the direction of the lenses. (The Joule effect is well known; it is, for example, the basis for the way electric radiators work).
- heating by electronic bombardment: an "ion gun", based on the same principle as those in cathode ray tubes (like those in old televisions), emits a beam of electrons, focused by electromagnets, over the material to be evaporated, placed in a suitably-shaped cavity. The electrons are absorbed by the target material and give up their energy in the form of heat, raising its temperature so that it evaporates.

To apply the coating by this process, it is necessary to measure and control the thickness of each layer in real time as it is deposited on the lens surface: one of the most common methods consists in weighing the deposited coating with a piezoelectric quartz microbalance. This is a quartz crystal that is capable of vibrating with a very precise frequency (and used for this reason in quartz watches). The value of this frequency can be modified by applying a mass to one of its surfaces. This is done by applying a thin layer on a quartz crystal placed in the chamber at the same level as the lenses. By means of the electronic coating process, the variation in frequency is converted to a precise measurement of the thickness and rate of application of the thin layer. In this way the thickness of the layers deposited can be controlled to a tenth of a nanometre.

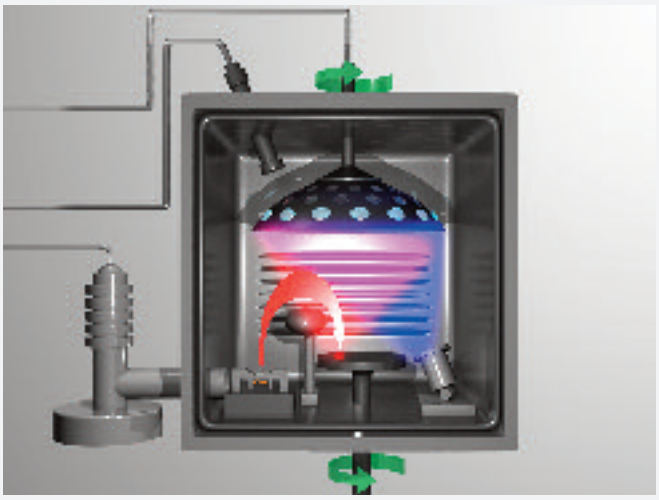

Figure 46: *Diagram of a vacuum evaporation chamber.*

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Supplement

What is a vacuum? And why use a vacuum?

In any chamber filled with gas, the molecules are in constant movement consisting of rectilinear trajectories and collisions, both with each other and with the chamber walls. If we reduce the number of molecules in the chamber, if we "empty" it, there will be too few molecules for them to collide with each other, but they will still collide with the chamber walls. This is what happens in the anti-reflective coating manufacturing process: the vacuum is created by a vacuum pump, and the coating molecules, vaporised in the chamber, propagate without colliding into each other, until they reach the walls of the vacuum chamber or the surface of the lenses to be coated.
The level of vacuum created in the chamber is very great: the pressure is lowered to approximately 10^{-6} millibars, or about ten times less than the "vacuum" existing on the surface of the moon, or a billion times less than the atmospheric pressure on the Earth!

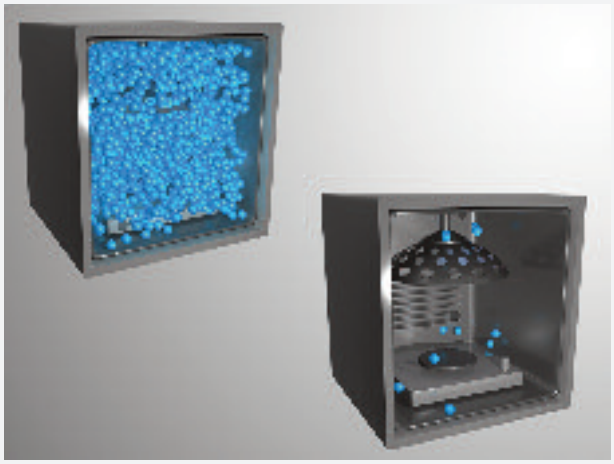

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Figure 47: *Atmospheric pressure and atmosphere in a vacuum chamber.*

Today, the only technology that enables quality anti-reflective coatings to be manufactured is vacuum evaporation. In fact:
- it enables the transfer onto the lenses, through condensation, of materials that are very pure and whose chemical composition can be vigorously controlled;
- it allows layers to be built up with perfect control and extreme accuracy of thickness (± 0.1 nm);
- it guarantees optimal adherence of the different layers as the interfaces are completely free of external pollution.

C) Characteristics of anti-reflective coatings

The anti-reflective effect is obtained by stacking layers of different materials, successively vaporised in the chamber and deposited on the surface of the lenses. The materials used are oxides, such as those of silicon (SiO_2), zirconium ($Zr0_2$), titanium (TiO_2), niobium (Nb_2O_5) and, for glass lenses, magnesium fluoride (MgF_2). The exact composition of the stacked layers and the relative thickness of the different layers are part of the manufacturer's proprietary knowledge.
The properties of the thin films depend essentially on those of the substrate to which they are applied. For example, although a glass lens can be heated up to 300 °C, it is impossible, on the other hand, to heat plastic materials above 100 °C: they turn yellow, then decompose. And so it was necessary to develop low temperature manufacturing processes for coating plastic lenses. In addition, coefficients of thermal expansion of plastic materials are much higher than those of mineral materials used for anti-reflective coating layers, and can cause the appearance of stress at the interface between the substrate and the coating. This explains, for example, the appearance of cracks when the lens is subjected to thermal shock (like excessive heating in the optician's frame heater or by prolonged exposure to the sun on the dashboard of a car). Also, when plastic lenses are coated, the surface temperature of the lenses must be perfectly controlled when the layers are applied. In summary, procedures for the application of anti-reflective coatings are complex and must be adapted to suit each material.

D) Manufacturing system

To receive their anti-reflective coating, the lenses are arranged one by one on quadrant-shaped supports and held by fitted rings. These frames are placed on a dome in the shape of a cupola which is then placed into the vacuum chamber. The chamber is closed and the vacuum is created by several primary and secondary pumps. The coating process consists of a succession of evaporations of the various components which are deposited on the lens surface facing the inside of the cupola. The pumping time is about half an hour, and the total evaporation cycle about one hour.
Once the cycle is completed, the chamber is opened, the cupola extracted and the lenses turned with meticulous care; the same operations of pumping and evaporation start over again to coat the second lens surface. Once the coating is completed, the lenses are taken out to be inspected.

Manufacture of anti-reflective coatings requires sophisticated, and therefore expensive, equipment, and above all complete control of the procedures; it is part of the art and expertise of the manufacturer.

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Manufacturing technology of anti-smudge coatings

The manufacture of anti-smudge coatings consists in applying, on top of the final layer of anti-reflective coating, a very thin layer (only a few nanometres) that is both hydrophobic and oleophobic.
This covering may be applied in two different ways:
- either by dip-coating in a process similar to that used to apply anti-reflective coating, but much simpler;
- or by vacuum evaporation in the anti-reflective coating chamber; the coating is applied immediately on top of the anti-reflective coating stack.

This covering is a chemical composition containing, on one hand, fluoride and hydrocarbon chains and, on the other hand, silicon-based molecules that allow the fluorinated molecules to adhere to the anti-reflective coating surface. It is most commonly introduced in the form of a liquid that is vaporised in the vacuum chamber following the application of the anti-reflective coating, using an evaporation process similar to the one used for the different layers of anti-reflective coating. It is deposited in an extremely thin layer – just a few nanometres – on the surface of the final layer of anti-reflective coating where it seals any irregularities and pores.

The first generation of anti-smudge coatings (Crizal®) consisted of a limited number of fluoride chains that made the surface partially hydrophobic and oleophobic. Later, their number was greatly increased until the surface became very slippery (Crizal Alizé®). At this stage, it became necessary to apply a temporary extra layer to reduce the slippery effect to allow opticians to edge them. Later, the High Surface Density Process™ (HSD) enabled the number of fluoride molecules deposited on top of the anti-reflective coating surface to be increased even more. This covered the surface with a denser, thicker layer, and so made the anti-smudge coating even more effective (Crizal Forte® or Crizal Avancé™ with Scotchgard™ protector).

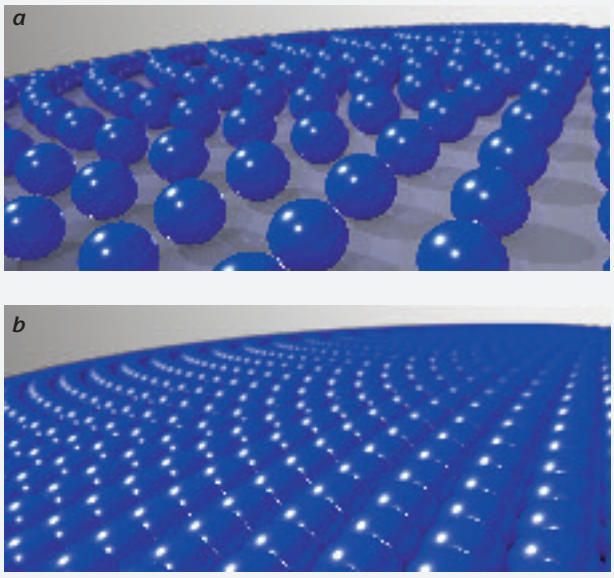

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Figure 48: *Densification of the anti-smudge coating through the HSD process.*

Manufacturing technology of anti-dust coatings

The principle of manufacturing anti-static coatings consists in introducing an extra, transparent layer into the anti-reflective coating stack to act as a conductor. This provides an anti-static effect as follows: the negative electrostatic charges created when the lenses are wiped are immediately eliminated by conduction and no longer attract positively charged dust particles.

The conditions must be perfectly controlled when this layer is applied in order to provide both good conductivity and perfect transparency. To do this, the thickness and density of the transparent layer are controlled by the use of i-technology™.
Adapted from space and fibre optic technology, it is a procedure of applying anti-reflective coating based on the use of ions:
- on one hand, before application of the anti-reflective stack, by ionic bombardment on the surface to clean it and enable perfect, durable adhesion of the coating;
- on the other hand, during the evaporation process, the molecules are energised by the ions, which greatly increases the density of the anti-static layer and makes the application perfectly uniform.

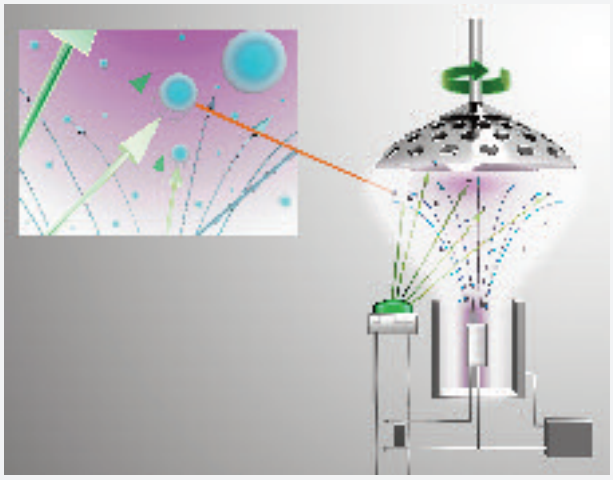
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Figure 49: *Anti-dust coating by i-technology™.*

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3. Resistance and protection

Beyond being thin, light and transparent, any ophthalmic lens must also be protective. It must resist impact and ensure effective eye protection against harmful effects of solar radiation.

In this third section, the lens' properties of resistance and filtration are addressed in detail.

A Resistance to impact

Resistance to impact is a fundamental property that is essential: any ophthalmic lens must be able to resist the wear and tear of daily life without breaking. Moreover, it should not present any risk to the wearer; on the contrary, it should offer protection for the eyes.
Over time, the impact resistance of ophthalmic lenses has been considerably reinforced. Lenses, made at first of glass, were naturally brittle and broke very easily: at the time, they were subjected to chemical and thermal tempering to improve their resistance. Later, plastic lenses appeared, with naturally superior qualities of resistance, and this property greatly contributed to their success. Finally, regulation was brought in to impose standards of resistance on ophthalmic lenses and ensure all the necessary safety to eyeglass wearers.
Let us describe how a lens may be caused to break and remind ourselves of the impact resistance standards that apply to ophthalmic lenses.

1. Mechanics of breakage

The impact resistance of a lens results from a combination of natural resistance and the material used, the thickness of the lens, and the presence of anti-scratch and anti-reflective coatings and subsequent impact resistance coating.
During impact, sustained most often on the front surface, the process of breakage of the lens is as follows: after a certain degree of deformation, a crack begins to be created on the rear surface; this constitutes a weak point where the mechanical energy of the impact is concentrated, causing the crack to enlarge and spread, in the form of a fissure, across the thickness of the lens.
When faced with an impact, plastic and mineral materials behave quite differently:

- glass lenses, very fragile under tension, have a very low resistance threshold and break relatively easily: their need to be tempered thermally or chemically, made them more difficult to use and caused their decline;
- plastic lenses behave intrinsically better: their molecular structure gives them good flexibility and great amplitude of deformation before breaking: this allows them to absorb a large part of the impact energy and to offer better resistance.

Different categories of plastic materials have different properties: thermoplastic materials, because of the relative freedom and mobility of their chain molecules, are better able to dissipate the energy of impact. Thermosetting materials, by reason of their reticulated network structure are more rigid and have less resistance. So, CR39® meets the standards under conditions of minimum thickness; Trivex® has a very good resistance, but can be broken; polycarbonate has excellent resistance and does not break, it is the impact resistant material "par excellence", and is, moreover, the material used to manufacture safety lenses. High-index plastic materials are generally more resistant than CR39® but are less so than polycarbonate.

In addition, it is important to note that anti-scratch and anti-reflective coatings tend to make the lenses more fragile and make them less resistant than uncoated lenses. On impact, a fissure is produced in the anti-reflective stack, that is naturally more brittle because of its mineral nature, and is transmitted to the anti-scratch varnish, then to the substrate: it is the entire lens that is made more fragile by its weakest component. To remedy this and reinforce the impact resistance of these lenses, a layer of elastomeric "primary varnish" is now incorporated between the substrate and the anti-scratch varnish, which is capable of halting the spread of the fissure by its elastic nature. This layer also helps the anti-scratch coating to adhere and enables harder varnishes to be applied.

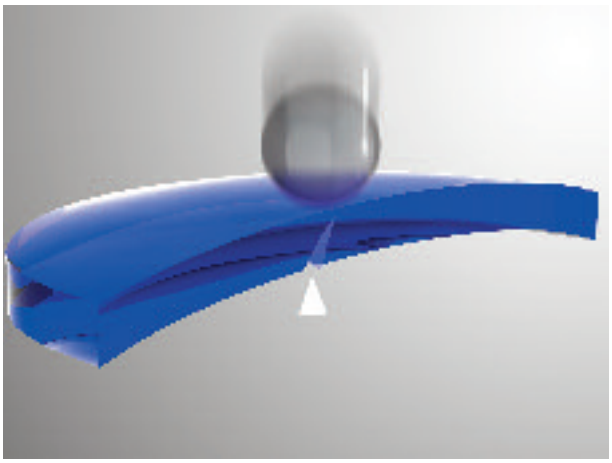

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Figure 50: *Mechanism of fracture in an ophthalmic lens: Start of cracks in the concave surface that can spread into the body of the lens and lead to fracture.*

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2. Impact resistance standards

The impact resistance standards that ophthalmic lenses must meet differ from one country to another: in the USA, the legal requirement is the drop ball test monitored by the Food and Drug Administration (FDA); in Europe and in Asia, it is resistance to the pressure from a 100 Newton load set out by the European Committee for Standardisation (CEN) that applies.

