Coatings
This volume of the Ophthalmic Optics Files presents a study of the Coatings applied to ophthalmic lenses. By “Coatings”, we mean all manufacturing procedures and the resultant products