The tests are detailed below:

- FDA Standard (of dynamic resistance): stipulates that any ophthalmic lens must withstand a 5/8 inch (16 mm) diameter steel ball with a mass of 16 g dropped from a height of 50 inches (1.27 m) at the centre of the convex surface of the lens. From the batch of samples tested, a tolerance of 6.5% of broken lenses is accepted. Introduced in 1972, this standard has been at the origin of strong development of plastic lenses in the U.S.A. and the countries that have adopted it.

- CEN Standard (of static resistance): stipulates that any ophthalmic lens must resist the pressure of a load of 100 Newtons (i.e. a mass of 10 kg) applied for 10 seconds on the convex surface: it must not break, it must not star with a loss of material, and it must not deform (it must not flex more than 4.5 mm). All lenses must meet the requirements of this standard; to be valid, tests are carried out on the most fragile lenses, i.e. minus lenses.

Note that these are the minimum impact-resistance standards that all lenses must meet. Manufacturers are free to go further with the quality of their products; that is the case with Essilor who have chosen to be far more demanding than these impact resistance standards for their lenses.

Impact resistance is an essential characteristic to protect wearers' eyes from any mechanical attack and give the lenses the durability that they deserve. It is of vital importance in the case of children. Plastic materials have provided a very satisfactory solution to this issue; polycarbonate is a very good answer to this question.

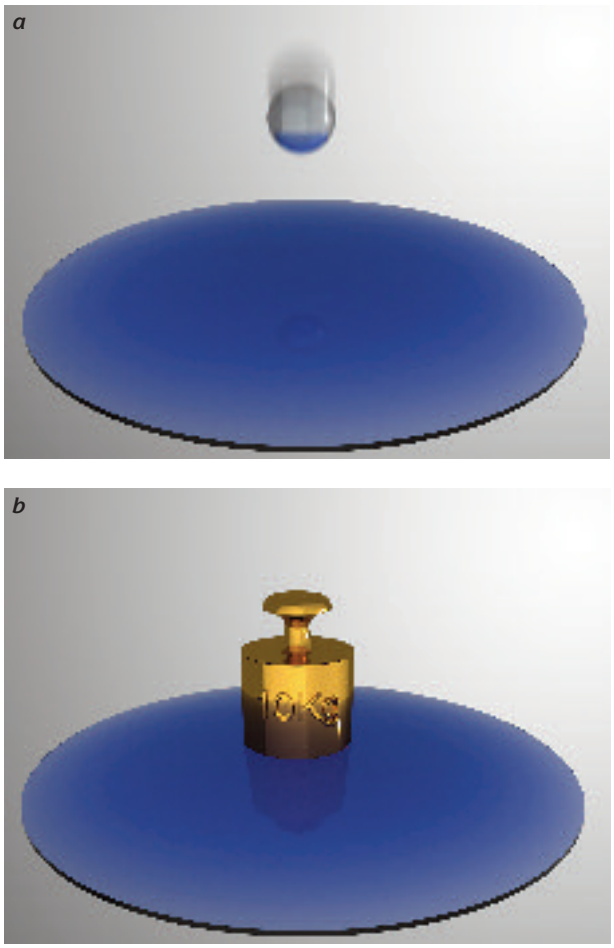

Figure 51: *Impact-resistance tests*
a) FDA Test: a steel ball, 16 mm in diameter, with a mass of 16 g, dropped from a heigth of 1.27 m on the convex surface of the lens
b) CEN Test: a load of 100 Newtons applied on the convex surface of the lens for 10 seconds

References of impact-resistance standards in effect:
ISO Standard 14889; ANSI Standard Z 80.1 - 1987; ISO Standard 2859-1

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B Protection against light

The human eye possesses several natural defences that protect it against light: the closing reflex of the eyelids, the reduction in pupillary diameter, the filtration by transparent media, retinal adaptation to luminous intensity, etc. However, this protection can be insufficient, and over time the eye itself may become damaged. The added protection of filter lenses is therefore needed either permanently, for increasing the overall level of protection and comfort for the eyes, or for specific occasions in which the eye needs protection against very intense light radiation. Filter lenses play a double role by reducing the intensity of light that reaches the eye and by absorbing and eliminating harmful radiation. These lenses may have fixed transmission (with a uniform or gradient tint) or variable transmission, i.e. photochromic. As a reminder of the need to protect against solar radiation, the general need for solar protection will be discussed before a description of the different types of filter lenses is given.

Reminder regarding solar emissions

The solar radiation that reaches the Earth is but a small part of the vast realm of electromagnetic vibrations that range from cosmic rays to radio waves. Each type of radiation is characterised by its frequency ν or by its wavelength $\lambda = c / \nu$ (c = the speed of light – 300,000 km/sec or 186,000 miles/sec). The solar radiation that reaches the Earth's surface has wavelengths between $\lambda = 300$ nm and $\lambda = 2000$ nm and includes:

- visible radiation which, after passing through the intra-ocular media, stimulates the retinal receptors and is perceived, according to standard measurements, at wavelengths from $\lambda = 380$ nm (violet) to $\lambda = 780$ nm (red).
- beyond one end of this visible spectrum is ultraviolet radiation (commonly referred to as "UV"), which exists at wavelengths between $\lambda = 380$ nm and 280 nm and is categorised into 2 types :
  - UVA (from 380 to 315 nm), whose tanning effect is well known
  - UVB (from 315 to 280 nm), which is responsible for sunburn.

The ultraviolet radiation that reaches the Earth is composed of 95% UVA and 5% UVB. Radiation in the range 280 to 200 nm is classified as UVC which, while dangerous, is blocked by the ozone layer that blankets the Earth's atmosphere.

- at the other end of the visible spectrum lies infrared radiation, with wavelengths in the range $\lambda = 780$ nm to $\lambda = 2000$ nm and is blocked by the water vapour present in the atmosphere.

Visible light thus represents a very small range of wavelengths in the total spectrum of electromagnetic radiation and is made remarkable by the fact that it interacts with our eyes and allows us to see the world.

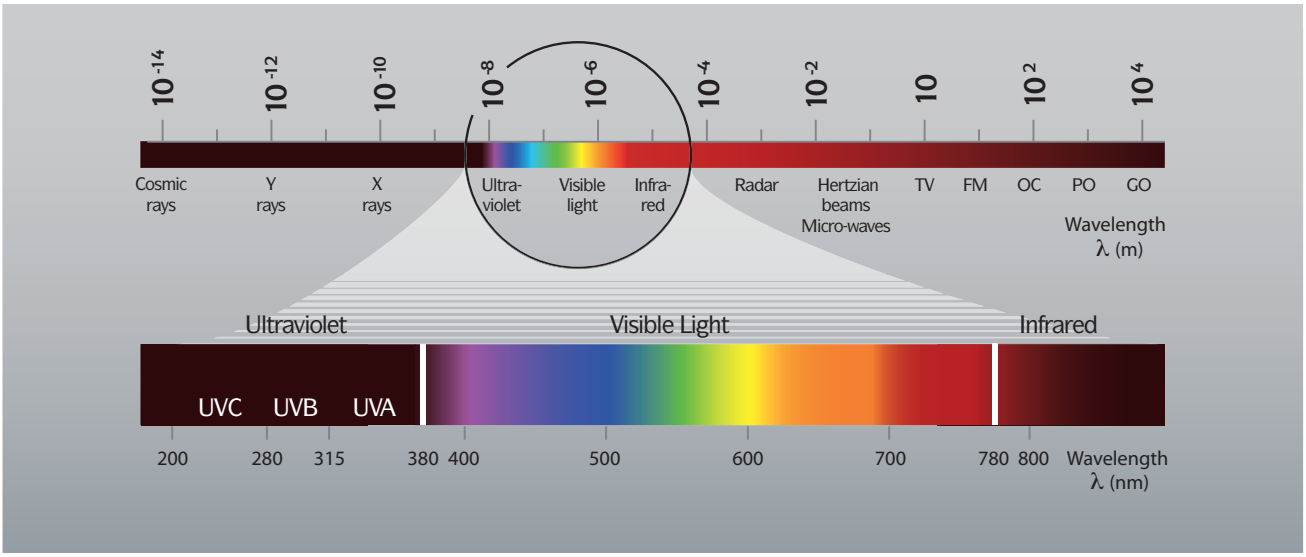

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Figure 52: *Electromagnetic radiation and sunlight.*

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1. The need to protect the eye against solar radiation

The sun, which regulates life on Earth, provides us not only with light and warmth but also all other radiation that is not as beneficial. Certain radiation, specifically blue and ultraviolet light, can pose long-term danger; their effects on vision and the structure of the eye are examined in detail below.

Light transmission through the different structures of the eye

- visible light and light with short, high-energy wavelengths, reach the retina.
- UVA is absorbed for the most part by the crystalline lens, but it can reach the retina, particularly in children;
- UVB is absorbed mostly by the cornea, but a small amount reaches the crystalline lens;
- UVC from the sun is completely absorbed by the ozone layer.

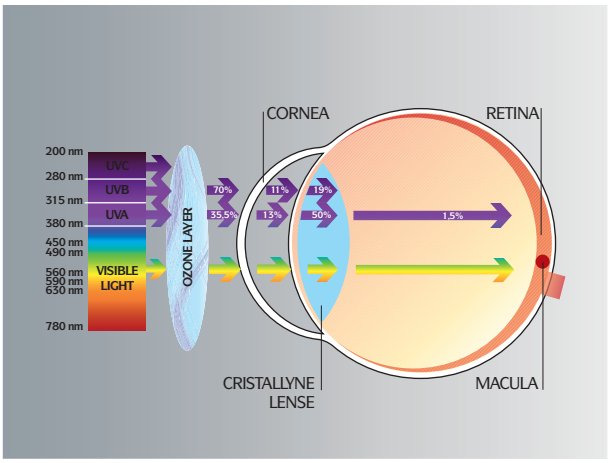

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Figure 53: *Light transmission through the different structures of the eye.*

a. The effect of ultraviolet radiation

Exposure to ultraviolet radiation is a major cause of ocular lesions. Some lesions are irreversible and can lead to partial or total vision loss. More precisely, ultraviolet light can give rise to ocular irritation, dry eyes, conjunctival lesions, photokeratitis, ophthalmia (or burns to the cornea such as "snow blindness"), lens opacity, early cataracts, and retinal damage, particularly in children.

Ultraviolet radiation is thus a danger that affects us daily, especially when its concentration is elevated: solar radiation is more intense during the summer, at midday when the sun is at its zenith, in the mountains where the snow reflects 80% of the radiation, at high altitudes where the amount increases 10% every 1,000 m (3,258 ft), next to bodies of water (20% reflection), sand (10% reflection) and in cities where bright surfaces reflect both visible and UV radiation.

It is, therefore, important to protect the eyes as much as the skin!

b. The effects of blue light

Blue light contains the most energy in the visible spectrum. Also known as "HEV" (High-Energy Visible light), blue light covers the spectral range of 380 to 500 nm, and includes violet light (380 to 420 nm) to blue light (420 to 500 nm). Since blue light is high in energy, it scatters through the atmosphere more than the other wavelengths in the visible spectrum (Rayleigh's Law); this is the reason why a clear sky appears blue. Blue light is present in direct sunlight, but it is also be emitted by numerous artificial light sources.

And, as it can penetrate the eye, it can have an effect on vision and the retina:

- Effects on vision: since blue light spreads more effectively through the transparent media, it is an important factor in creating glare; moreover, since it is focused before the retina by the eye's optical system, it can create a blurry sensation.
- Effects on the retina: as with ultraviolet radiation, blue light contributes to the deterioration of the retinal cells (pigment epithelium and photoreceptors) and repeated and/or prolonged exposure to blue light can result in photodamage to the retina. Over the long term, the cumulative effects of exposure to blue light are considered a risk factor in age-related macular degeneration, which thus represents a loss in visual acuity.

It is important to state at this point that not all sunglass lenses protect the eyes effectively against ultraviolet radiation and even less so against blue light. Tinted lenses that do not filter harmful radiation only protect the eyes from the ambient brightness by reducing the intensity of visible light; however, this causes the pupil to dilate reflexively, which allows more light to enter and, in consequence, a higher level of harmful radiation. It will be realised that low quality sunglasses can actually be worse than no protection at all. Thus, it is clearly unacceptable that such lenses should ever be offered by eyecare professionals.

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2. General points regarding filter lenses

a. Lens absorption/filtering principle

Matter is composed of molecules constructed from atoms, which are the basic units of matter and are themselves comprised of a nucleus and electrons. The interaction of these molecules with light can be expressed mainly as the excitement of the electrons as they pass from the ground state S_0 to an excited state S_1. The difference between these two energy levels can be detected by a spectrophotometer, which can generate a graphic representation of either an absorption spectrum (or curve) or a transmission spectrum for the sample under test. A given molecule or chain of molecules has its own characteristic spectrum, which acts as a "fingerprint". All matter absorbs light, but in distinct portions of the solar spectrum.

The greater electron density that a chain of molecules which constitutes a polymer has – which is linked to the nature of atoms and to the way they bond with each other – the more the transmission spectrum shifts towards the longer wavelengths. With clear lenses, the intrinsic structure of the polymer is generally sufficient to block most ultraviolet radiation; however, when this is not the case, it is possible to add extra molecules called "UV absorbers" in order to obtain total protection. For obtaining additional protection for visible light, for sunglasses for example, dyes can be incorporated into the polymer material that, by virtue of their high electron density, shift the absorption spectrum within the range of visible light and thus create a filtering effect.

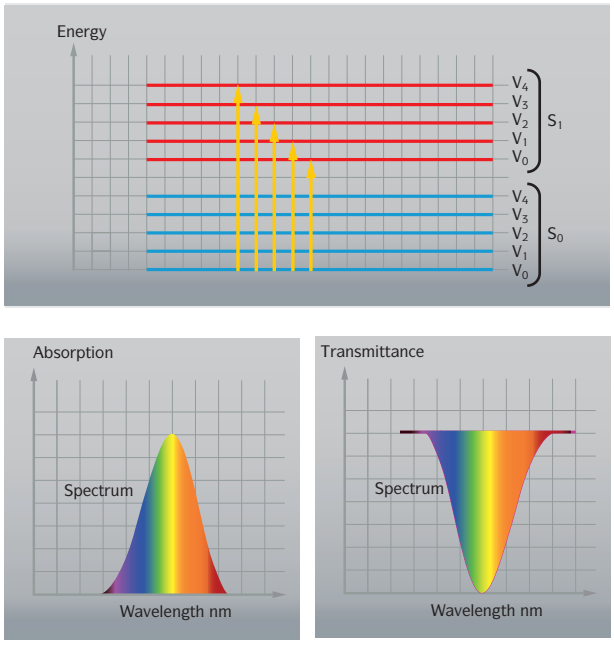

Figure 54: *Theoretical model of light absorption.*

b. Classification of lenses according to their light transmittance

All light filters can be characterised by their physical properties with regard to light transmission – transmittance **T**, transmission curve and UV cut-off – and by their physiological properties: the luminous transmittance in the visible range $\mathbf{T_v}$. This $\mathbf{T_v}$ factor is specific to ophthalmic optics, and it represents the filter's physiological properties with a single number, which is the ratio between the luminous flux emerging from the lens and the luminous flux incident on the outer lens surface as perceived by the eye, i.e. weighted for each wavelength by the relative spectral luminous efficiency $\mathbf{V_\lambda}$ of the eye (see the precise definition in the supplement "Characterisation of ophthalmic lens transmission properties"). This factor comes from a standardised international definition and is used to classify lenses into 5 categories of luminous transmittance ranging from 0 for clear lenses to 4 for the darkest lenses. The classification criteria concern lens transmission properties not only in the visible range but also in the UVA and UVB ranges. These criteria were established for plano lenses, 2.0 mm thick for normally incident light.

Filter category	Ultraviolet range of the spectrum		Visible range of the spectrum	
	Maximum value of solar UV-B transmission τ_{SUVB}	Maximum value of solar UV-A transmission τ_{SUVA}	Transmission in visible τ_v 380-780nm	
	280-315 nm UVB (%)	315-380 nm UVB (%)	From (%)	To (%)
0	τ_V	τ_V	80,0	100,0
1	0,125 τ_V		43,0	80,0
2			18,0	43,0
3		0,5 τ_V	8,0	18,0
4	1,0		3,0	8,0

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Figure 55: *Classification of lenses according to their light transmittance.*

Each luminous transmittance category includes a description, instructions for use and a standardised graphic representation as indicated in figure 56:

- category 0 is characterised by clear lenses or lightly tinted lenses worn permanently;
- category 1 contains all intermediate tints falling between clear lenses and sunglasses;
- categories 2, 3 and 4 are reserved for sunglasses and correspond to their respective level of solar radiation protection: medium, high and extremely high.

The pictograms representing these categories are internationally standardised images that specify the recommended use and limitations of each tint category. In fact, this standardisation for classifying tints comes with information regarding restrictions for use that must be passed on to wearers and which include, more specifically, information on using lenses not recommended for night driving – categories 1 to 3 – and lenses not recommended for driving under any circumstances – category 4.

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Cat.	Description	Pictograms	Instructions for use
0	Clear or very light tint		Indoors - Cloudy sky
1	Light tint		Partially cloudy sky
2	Medium tint		Medium sun
3	Dark tint		Strong sun
4	Very dark tint		Very strong sun Not suitable for driving and road use

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Figure 56: *Description and instructions for use of the five luminous transmittance categories.*

c. Lens tint and transmission

Lens tint is determined by the chromatic composition of the light that it transmits (except for mirrored lenses). This composition is the summation of the visible radiation that the observer's eye receives.
It is difficult, however, to precisely analyse lens transmission properties based on tint alone; nevertheless, certain general principles can be established:

- grey tints transmit visible radiation more uniformly,
- brown tints absorb more blue-green light than orange-red,
- the intensity of a tint is proportional to the absorption of visible light,
- tints have no effect in absorbing ultraviolet and infrared light.

Conversely, it is just as difficult to predict a lens colour from its transmission curve. Choosing a tint is a function of the absorption properties desired, the wearer's possible ametropic condition—myopes generally prefer brown while hyperopes prefer green—as well as the wearer's personal tastes. Cultural tradition can also play a role: whereas grey and neutral colours are considered "good filters" in the English-speaking world, continental Europe prefers brown-coloured lenses, which sharpen contrast and provide better protection against radiation in the lower portion of the visible spectrum.

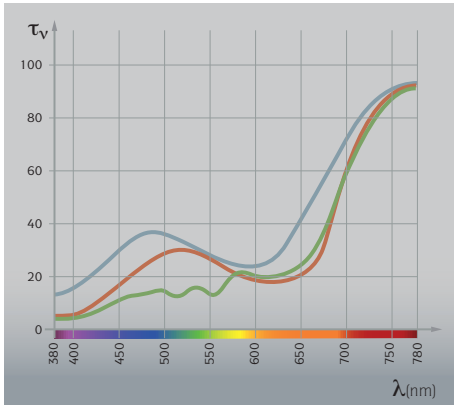

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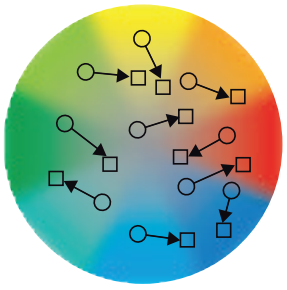
Figure 57: *Transmission curves for different tints (grey, brown and green).*

d. Maintaining the wearer's colour perception

Beyond the reduction in light afforded by filter lenses, one must also think about how they might affect the wearer's colour vision. In fact, any coloured filter, once it possesses a certain spectral selectivity, inevitably distorts colour vision. The human brain, due to a phenomenon called "chromatic adaptation", is capable of minimising this distorting effect and for the most part restore the relative scale of natural colours. This phenomenon, however, has its limits, as the perceived colour corresponds to the residual distortion after chromatic adaptation. This distortion is a function of the light filter and, more specifically, of its spectral selectivity.
Therefore, certain types of tints (like the PhysioTints®) have been designed to minimise colour distortion and, more specifically, reduce the adaptive "chromatic shift" that the visual system must undergo. The general rule is that for each of the classic lens tints – brown, grey, grey-green or dark grey – the selected tint is that which, from a theoretical point of view, transforms the colorimetric co-ordinates of a reference chromatic light source the least (see figure 58) and, from a practical point of view, is that most liked by wearers.
To determine this, a theoretical colour rendering index is initially calculated using the sum of the final chromatic distortions of the sample reference colours after a simulated chromatic adaptation. This index is then used to make an initial selection of tints that will then be evaluated by a sample group of patients who will use them. Better vision comfort can thus be offered to those who wear sunglasses, and a choice of tints can be created based not only on subjective or aesthetic criteria, but also on physiological criteria.

a



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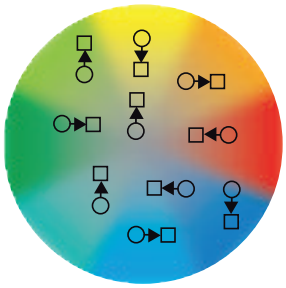

Figure 58: *Colour distortion index: vector field of a tinted lens a) Classic tint b) PhysioTints®. (short vectors indicate low colour distortion, which means less disturbance and more comfortable vision).*

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Supplement

Characterisation of the transmission properties of an ophthalmic lens

Light transmitted through a lens is the light which is neither reflected nor absorbed by the lens. The type and quantity of light transmitted depends on the chemical composition of the lens material and any coatings applied to the surfaces of the lens.
Thus, the flux Φ_τ that reaches the eye corresponds to the incident flux Φ on the front face of the lens minus the flux Φ_ρ reflected by both lens surfaces and any flux Φ_α absorbed by the material, so that $\Phi_\tau + \Phi_\rho + \Phi_\alpha = \Phi$.
The wearer's perception is thus the result of the combination of 3 elements: the intensity and spectral composition of the incident light, reflection and absorption by the lens and their respective spectral selectivity and finally, the eye's sensibility to different portions of visible radiation.
The different factors used to characterise the properties of ophthalmic lenses regarding transmission, reflection and absorption are described in detail below.

Light transmission vs. light absorption

The light that passes through a lens is attenuated due to reflection from the lens surfaces and absorption by the material. Reflection is characterised by the reflection factor ρ_V and absorption by the internal absorption α_i , which is the proportion of light absorbed between the entrance and exit surfaces of the lens (see below). Therefore, when one speaks of 15% absorption, this signifies that a 15% internal reduction in the luminous flux is combined with that already subtracted by the reflection of the light off the surfaces of a clear lens. This absorption is negligible with regards to clear ophthalmic lenses; with filter lenses, however, it is a direct function of the lens.
As it is defined, absorption is only characterised by the internal attenuation and not by the lens's total attenuation of luminous intensity. This is why one speaks often of "light transmitted", which takes into account all phenomena acting on the luminous intensity, rather than "light absorbed", which is only characterised by the internal light absorption by the lens.

A. Characterisation of transmission by an ophthalmic lens

Transmittance T

The transmittance **T** is characterised by the transmission properties of a lens in the ratio $\mathbf{T} = \Phi_\tau/\Phi$, in which Φ_τ is the radiant flux emerging from the exit surface and Φ is the incident radiant flux at the entrance surface. As this factor is usually calculated for each wavelength of light λ, it is thus called the spectral transmittance $\mathbf{T}_{(\lambda)}$.

Transmission curve

A transmission curve describes the lens physical properties as a light filter by presenting the variation of its spectral transmittance $\mathbf{T}_{(\lambda)}$ as a function of wavelength. This curve shows the filter's spectral selectivity.

Luminous transmittance in the visible range T_V

This factor is specific to ophthalmic optics, and it summarises the filter's physiological properties with a single number, which is the ratio between the luminous flux emerging from the lens and the luminous flux incident on the lens as perceived by the eye, i.e. weighted for each wavelength by the relative spectral luminous efficiency $V_{(\lambda)}$ of the eye. This factor is calculated using the following formula:

$$\tau_V = \frac{\int_{380}^{780} \tau_{(\lambda)} \cdot V_{(\lambda)} \cdot S_{D65(\lambda)} \cdot d\lambda}{\int_{380}^{780} V_{(\lambda)} \cdot S_{D65(\lambda)} \cdot d\lambda}$$

where $\mathbf{T}_{(\lambda)}$ = the filter's spectral transmittance, $V_{(\lambda)}$ = the relative spectral luminous efficiency of the eye and $S_{D65(\lambda)}$ = the spectral distribution of the radiation from the standard illuminant, D_{65}. This $\mathbf{T_V}$ coefficient is used to define the tint categories for ophthalmic lenses as well as their classification according to luminous transmittance.

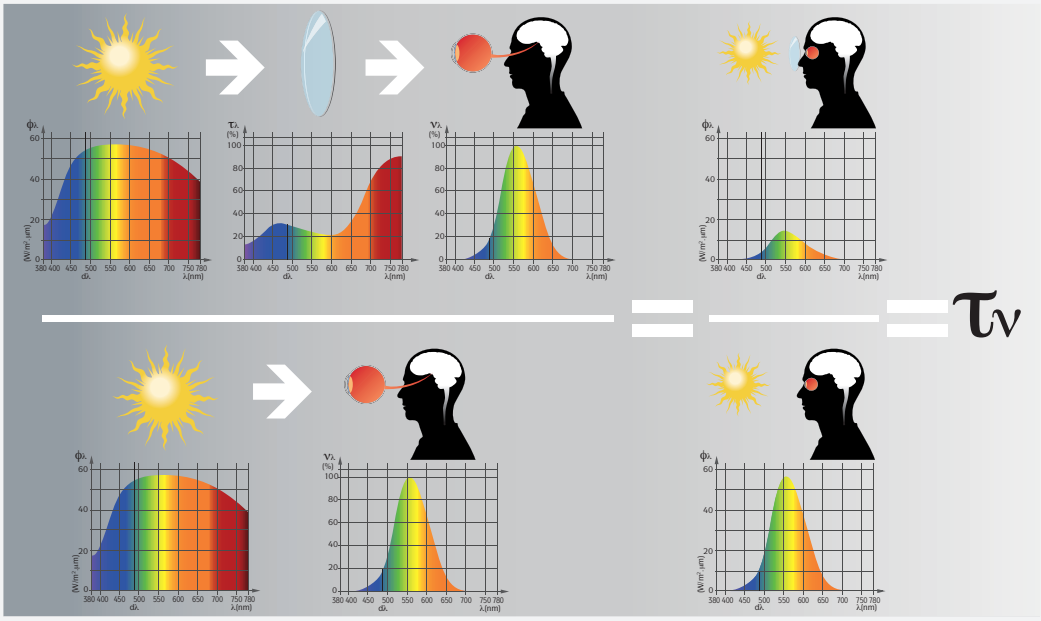

Figure 59: *Transmission for an ophthalmic lens.*

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UV transmission and cutoff

Ophthalmic optics is particularly interested in ultraviolet absorption properties, which are characterised by a lens' UV transmittance rate (for UVA and UVB) or its UV cut-off. The UV transmittance rate, expressed in %, is the proportion of light transmitted in the UVA range (315 to 380 nm) and the UVB range (280 to 315 nm). UV cut-off, expressed in nm, is determined by finding the wavelength on the lens' transmission curve at which the lens transmits less than 1 % of the light.

B) Characterisation of reflection by an ophthalmic lens

Reflectance ρ

Reflection at the interface of two transparent media is characterised by the reflectance $\rho = \Phi_\rho/\Phi$, which is the ratio between reflected radiant flux Φ_ρ and incident radiant flux Φ. The spectral reflectance, $\rho_{(\lambda)}$ is generally determined for each wavelength λ of the incident light.

At a refracting surface separating air from a transparent medium with refractive index n, the reflectance is defined by the following formula established by Fresnel (Augustin Fresnel, French Physicist, 1788–1827):

$$\rho = \left(\frac{n - 1}{n + 1} \right)^2$$

assuming normally incident light, This factor, which represents how light is restricted from passing through the refracting surface, is used as an attenuation coefficient applied to the incident light flux. Consequently, the luminous flux Φ passing through a refracting surface with reflectance, ρ loses a fraction Φ_ρ and thus becomes $\Phi.(1 - \rho)$ upon passing through. In the case of ophthalmic lenses, reflection occurs on both the front and rear surfaces of the lens, with the total reflected flux given by $\Phi_\rho = \Phi.\rho.(2 - \rho)$ assuming the absence of any internal absorption of light.

Luminous Reflectance in the visible range ρ_v

This factor is used in ophthalmic optics to characterise a reflection's visual effect by the ratio between reflected light flux and luminous flux incident as they are perceived by the eye, i.e. weighted for each wavelength by the relative spectral luminous efficiency $V_{(\lambda)}$ of the eye. The luminous reflectance is calculated in the following manner:

$$\rho_v = \frac{\int_{380}^{780} \rho_{(\lambda)} \cdot V_{(\lambda)} \cdot S_{D65\,(\lambda)} . d\lambda}{\int_{380}^{780} V_{(\lambda)} \cdot S_{D65\,(\lambda)} . d\lambda}$$

where $\rho_{(\lambda)}$ = the filter's spectral reflection factor, $V_{(\lambda)}$ = the relative spectral luminous efficiency of the eye and $S_{D65(\lambda)}$ = the spectral distribution of the radiation from the standard illuminant, D_{65}.

C) Characterisation of absorption by a ophthalmic lens

Absorptance α_i

Absorption by a lens is characterised by the ratio $\alpha_i = \Phi_\alpha/\Phi_{in}$, where Φ_α is the radiant flux absorbed between the entrance and exit surfaces of the lens, represented by $\Phi_{in} - \Phi_{ex}$, and Φ_{in} is the radiant flux that has successfully passed through the lens. If lens absorption varies with wavelength, the lens' internal spectral absorption factor $\alpha_{i\lambda}$ is determined in the same way for each wavelength λ of incident light.

The quantity of light absorbed as it passes through the material is given by Lambert's Law (Johann Heinrich Lambert, French mathematician, 1728–1777), which states that layers of material of equal thickness absorb an equal amount of light (in %) regardless of the light's intensity (in other words, absorption is an exponential function of thickness). It is thus possible to deduce that the luminous flux Φex reaching the exit surface of a lens can be represented by the formula $\Phi_{ex} = \Phi_{in} . e^{-kx}$, where k is the material's specific extinction coefficient and x is the thickness of the material through which the light passes. The internal absorption factor is represented by the formula $\alpha_i = 1 - e^{-kx}$ and is applied as an attenuation coefficient as in $\Phi_{ex} = \Phi_{in} . (1 - \alpha_i)$.

Application: Calculation of the light flux transmitted by a lens

Assuming an incident light flux Φ reaches the surface of a lens:
- after its partial reflection by the first refracting surface, the flux that enters the lens is: $\Phi.(1 - \rho)$;
- this flux is attenuated as it passes through the lens and becomes $\Phi.(1 - \rho).(1 - \alpha i)$ when it reaches the second lens surface;
- the flux is reflected once again and exits the lens, after refraction, as: $\Phi\tau = \Phi.(1 - \rho)2.(1 - \alpha i)$.

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3. Filter lenses with fixed transmission

a. Sunglass lenses

Protection for the eyes against solar radiation is generally provided in two ways: by reducing the intensity level of visible light (about 60 to 95%) and by eliminating harmful radiation, in particular ultraviolet radiation. Sunglass lenses achieve this in the following manner: the lens material eliminates ultraviolet radiation while the tint reduces the intensity of visible light.

The international standard for lens categories described previously in this document designates three lens categories that can be used for protection against solar radiation:

- category 2 (τ_V from 43 to 18%) for medium levels of solar radiation,
- category 3 (τ_V from 18 to 8%) for high levels of solar radiation,
- category 4 (τ_V from 8 to 3%) for extremely high levels of solar radiation.

UVA transmission (λ = 315 to 380 nm) for category 2 must not surpass the maximum value of τ_V while UVA transmission for categories 3 and 4 must not surpass half the maximum value. UVB transmission (λ = 280 to 315 nm) must not surpass 10% of the τ_V regardless of the tint category.

The elimination of ultraviolet radiation is an essential factor in solar protection. Although high-index plastic materials systematically block UV radiation, this is not the case with CR39, which must always contain a UV absorber: this absorber must be added to the monomer, as in the case of mass-produced plano sunglass lenses, or applied to the surface, as with individually made corrective lenses. It goes without saying that offering wearers lenses that do not filter UV, risks being more harmful than good and is thus unthinkable. Unfortunately, this is not the case with some sunglass lenses offered on the market; it is therefore essential that professionals talk to their suppliers and verify a lens' characteristics before offering it to their clients. Also, solar filters can be selective with regard to the spectrum, i.e. they can eliminate certain colours in the spectrum and/or improve the transmission of a specific portion of the spectrum. This selectivity is often exploited for eliminating ultraviolet and blue light.

Finally, in the section on anti-reflective coatings, the visual benefits that such coatings provide when applied to the back surface of tinted lenses have already been pointed out. Besides the visual comfort that these lenses provide, certain anti-reflective coatings have been studied and designed especially for sunglass lenses in order to reduce the reflection of not only visible light on the back surface of the lens, but more specifically ultraviolet radiation (Crizal Sun®, for example).

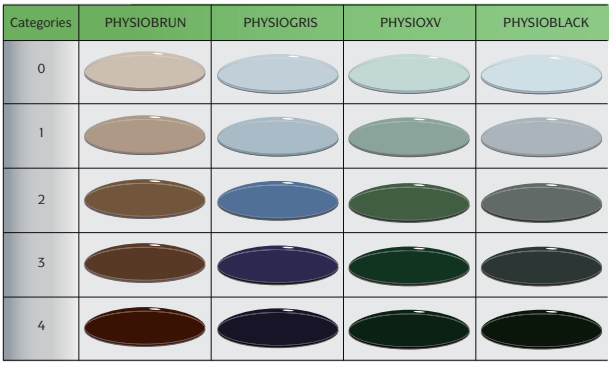

Figure 60: *PhysioTints® line of lenses.*

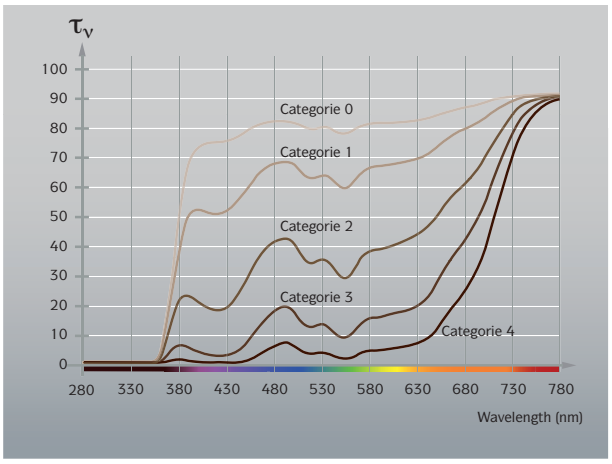

Figure 61: *Transmission curves for the different categories of intensity (CR39 brown categories 0 to 4).*

b. UV- and blue-light-filtering lenses

1) Lenses with melanin

Melanin is a natural pigment found in the hair, skin and eyes that protects against the harmful effects of the sun, ultraviolet radiation and blue light in particular. For example, melanin protects the skin by darkening it into a tan. In the eye, melanin fights the deterioration of the retinal cells by absorbing photons and dissipating their energy. Generally speaking, the greater the quantity of melanin that is naturally present in the body, the darker the colour of the eyes, hair and skin.

The general idea behind these lenses is that by incorporating synthetic melanin pigments into the very core of the lens, the natural protection afforded by the eye will be reinforced. These lenses protect against ambient glare (essentially caused by blue light), improve visual contrast and contribute in slowing down the ageing process of the retina as well as the skin around the eyes. They eliminate 100% of UV light and 98% of blue light, thus helping to preserve a wearer's optimal vision.

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These polycarbonate lenses have a brown tint provided by a film of uniform thickness that is affixed to the front lens surface during manufacturing and covered with a protective varnish. The resulting tint is both natural and uniform regardless of the corrective power of the lens. Melanin lenses are especially designed with children in mind, for whom protection is essential, and also persons with light-coloured eyes and white skin who have less natural protection and those over 60 years old whose natural protection decreases over time.

2) Tints for sports

Special eye protection is often needed for participating in certain sports. Since the environment, light conditions and eye strain differ with each sport, the type of lens recommended for sports differs as well. Besides offering ophthalmic correction, lenses play a role in improving visual contrast thanks to their specific tint and thus optimise visual performance for sports participants. As an answer to this need, a range of "sports tints" (SOL-utions™) has been designed in collaboration with elite sports figures. This line is comprised of a series of tints, each one specifically adapted to the needs of a particular sport or activity: for example, light brown/category 2 for golf, polarised yellow/category 2 for cycling, polarised brown/category 3 for nautical sports, dark brown/category 4 for mountaineering, etc. These lenses are made in polycarbonate which combine lightness with impact resistance. All the lenses in this range eliminate 100% of UV and at least 92% of blue light in order to offer perfect eye protection while improving visual contrast. In addition, these lenses can also benefit from the application of an anti-reflective/anti-UV coating on their back surfaces that is designed especially for sunglass lenses (Crizal® Sun) as well as a mirror coating on the front surface (Option Flash Clean Touch).

c. Polarising lenses

Light is actually an electromagnetic vibration that diffuses out in all directions around the light's direction of propagation, and when it reflects off a flat surface, it becomes polarised, i.e. it mainly vibrates in one plane—the plane perpendicular to the incident plane (which is defined by the direction of the light ray and the perpendicular on the surface at the point of incidence). For example, when sunlight is reflected by a horizontal surface such as the ground or a body of water, it only vibrates in the plane perpendicular to the vertical plane passing through the point of incidence and in the direction in which the light is reflected (see figure 62); in this plane, the light's axis of vibration is horizontal. If a polarising filter with a vertical axis is inserted between the reflected light and the eye – which is the direction of polarisation perpendicular to the reflected light's plane of vibration – it is possible to eliminate this light completely. Polarising lenses function according to this principle.

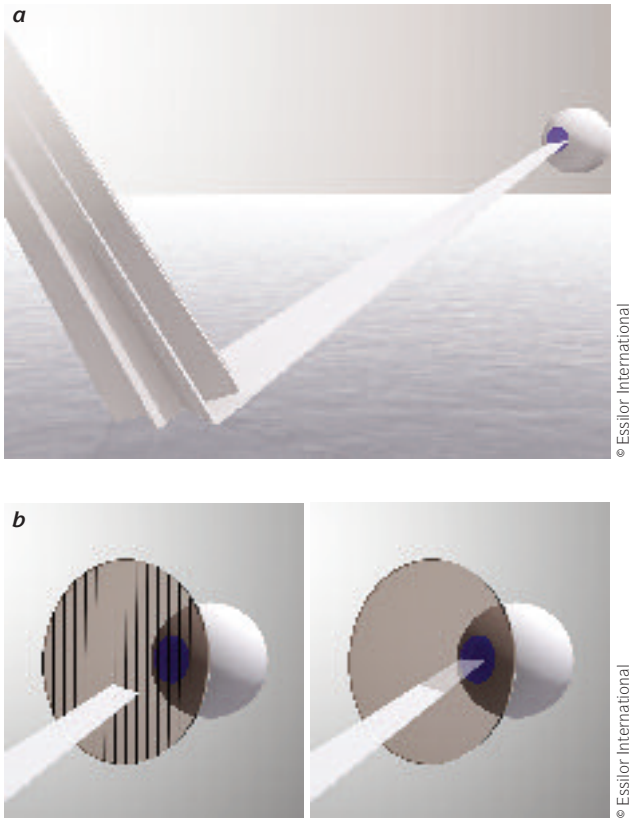

Figure 62: Principle governing how a polarising lens works:
a) Polarisation of reflected light
b) Elimination by a polarising filter.

The benefits of polarising lenses

Polarising lenses provide sunglass wearers with three essential benefits: a reduction in glare, improved three-dimensional perception and better discernment of colours. These three benefits come from the elimination of the horizontally reflected light. In fact, not only is this re-emitted, reflected light very intense and an important cause of glare, it is also bothersome because it superimposes itself on the light coming from the object being looked at. By selectively eliminating this light, an important cause of glare is removed as well as a component of light that interferes with contrast. Vision thus becomes more comfortable and pleasant due to the reduction in visual fatigue caused by glare and the improvement in the visual contrast of objects.

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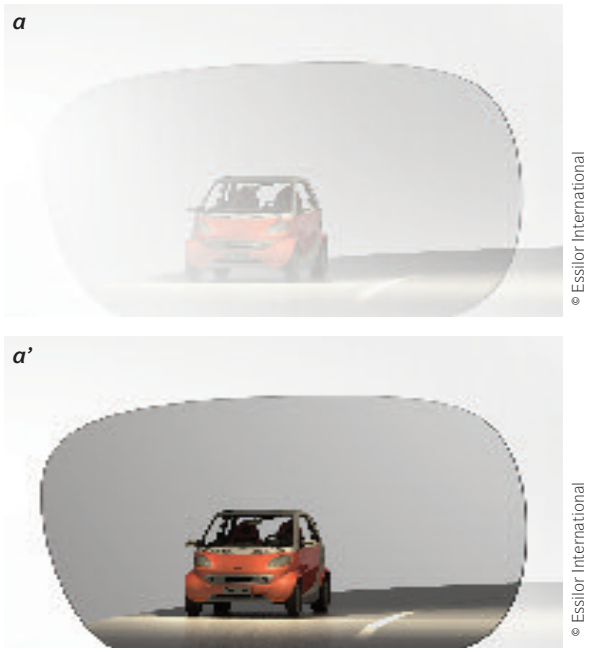

Figure 63 : Effects of polarising lenses:
a-a') Anti-dazzle
b-b') Increased contrast.

In comparison, traditional sunglass lenses help reduce glare from the sun and its reflected light by reducing the overall level of visible light transmission; they do not specifically deal with interfering reflected light, so the visual comfort they provide is more limited than that offered by polarising lenses.

As for the qualities polarising glasses possess as filters, it is worth noting the following:

- light attenuation is in part provided by the very principle of polarisation, which is the elimination of all waves that don't vibrate in the vertical plane;
- polarising films are always tinted: they are most often grey, grey-green or brown, but they can also have other colours and their intensity can go up to category 3;
- a polarising filter does not intrinsically protect against UV radiation: this property depends on the qualities the lens material possesses and/or the particular coating applied to the material.

It's also worth pointing out that the use of polarising lenses can give rise to certain particular phenomena:

- some car windscreens may appear blue or purple due to the polarisation of the light transmitted through the windshield, which results from its composition or treatment;
- a major reduction or even the disappearance of light while watching LCD and plasma screens (like those used by GPS devices, telephones, laptops, televisions, etc.) due to the polarised light that they emit; this problem has now been resolved by polarising light at an oblique angle instead of horizontally.

How to recognise a polarising lens

It is relatively easy to check whether a lens is polarised or not: all you have to do is to look through the lens and observe the intensity of light reflected off a polished surface such as the bonnet of a car, for example, or light emitted from an LCD or plasma screen: if the light diminishes or disappears at a certain angle when you rotate the lens and then returns to its maximum intensity when the lens is once more perpendicular, the lens is polarised; if the intensity of light remains constant throughout the rotation, the lens is not polarised.

Polarising lenses can be made, for example, by using stretched polyvinyl acetate (PVA) films that are darkened with dyes and whose intensely stretched molecules polarise light. For ophthalmic lenses, whether afocal sunglass lenses or corrective lenses, the polarising effect is obtained by inserting a very thin polarising film into the interior of the lens during manufacture (see the Supplement which follows). It is important to note that this film works in a particular orientation; therefore, the axis at which a prescription is adjusted must be taken into account during its insertion into the lens (the axis of astigmatism or orientation of a progressive lens, for example). Because of this, semi-finished blanks of polarising lenses are supplied with permanent markings (engravings) and temporary markings (paintings) which ensure proper orientation during blocking prior to surfacing. Polarising lenses are made mostly from CR39 and polycarbonate, but they also come in high-index plastic and glass.

A variety of applications for polarising lenses has been found for sunglass wearers thanks not only to the reduction in the intensity of light, but also the reduction of glare and improved visual contrast. Drivers, fisherman and water-sport enthusiasts in general have a particular interest in eliminating the light reflected off wet roads or bodies of water.
Although polarising lenses have enjoyed great success with afocal sunglass lenses, their application in sunglasses with corrective lenses – single vision or progressive – is more recent and still not widespread. The Xperio™ range of lenses, whose name signifies "eXperience the outdoors like never before", was designed to develop and expand this market.

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d. Special filters

These filters are designed to selectively transmit certain wavelengths of radiation and partially or totally absorb others. These filters can play two different roles:

- a protective role by reducing or eliminating certain harmful wavelengths of light and/or decreasing the light energy that enters the eye;
- an enhancing role by selectively transmitting certain wavelengths that will improve a wearer's perception.

Below is a description of just some of the many filters that exist:

Ultraviolet light filters

Filters improving the natural UV absorption characteristics provided by plastic and glass lens materials can be used to increase protection against this type of radiation. For lenses that will be worn on a permanent basis, filters are desired that only slightly reduce the transmission of the visible spectrum. For example, the UV cutoff of a traditional plastic material like CR39 is 355 nm; however this can be increased to 400 nm by applying a surface coating containing a UV filter and a slight brown category 0 tint (Figure 64a), which prevents the lens from taking on a yellowish tint.
Plastic is generally considered a better UV filter than glass, and among plastics, higher-index materials such as polycarbonate are better UV filters than CR39.

Contrast-enhancing filters

These filters absorb ultraviolet and blue light while specifically transmitting the central portion of the visible spectrum. For example, a filter with a light yellow tint (category 1) eliminates the diffusion of blue light and specifically transmits wavelengths nearing the eye's maximum level of sensitivity (Figure 64b). This enhances visual contrast in overcast weather and is useful for drivers, hunters and those in mountainous areas. Likewise, a more intense yellow-orange filter from category 1, 2 or 3 will filter UV and blue light up to 400, 445 and 455 nm respectively and specifically transmit the middle portion of the spectrum (Figure 64b). This type of filter can be used to improve vision and comfort for those who suffer from amblyopia or aphakia.

High absorption filters

These filters absorb UV radiation and the lower portion of the visible spectrum while transmitting only the upper portion. For example, a coating with a dark red-brown tint (category 3 or 4) that blocks all radiation up to 445 nm (category 3) or 560 nm (category 4) and selectively transmits the upper portion of the visible spectrum reduces stimulation of the retinal rod cells and eases the strain on the scotopic system (peripheral retina) while maintaining visual acuity (Figure 64c).

Numerous filters can be used with afocal or corrective CR39 plastic lenses. They can be effective for patients suffering from amblyopia, aphakia, albinism, ARMD, diabetic retinopathy, retinitis pigmentosa or glaucoma. These filters provide protection against UV radiation, enhance visual contrast, improve visual comfort and sometimes even provide enhanced visual acuity. Unfortunately, there is no direct relationship between the characteristics of these filters and the specific visual damage suffered or the comfort that they may provide. The most appropriate tint and tint intensity for a patient can only be determined by testing in real-life conditions using additional removable lens faces.

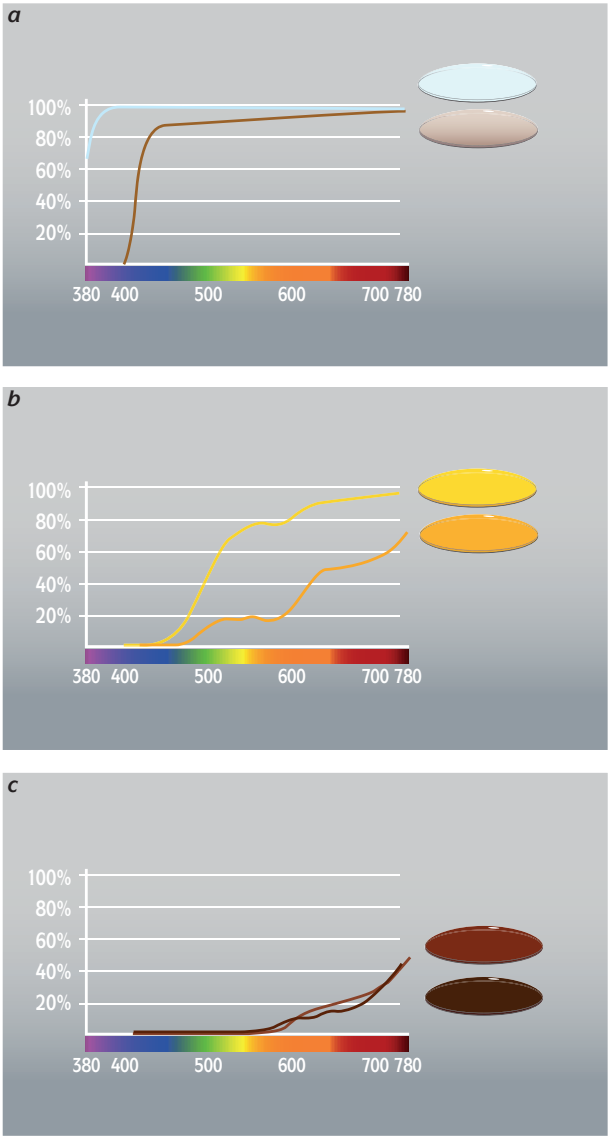

Figure 64: *Transmission curves for special filters:*
a) Orma (UVX®) UV filter
b) Yellow (Kiros®) and yellow-orange (Lumior®) filters
c) Red-brown (RT®) filter.

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Supplement

Manufacturing technology of filter lenses with fixed transmission

Solid tinting vs surface tinting

From a manufacturing point of view, there are two major types of tinted lenses:

- solid tints, in which the lens material itself is tinted prior to surfacing
- surface tints, which consists in applying a tinted coating after surfacing.

These two techniques can be applied to both plastic and glass lenses; choosing one technique over the other depends of course on the materials, but also on logistical constraints – specifically the volume of lenses to be manufactured. On the whole, one could say that most afocal sunglass lenses are manufactured with solid tints while most corrective sunglass lenses come with surface tints.

A. Plastic lenses

1. Solid tinting

Solid tinted plastic material is used exclusively for manufacturing afocal sunglass lenses; it is hardly ever used any more for corrective lenses. For thermosetting materials, different coloured dyes are added to the monomer during its formulation and before polymerisation. For thermoplastics, particularly polycarbonate, dyes are either incorporated directly into the polymer granules during manufacture or when the polymer is melted prior to being injection-moulded. UV absorbers are generally incorporated into these materials as well in order to increase protection against this type of radiation. Solid tinted plastic allows plano sunglass lenses to be mass produced in all tints and intensities.

2. Tinting by impregnating the lens surface

This technique consists in impregnating the lens surface with coloured dyes. Lenses are immersed in a solution containing these dyes and various additives that foster the colouring process. The coloured dyes penetrate the lens material to a depth of 6 to 10 microns. Tinting is most often performed before any scratch-resistant coating is applied.

Tint intensity is determined by the type of coloured dye used, its concentration and the lens immersion time: from 1 minute for lighter tints up to 2 hours for the darkest tints. Tint colour is determined by the relative concentrations of the three dyes colours – red, yellow and blue – which offers an unlimited possibility of shades. Furthermore, tints can be uniform over the entire lens, have a colour gradient from top to bottom, a double-gradient starting at both the top and the bottom, and even a "triple" tint by applying a double gradient tint over a uniformly tinted lens! Gradient tints are obtained by slowly removing the lens from the tint bath. In this process, the lens is held upside-down by a lens holder, completely submerged into the bath and then removed very slowly: the top part of the lens, which spends the most time in the bath, becomes impregnated with more dye than the bottom part, thus creating the gradient.

Plastic lens tinting offers many possibilities, and it can be done relatively easily: lenses can be tinted individually, in pairs or by the batch by copying benchmark lens tints. The operator's experience and "eye" for colours are essential: tinting plastic lenses is a true craft if not an art!

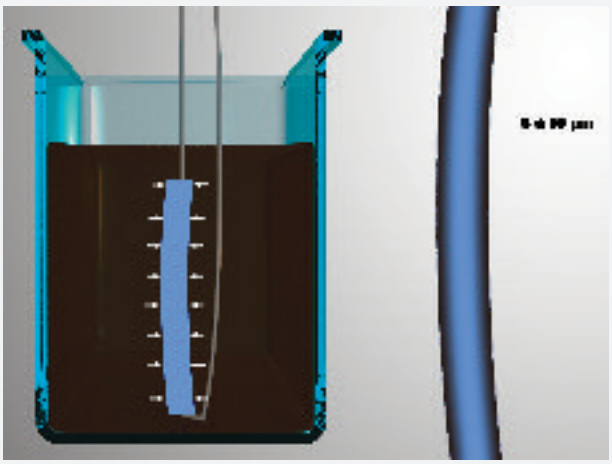

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Figure 65: *Tinting plastic lenses by impregnating the lens surfaces.*

3. Tinting by impregnating the lens surface with varnish

Although CR39 is easily penetrated by coloured dyes, this is not the case will all materials, especially thermoplastics like polycarbonate. Different tinting techniques are therefore available for these materials according to the absorption qualities sought after. For example, these techniques consist in blocking UV radiation at the surface by diffusing coloured dye throughout the lens from the lens surface or by applying a special varnish on the back lens surface that can receive colour and then impregnating it with coloured dye.

4. Dye sublimation tinting

This newest tinting process is performed in the following manner: the coloured dye used to impregnate the lenses is printed on a special sheet of paper that is placed over a series of lenses in individual round holders resting on a tray. The tray is then passed through a vacuum furnace which causes the dye to pass from a solid state to a gaseous state (sublimation) which is deposited onto the lens surface. The lenses are then placed in an oven for several hours at 150 °C, which allows the dye to migrate through the lens surface and become fixed in the substrate.

This dye sublimation tinting process, which was initially developed for tinting very high-index plastics that cannot be tinted by dip coating, may herald a new era in lens tinting. Besides opening up the possibility of tinting new materials, it also has the advantage of being a "clean" process: since printed sheets are used instead of chemical powders, there is no risk of dangerous fumes, no need to change or replace the tint baths and no water consumption. This process thus has all the benefits required for development in the long term.

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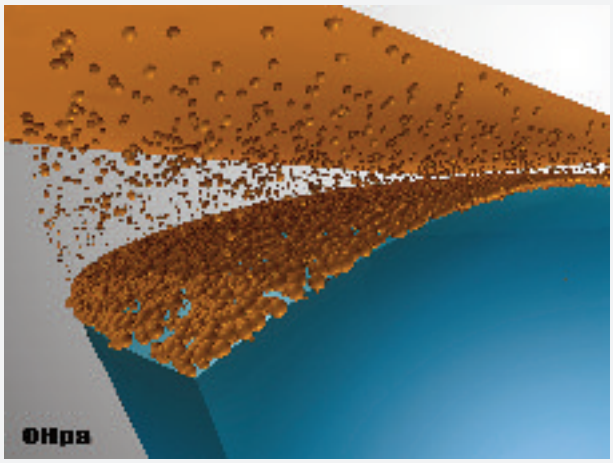

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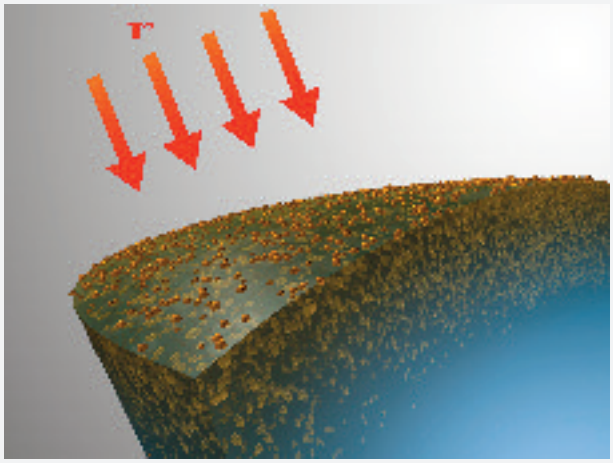

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Figure 66: *Dye sublimation tinting.*

5. "Dyeing" by inserting a film

Polarising lenses present a special case for lens "dyeing": these lenses are tinted by inserting a very thin film of coloured polyvinyl acetate (or (PVA) with a thickness of approximately 35 to 40 microns into the middle of the plastic lens. For prescription lenses, two different techniques are used during manufacturing:

- embedded film technology, which is used for thermoplastics (CR39®, for example): this technique consists in inserting a polarising film into the mould, pouring the monomer over the film to submerge it and then proceeding with the polymerisation process.

- wafer technology, which is used for polycarbonate lenses: this technique consists in manufacturing very thin polarising films composed of a polarising film sandwiched between two fine layers of polycarbonate for a total thickness of approximately 0.6 mm. This film composite is then placed on the front surface of the moulds (inserts) which in turn are put into the injection moulding press.

In both cases, the polarising film is sandwiched between two layers of material. These two processes are essentially used to manufacture semi-finished single vision or progressive lenses whose back surfaces will be surfaced later. Identical techniques are used to manufacture polarising sunglass lenses, but on a large scale.

It must be borne in mind that polarising film has a particular orientation (vertical polarisation axis) and must be inserted into the lens taking into account the axis of any possible astigmatic prescription or the orientation of a progressive lens surface. In consequence, although the logistics of manufacturing polarising lenses proves to be relatively simple for afocal sunglass lenses (that can be oriented at a later time), it turns out to be much more complex for corrective lenses (that must be oriented during their manufacture).

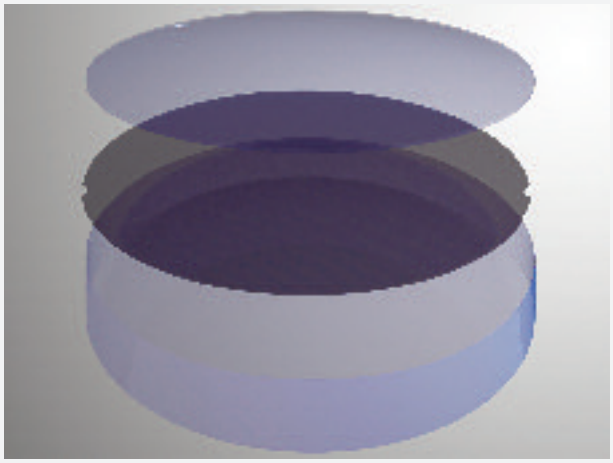

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Figure 67: *Polarising lenses: insertion of a polarising film into a lens.*

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B. Glass lenses

1. Solid tinting

The solid tinting of glass is done by incorporating metallic salts with specific absorption properties such as nickel and cobalt (purples), cobalt and copper (blues), chromium (green), Iron, cadmium (yellow), gold, copper, selenium (reds), etc. into the glass composition. These solid tinted materials are used essentially for the mass production of afocal sunglass lenses and protective lenses. Materials with a slight solid tint – in brown, grey, green or pink – also exist, particularly as filters used in the manufacture of corrective lenses; however, their use today is quite limited since they have the drawback of providing an intensity level which is a function of the thickness of the glass; they have thus been replaced by plastic lenses.

2. Surface tinting

The surface tinting of glass lenses consists in depositing a coating of metallic composites onto a lens surface in a vacuum. The lenses are then heated to 200-300 °C, and the coating is deposited by evaporation in high vacuum (10^{-5} millibars). These metallic composites can be chromium, molybdenum or titanium oxides mixed with silicon monoxide or magnesium fluoride, for example. Depending on the material used and the desired colour intensity, the coating can be one thick, continuous layer or a series of alternating thin layers whose total thickness equals approximately 1 micron. Tint intensity is determined by the thickness of the applied layer while its colour is defined by the materials used: oxides generally produce brown tints while grey tints are obtained from mixing metals with transparent compounds such as silica. The deposited layers have a uniform thickness in order to give the lens a uniform tint. The possible palette of colours is relatively limited. The technology used for vacuum tinting glass lenses is sophisticated and similar to that used for anti-reflective coatings.

4. Filter lenses with variable transmission

a. General principles of photochromism

The protection provided by a protective lens with fixed transmittance is effective, but its drawback is that such lenses cannot be used in all circumstances: filters in the sunglass lens category are too strong for indoor use while those with low intensities are too light for outdoor use. Photochromic lenses, whose transmission varies with the intensity of light and thus adapt to diverse lighting conditions, are therefore a solution to this problem. Besides their ability to filter out visible light, these lenses also eliminate all UVA and UVB radiation. When worn permanently, these lenses provide true protection for the eyes and can contribute to preserving a wearer's optimal vision over the long term.

From a technical point of view, the fundamental property of photochromic lenses (from the Greek "photōs" (light) and "khrōma" (colour)) is the ability to darken when subjected to ultraviolet radiation and revert to the clear state in its absence and under the effect of ambient heat. The reversible nature and the transmission characteristics of these lenses oscillate between two extremes: the clearest state, called "inactivated" and the darkest state, called "activated". From a chemical point of view, photochromism is the reversible transformation between the two states that provide lenses with varying transmission properties and colour. Photochromism operates in the following manner: ultraviolet radiation (wavelengths between 340 and 380 nm) contains the energy necessary to initiate the chemical transformation which darkens the lens whereas removal from the source causes the lens to return to its initial clear state.

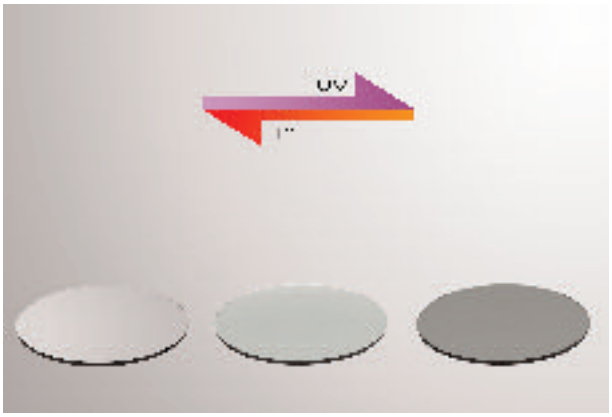

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Figure 68: *General principles of photochromism.*

Several consequences arise from these general principles:

- since the photochromic effect is activated by UV, a photochromic lens can darken in the absence of direct sunlight such as when the sky is overcast, for example:
- since the intensity of the tint results from the equilibrium between the number of molecules activated by the UV radiation and those molecules deactivated by heat, a photochromic lens tends to darken less in hot conditions than in cold conditions.
- since the darkening effect is activated by UV radiation, which is partially or totally blocked by windows, photochromic lenses do not work indoors and, more significantly, darken very little if not at all behind a car windshield (except for a special type of lens activated by visible light, but which, in consequence, always retains a light tint).

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b. Photochromism in plastic lenses

Plastic photochromic lenses have appeared fairly recently: their popularity only took off in 1990 with the introduction of the first Transitions® lenses – this more than 25 years after the introduction of the first photochromic glass lenses. The principles of glass photochromism weren't applicable to plastic since their molecular sizes and structures are different; other molecules therefore had to be found. For plastic lenses, the photochromic effect is achieved with photosensitive components introduced into the material itself or deposited as a layer onto the lens; when subjected to specific UV radiation, these composites undergo a change in structure that modifies their absorption properties for visible light. Several families of molecules are used whose structural changes can occur in different ways: the formation or breaking of molecular bonds, isomerisation, etc.

The principle on which a photochromic molecule used in Transitions® lenses operates is illustrated in figure 69: when subjected to UV radiation, the molecule opens up and spreads out on the lens surface so that it temporarily adopts a flat configuration in which the maximum displacement of electrons is achieved, this in turn produces a high absorption of visible light that causes the lens to darken. Once this UV stimulation ends, the molecule returns to its original clear state.

Plastic photochromic lenses use several types of molecules simultaneously whose combined effect can create, depending on their proportions, the grey or brown tints that wearers desire.

The development of plastic photochromic lenses has been such that several versions are now available—such as a less intense version with faster kinetics currently available in new tints (Transitions® Light)—that offer customers the possibility to choose their photochromic lenses according to their particular tastes and lifestyles.

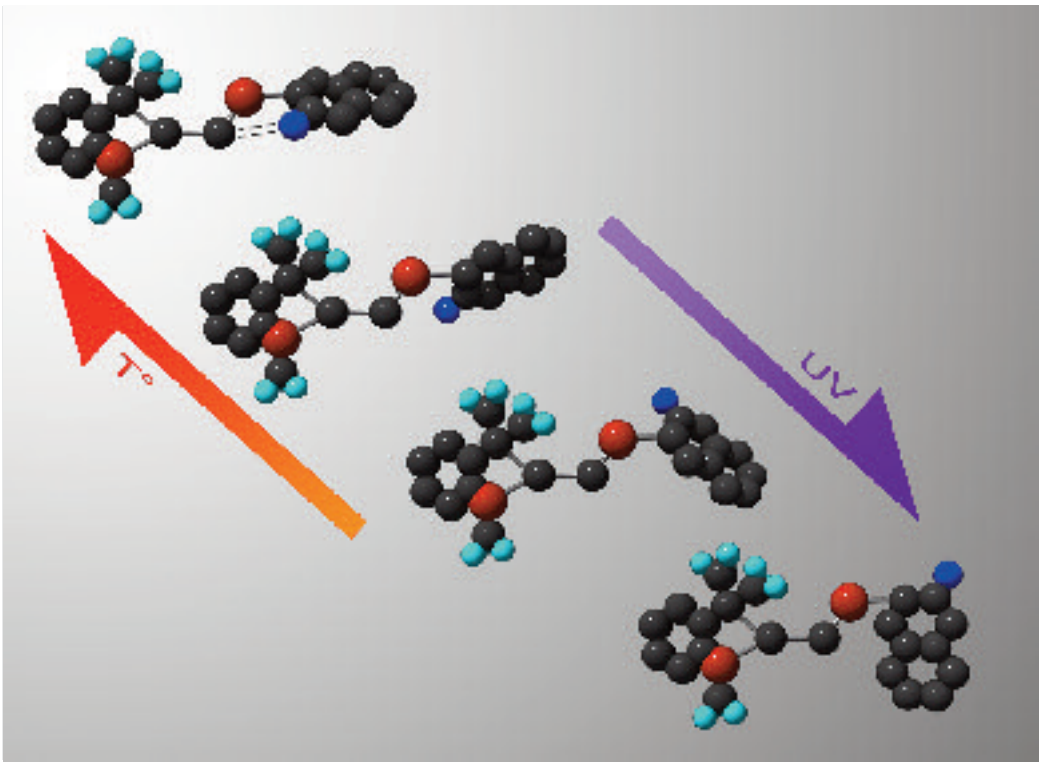

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Figure 69: *Principle on which plastic photochromic lenses operate.*

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Supplement

Characterisation of photochromic lens properties

Transmission in the clear and darkened states

The light transmission properties for a photochromic lens are accurately described by its transmission curves and τ_v coefficients as measured in both its clear and darkened states; from this, we can also establish a perfect description of the variations in transmission created by the photochromic phenomenon. The latest generations of plastic photochromic lenses have remarkable performances: these lenses can achieve absolute transparency in their clear state (τ_v > 90%) as well as a category 3 solar tint in their darkened state (τ_v < 20%) at a mild ambient temperature.

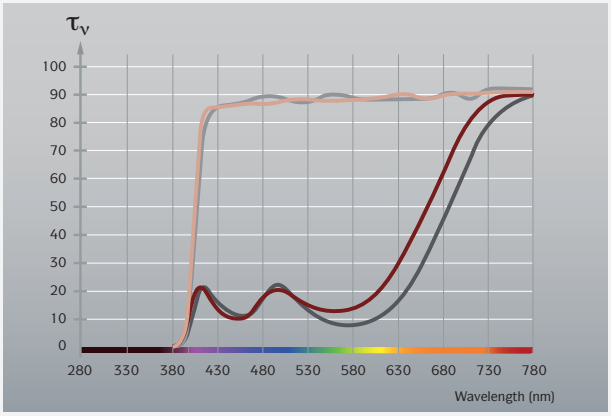

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Figure 70: *Transmission curves for both clear and darkened states (Transitions® VI Grey and Brown) (Source: Transitions® Optical).*

Darkening and fading kinetics

The photochromic properties of a lens are generally represented by graphs of its darkening and fading curves. These graphs show the change in τ_v as a function of time during the lens' darkening phase and fading phase at 23°C/73°F. As seen in the example in Figure 71, τ_v decreases during the darkening phase and increases during the subsequent fading phase. The slope of the curves shows that darkening takes place much more rapidly than the subsequent fading.

Colour stability

A lens obtains its photochromic effect from photosensitive molecules that are stimulated by ultraviolet radiation. Several molecules are used together for plastic photochromic lenses (Transitions® VI lenses use 5 to 7 different molecules depending on the version) and each molecule absorbs a specific portion of the visible light spectrum. If these molecules do not react at the same speed, the lens will vary in colour during the photochromic process (the "chameleon" effect) This effect, which was observed during the first generation of plastic photochromic lens development, has been almost eliminated over subsequent generations.

Sensitivity to climatic conditions

A rise in temperature naturally stimulates the fading process of a photochromic lens and ensures that the darkening phenomenon will reverse itself. The photochromic tendency to darken with UV radiation conflicts with the fading effect produced by heat whereby the same amount of UV radiation will tend to darken a photochromic lens more as temperature decreases. The same photochromic lens will thus appear darker in winter in the mountains than in the summer on the beach! To quantify this effect, a lens' capacity to darken is measured during different climatic condition simulations, particularly in high temperature conditions (35°C/95°F). The different darkening curves show the extent to which real-life climatic conditions affect the photochromic phenomenon.

Change over time

The photochromic properties of plastic lenses change over time since the photochromic mechanism's amplitude tends to decrease due to the oxidation of the photosensitive molecules: after a few years, a lens will darken slightly less than it did when first manufactured. It is thus interesting to measure the true amplitude of this change in the laboratory. This is done by selecting a lens immediately after its manufacture and measuring its darkening and fading kinetics. The lens is then subjected to artificial aging by exposing it to intense UV radiation for 200 hours. The photochromic kinetics are then measured once more and compared to the original measurements in order to quantify the change in its properties.

All measurements of these photochromic lens properties made in the laboratory are done using a sophisticated instrument whose purpose is to artificially recreate the real-life climatic conditions in which the lenses will be used.

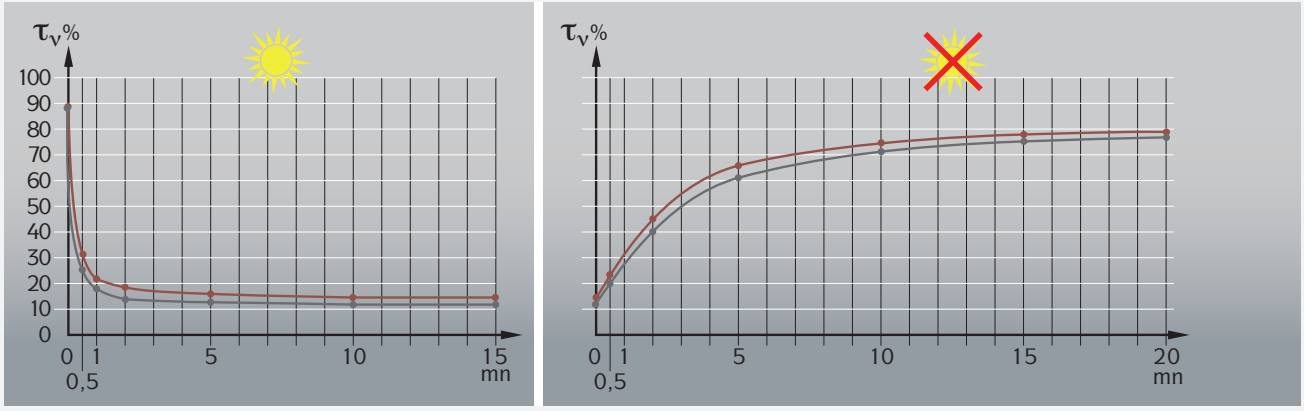

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Figure 71: *Darkening and fading kinetics (Transitions® VI Grey and Brown) (Source: Transitions® Optical).*

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Photochromic performance in plastic lenses

Plastic photochromic lenses have improved considerably over succeeding generations. As an example, the performance data for Transitions® VI lenses will be illustrated:

- As transparent as a clear lens in its inactivated state (figure 72a): in its clear state, a photochromic lens provides approximately 90% light transmission, which increases to 95% if it has an anti-reflective coating. A photochromic lens thus proves to be perfectly clear in its inactivated state, and with an anti-reflective coating, even more transparent than an uncoated clear lens! Also, it is worth noting that an anti-reflective coating enhances the photochromic phenomenon by increasing the intensity of the light which penetrates the lens; this is why, apart from the improvement in lens transparency, anti-reflective coatings are especially recommended for photochromic lenses.

- As dark as a sunglass lens in its activated state (figure 72b): in its darkened state, lens transmission decreases to approximately 12 to 15% after 15 minutes of total activation at 23°C/73°F, thus classifying it as a category 3 filter. Consequently, photochromic lenses can easily rival traditional sunglass lenses; note that a grey tint darkens slightly more than a brown tint.

- Very fast darkening kinetics (figure 72c): after 30 seconds of activation, lens transmission decrease to approximately 30%; after 1 minute it drops to 20% and after 2 minutes to 15%. This shows how quickly the photochromic phenomenon takes place—near-total darkness is achieved in less than 2 minutes.

- Improved fading kinetics after darkening (figure 72d): the time necessary for a lens to return to its clear state is always longer than the time it takes the lens to reach its dark state. This represents the weak point of photochromic lenses despite the fact that the time taken to fade has reduced considerably from earlier generations. In 30 seconds, transmission increases on average from 12-15% to 25%, reaching 45% after 2 minutes. In order to return to 70% transmission after a fully activated state, the lens needs 7 and 9 minutes respectively for brown and grey tints; the return to a clear state requires approximately 20 to 25 minutes.

- Less sensitivity to temperature: the effect which temperature has on photochromic lenses has long hindered their expansion into the lens markets of countries with hot climates, but this is now no longer true: at 35°C/95°F, lens transmission decreases to approximately 30%, with grey tints showing slightly more darkening capacity than brown; the lens thus fall into filter lens category 2.

The performance of plastic photochromic lenses has improved considerably over time, which allows them to be used in any circumstance, whether indoors or outdoors, and ensures that wearers receive permanent, optimal protection against visible and ultraviolet light.

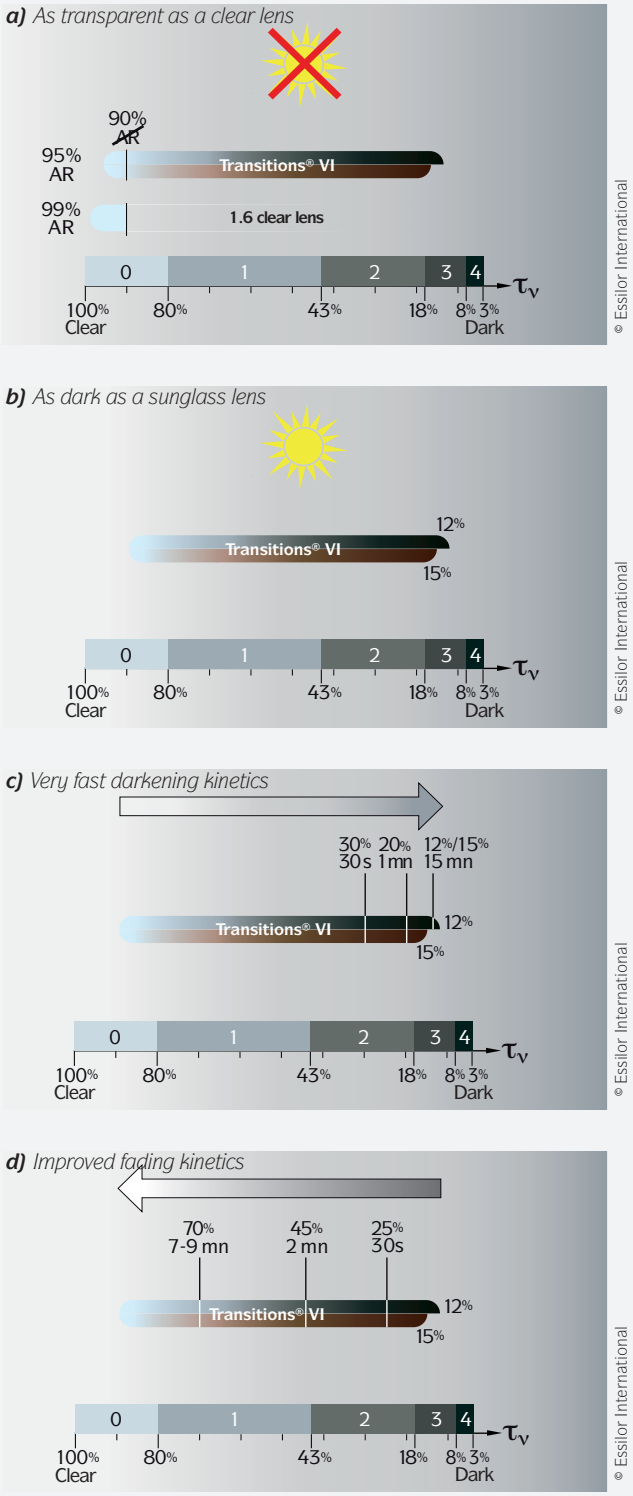

Figure 72: *Performance of photochromic lenses (Transitions® VI) (Source: Transitions® Optical).*

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c. Photochromism in glass lenses

The concept of applying photochromism to glass lenses has been around for many years: It was introduced by Corning Incorporated around 1965 with the introduction of their first Photogray® lenses and improved upon in subsequent generations of lens development. The photochromism effect was achieved in these lenses by incorporating silver halide crystals into the glass that darken when subjected to ultraviolet radiation. At the atomic level, the fundamental mechanism driving this type of photochromism is the exchange of electrons between silver atoms and chlorine atoms—present in the form of silver chloride (Figure 73)—and their immediate environment. In the absence of light, the silver-chlorine bond is ionic and the silver atom is transparent, thus maintaining the lens in a clear state. With UV radiation, the unstable electron breaks from the chlorine ion and attaches to the silver ion, which transforms into its metallic form and thus blocks light; this in turn causes the lens to darken. When the UV radiation decreases or disappears, the additional electron breaks off from the silver atoms, returns to the chlorine atom again and the lens returns to its initial clear state.

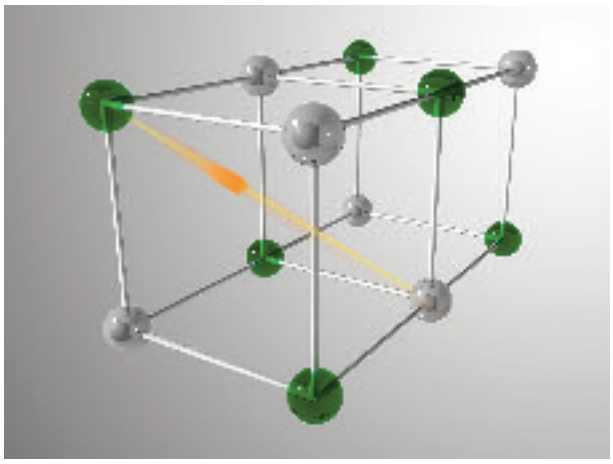

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Figure 73 : *Photochromism in glass lenses.*

Benefits of photochromic lenses

Photochromic lenses provide wearers with two essential benefits: they help in adapting to variations in light intensity and provide permanent protection against harmful radiation.
These lenses adapt to variations in light by automatically adjusting the level of light transmission according to the intensity of sunlight. This helps the eye adapt to changes in light intensity, reduces the effects of glare and thus decreases visual fatigue associated with changing light conditions, problems of which wearers often complain.
Protection against harmful radiation is provided by photochromic lenses' filtering properties, which block out 100% of the UVA and UVB radiation in their clear state and increase protection against blue light in their darkened state. This permanent protection, which increases as the light becomes more intense, does away with the cumulative effects of sunlight that can lead to ocular lesions. Over the long term, photochromic lenses can thus help preserve a wearer's optimal vision.

Even though photochromic lenses have enjoyed increasing popularity, their use is still not widespread. Use differs according to continent: in North America and Australia, 15 to 20% of corrective lenses are photochromic while in Europe the number is 10% and in Asia, 5%. The development and expanded use of plastic photochromic lenses, particularly those from Transitions® Optical, have definitively sealed the success of plastic lenses at the expense of glass lenses. With the performance that the latest generations of lenses have shown, together with the pressing need of each individual to protect optimal vision, it is judged that photochromic lenses will continue to enjoy increasing success.

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Manufacturing technology of filter lenses with variable transmission

1. Plastic lenses

The manufacture of plastic photochromic lenses involves the incorporation of photosensitive dyes into the lenses. Different processes are used to do this:

- imbibition (or impregnation) of the front surface of the lens,
- the deposition of a layer on the front surface of the lens ("trans-bonding"),
- the addition of dyes into the liquid monomer before polymerisation,
- the insertion of a photochromic film ("wafer") into the lens.

Although imbibition technology is widely used in the manufacture of lenses with a refractive index of 1.5, trans-bonding technology is used for high-index plastic lenses and polycarbonate lenses. Due to the predictable growth of high index plastic and polycarbonate lenses and the advantageous fact that the photochromic layer is not dependent on the material on which it is deposited, trans-bonding promises to become the benchmark technology in the industry. Both of these technologies are used for manufacturing Transitions® lenses. The technique of adding photochromic dye components into a monomer before polymerisation is used by certain manufacturers (such as Corning with their SunSensors® lenses). Photochromic "wafer" technology is used very little.

Imbibition is performed on semi-finished lenses manufactured with a material whose chemical composition is adapted to the requirements of photochromism. A varnish containing photochromic dyes is deposited onto the front surface of the semi-finished lens by means of a centrifuge, or "spin-coating". The lens is then placed into an oven at high temperature and the heat causes the structure of the material to "open up"; the dyes then penetrate the material (to a depth of approximately 150 to 200 microns) and remain trapped there after the lens cools. The photochromic varnish, which is now free of its dyes, is then rinsed from the lens surface.

With trans-bonding, a varnish containing photochromic molecules is deposited directly onto the front surface of the lens before any scratch-resistant and anti-reflective coatings are applied; this layer has a total thickness of approximately 15 to 20 microns. The technology used to deposit this varnish onto the lens is similar to that used to apply scratch-resistant coatings. Not only must this varnish provide the lens with its photochromic effect, it must also provide a base for subsequent scratch-resistant and anti-reflective coatings. It must possess the mechanical properties necessary to work harmoniously with the substrate, the scratch-resistant coating and the anti-reflective coating in order to help create a perfectly consistent and resistant lens.

All of these photochromic processes are performed on a large scale in specialised plants before the lenses are sent to be surfaced. After receiving their photochromic coating, lenses are then systematically given a scratch-resistant coating. All lens geometries are possible with photochromic plastic; whether for single vision or progressive corrections, they can be manufactured using the entire range of normal-, mid- and high-refractive index materials.

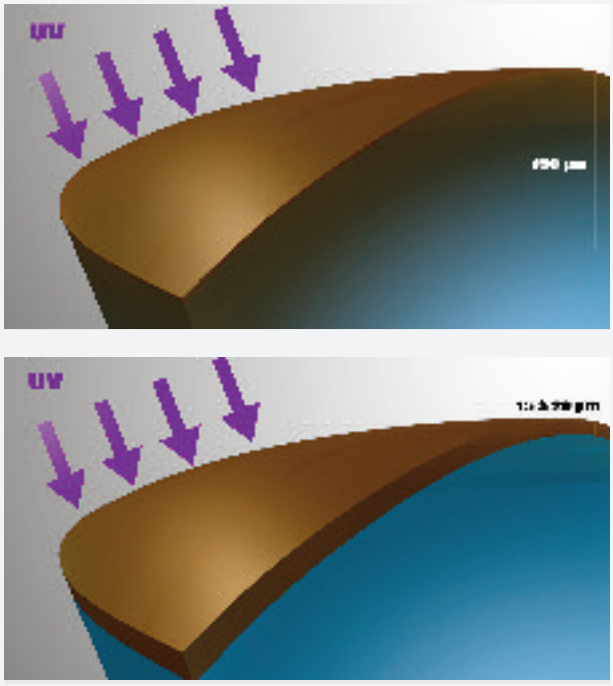

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Figure 74: *Manufacture of plastic photochromic lenses:*
a) By imbibition
b) By trans-bonding.

2. Glass Lenses

For glass lenses, the photochromic effect is achieved by introducing photochromic substances into the material itself, which are, in this case, silver halide crystals. These substances are introduced into the glass by the glass-making industry during manufacture at the moment when the different constituents that make up the glass are fused together at high temperature. The resulting blanks, which possess perfectly homogenous structures yet still have irregular surfaces, are then surfaced both front and back (using the techniques previously described). All lens geometries are possible from these blanks: whether for single vision, bifocal or progressive corrections or for refractive indices of 1.5 and 1.6. In the special case of certain very high index glass lenses, photochromism is achieved with a thin film of photochromic glass that is bonded (that is to say, attached) to the front surface of the lens; use of this type of lens is very limited nowadays.
Generally speaking, since the photochromic dye components are introduced directly into the material itself, glass photochromic lenses possess the same disadvantages as tints do when introduced using an in-mass (solid tinting) process: when activated, the lenses become darker depending on their thickness; plus lenses are thus darker in the centre while minus lenses are darker towards their edges. It goes without saying that the use of glass photochromic lenses, following the use of glass material in general, is in sharp decline – especially so since the performance of photochromic plastic has equalled if not surpassed that of photochromic glass.

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4. Aesthetic qualities and fashion

Wearing spectacles with ophthalmic lenses is most often considered a need or obligation and rarely thought of as a pleasurable experience. In order to make lenses more attractive, increased attention is being given to developing their aesthetic qualities. Moreover, the evolution of frames and fashion trends naturally generates a demand for the evolution of lenses. This demand is particularly expressed by those who wear sunglasses with ophthalmic correction and wish to combine their ophthalmic needs with the latest fashion trends. Eyewear has also become a fashion accessory, so the incorporation of aesthetic qualities must be an integral part of lens design. Three characteristics are given particular attention: lens curvature, tints and reflective features. Each is described in order below:

A Curvature

Two opposing trends have developed with regard to lens curvature: a general demand for flat lenses in order to make them more discreet, and conversely, a demand for high-curvature lenses that wrap towards the sides. These two trends represent a single desire: that of lenses whose curvature is adapted to the frames. Whereas the demand for flat lenses exists mainly for ophthalmic correction, that for curved lenses highlights the demands made for aesthetic, protective and sporting purposes.

Lens curvature and optical quality

Curvature in ophthalmic lenses is an aesthetic demand which raises interesting optical questions. It is important to note that the corrective power of an ophthalmic lens comes from the (algebraic) sum of the positive power of the front surface and the negative power of the back surface, and when purely spherical and toroidal surfaces are employed, there is an optimal combination of curvatures for the two surfaces that reduces optical aberrations (the combination that gives lenses their "best form" according to Tscherning's Ellipse). Apart from this combination, optical aberrations appear – power error and oblique astigmatism – that can significantly alter a wearer's vision when he or she gazes to the side. This is when aspherical lens surfaces are of great service: they allow the curvature of a lens to be modified without altering the optical qualities that correct the eye's optical defect by adding correction to one or both surfaces of the lens. Whereas aspherisation has been used essentially to make lenses flatter and thus thinner, it's worth noting that it is used in curved lenses for the same reasons. In fact, aspherisation constitutes the way to break free, to a relative degree, of the constraints imposed by lens curvature and offer designers an additional amount of freedom in their choice of curvatures.

Furthermore, although curved lenses can lead to optical aberrations laterally, it's worth noting that they are most often mounted in frames that are very curved and whose front has a significant wrap angle with respect to the wearer's face. The wearer's gaze axis meets the back lens surface obliquely and generates optical aberrations – power error, oblique astigmatism and distortion – that are perceived by the wearer along the primary position of gaze. It is thus necessary to compensate for these aberrations during surfacing by adjusting the lens' power and incorporating prism correction into the lens (as with Essilor Openview® lenses). This correction is added step-by-step thanks to digital surfacing technology. These lenses thus possess a measurable power that is slightly different from the prescription and must carry double-labelling that states the "prescription power" and the "actual power" as would be read by the focimeter.

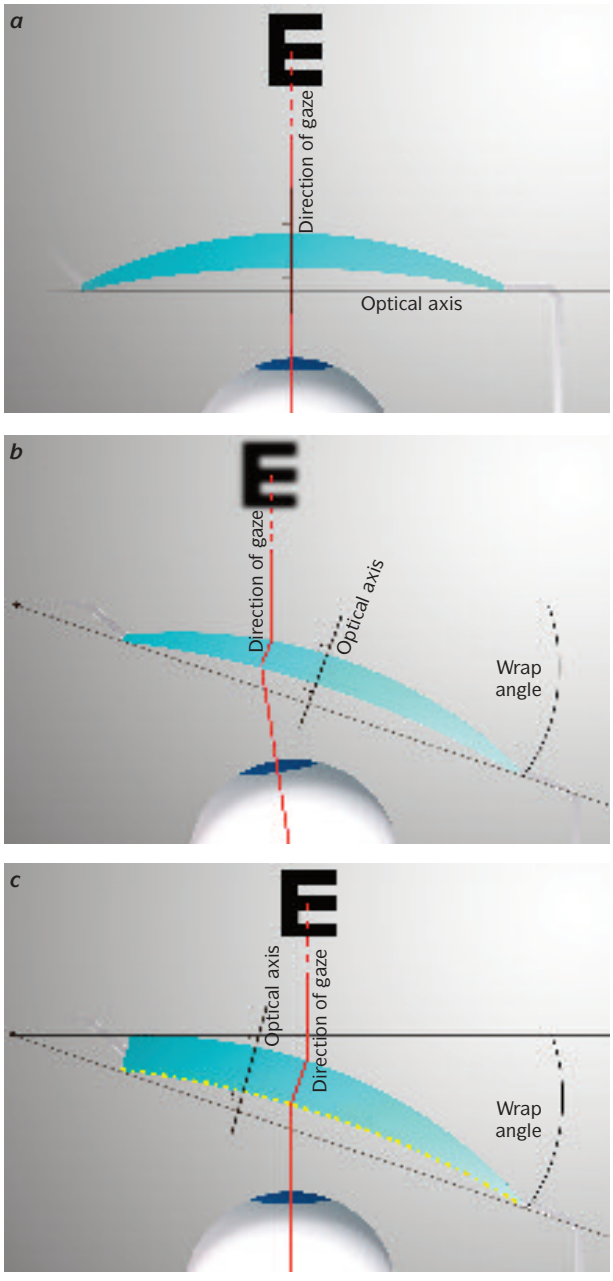

Figure 75: *Lens curvature and optical quality:*
a) Lenses with no curvature mounted in traditional frames
b) Standard curved lenses mounted in wrap frames
c) Curved lenses for wrap frames

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B Tints

Numerous uniform or gradient tints are possible for comfort or fashion needs. These tints are only intended to reduce light transmission slightly, highlight a look, introduce a coloured note to the eyewear or to convey a particular style; they are for the most part, low intensity tints that in no way provide true protection against sunlight. Their light transmission factor most often falls into category 0 (T_V from 100 to 80%) and sometimes category 1 (T_V from 80 to 43%). Depending on the material used, they may or may not be an effective filter against ultraviolet radiation. Apart from the aesthetic aspect, the wearer needs to be well informed of the limited protective properties lenses which these tints provide; the standardised tint categories and their systematic instructions were designed with this end in mind.

A very large palette of tints is possible (for plastic lenses). These tints can vary considerably according to customer taste and frequently change as fashion trends evolve. The tints shown below are but a small representation of the possibilities available!

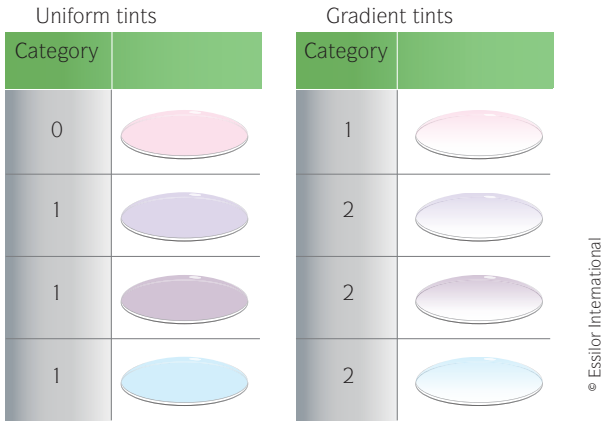

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Figure 76: *Example of a line of fashion tints (Beauty Eyes®).*

As for lens materials, only plastics can offer such a wide variety of tints, sizes, shapes and curvatures. For sports, polycarbonate is the material of choice.

C Reflections

The reflective features of lenses have also been given special attention.
Mirror coating is one of techniques used to contribute to a lens' aesthetic qualities and/or enhance its filtering properties. Mirror coatings can vary in intensity:

- weak to moderate intensities (with approximately 20% reflection) represent basically an aesthetic feature that provides a lens with a mirrored effect that does not affect the appearance of its tint; they only help slightly in protecting against solar radiation.
- high reflective intensities (reflection superior to 60%) act as true mirrors and inhibit an observer from seeing the lens tint; these intensities play a real protective role by eliminating a significant amount of light (this is the case with lenses that provide high solar protection for skiing, for example).

Technically, this mirror coating consists of a layer of metal oxide deposited on the front surface of the lens that, depending on the nature of the deposited layer, can be neutral – which is to say silver – or have a gold or coloured appearance. Mirror coatings are most often applied to tinted lenses, sunglass lenses or fashion lenses and can have a gradient or double-gradient tint.

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Figure 77: *Mirror lenses.*

In addition, thanks to the advanced development of anti-reflective coating technology, it has also become possible to select the colour of the residual reflection in order to satisfy customer tastes or match the colour of the frames.

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Conclusion

Materials & Treatments

As this voyage through the world of ophthalmic lenses comes to an end, we would like to emphasise once more the complex nature of this product that in appearance seems so simple. Today's ophthalmic lenses are a sophisticated and inextricably interwoven ensemble of materials and coatings that provide the wearer with maximum visual comfort; they are a veritable "alchemy of performance".

Researchers, engineers and technicians, whether they be chemists, physicists, opticians, mechanics, logisticians or producers, develop ingenious inventions that continuously improve ophthalmic lens performance. Proof of this lies in the numerous innovations made over the course of the last few decades and the ever-more sophisticated technologies that can be called into use. The technological nature and complexity of ophthalmic lenses is clearly ignored by the general public and, at times, even by eyecare professionals themselves.

There is no doubt that ophthalmic lenses will continue to see numerous improvements in the future that will make them more discreet and more comfortable. These innovations will probably come from technologies developed in other industries, still in their infancy or that do not even exist today. This will surely lead to yet another update of this optics file!

We hope that this volume in our Ophthalmic Optics Files series provides the eyecare professionals with an even better understanding of the "Materials and Treatments" that ophthalmic lenses are manufactured with today. We also hope that this information educates the eyecare professional in how to promote the performance and qualities of these distinguished materials and coatings as well as put them to better use in their work. This translates into being able to make enlightened choices regarding the lenses that are best adapted to the needs of their patients and customers, who will be able to say, "To see more comfortably is to live more comfortably!"

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Appendix

Review of the nature and structure of matter

The study of materials and coatings requires having some basic knowledge of physics and chemistry; a brief review therefore is given below.

The building blocks of matter

The field of physics is built around the fact that all matter in the universe is made up of atoms. These perpetually moving, basic units of matter are themselves made up of elementary particles called protons and neutrons that are bound together in a nucleus that is orbited by even smaller particles called electrons. Atoms, whose radii measure between 0.1 to 0.2 nanometers, are known as the "building blocks" of all matter. Physicists have discovered that no more than a hundred or so distinct atoms exist in the entire universe. Russian physicist Dmitri Mendeleïev (1834-1907) predicted their existence and classified them in a table format before all of them were actually discovered; this classification is known as the periodic table of elements (Figure 78).

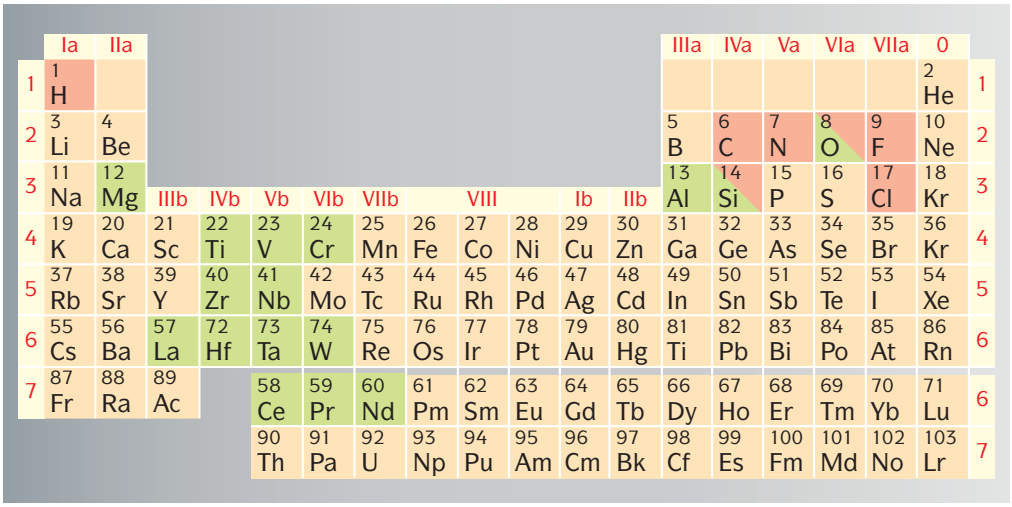

Figure 78: *Mendeleïev's periodic table of elements.*

Bodies of matter are made up of atoms assembled into more or less complex structures that chemists describe in the following manner:

- Elements, which are uniquely distinct atoms: hydrogen, oxygen, carbon, aluminum, iron, sulphur, helium, neon, titanium, etc.
- Compounds, which represent distinct types of molecules, are chemical substances consisting of two or more different elements: water (H_2O), sodium chloride (NaCl), ethyl alcohol (C_2H_6O), silica (SiO_2), etc.

Elements and compounds are called pure substances and are characterised particularly by the temperatures at which they change between the three states of matter – solid, liquid and gas. These temperatures are very precisely defined and represent one of the physical constants of matter.

- Mixtures, which are made up of elements and pure substances that do not bear a fixed proportion to one another and thus impossible to represent with a definite chemical formula: air, steel, glass, rubber, petroleum, honey, blood, etc. The temperatures at which they change states are not fixed and vary according to their composition.

Organic vs. Mineral

The Earth's environment contains materials that have been classified according to their basic atomic composition, which allows one to distinguish between:

- Mineral matter, which consists of the pure substances and mixtures that make up the rocks found in the earth's crust—called "SIAL" and essentially composed of SIlicon and ALuminum—as well as their derivatives. Their molecules are a varied combination of a small number of atoms (from one to around twenty) found on the periodic table. The elements primarily found in ophthalmic optics appear in green on the periodic table in Figure 78.
- Organic matter, which consists of the pure substances, mixtures and their derivatives that come from the vegetable and animal kingdoms along with fossil fuels and synthetic materials obtained from organic chemistry. Organic materials, which are very numerous and complex (living organisms are an example), contain molecules that, although often composed of a significant number of atoms (as many as several thousand) contain only a very small number of elements: essentially C, H, O and N (shown in pink in Figure 78). Carbon (C) is commonly considered the chemical basis of life while H, O and N are the elements in the atmosphere that are essential to maintaining life.

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The three states of matter

Matter can exist in one of three states: solid, liquid or gas.

A drop of water, for example, is composed of H_2O molecules made up of two hydrogen atoms and one oxygen atom.
At ambient temperatures these molecules are in a permanently agitated state yet stay bound together due to the mutual attraction that maintains the drop's cohesion in what is known as the liquid state. Molecular agitation is proportional to the temperature; increased temperature accelerates the movement of molecules and the distance between them grows.
At a certain temperature, intermolecular attraction becomes insufficient to keep the molecules together: the molecules then disperse in all directions in the form of steam, which is the gaseous state. Before our very eyes, the drop of water turns into an invisible vapour and disappears; nevertheless, this vapour is still made up of H_2O molecules.
Conversely, if the drop of water is cooled, molecular movement slows until their intermolecular attraction causes them to stop moving in relationship to one another; this causes the drop to take on a fixed shape: we call this ice, which is the solid state of water. Ice has a regular, periodic structure in the form of a "crystalline network" (Figure 79); the solid state of glass, on the other hand, has a non-periodic structure otherwise known as an "amorphous" structure.

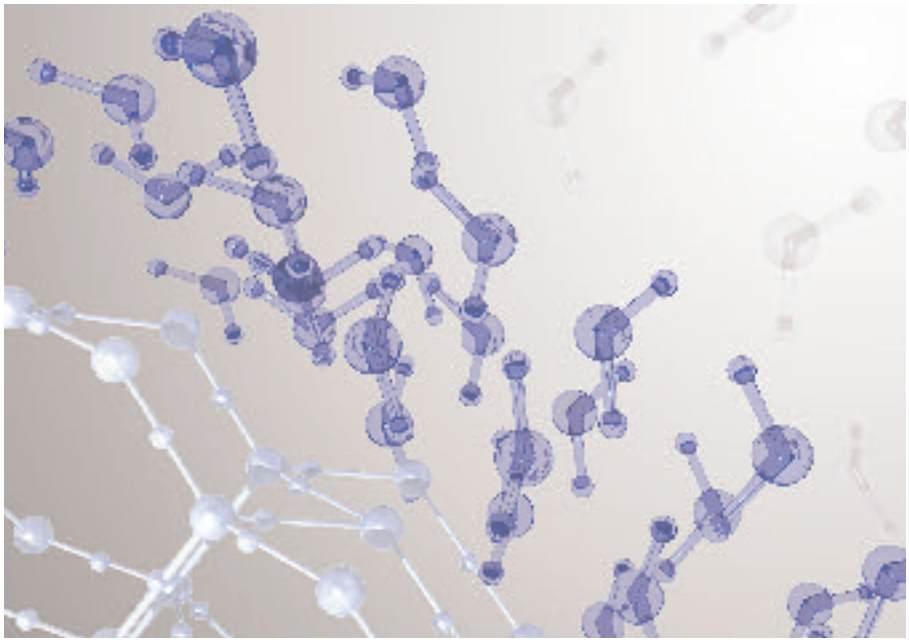
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Figure 79: *The 3 states of matter for water.*

Precise terminology is used to define the passage of matter from one state to another:
- passage from a solid state to a liquid state is called fusion; inversely, the passage from a liquid to a solid state is known as solidification
- vaporisation is what occurs when a liquid passes to a gaseous state; inversely, the passage from a gaseous state to a liquid state is called liquefaction
- direct passage from the solid state to the gaseous state is known as sublimation; the inverse transformation, from a gaseous state to a solid state, is also called solidification.

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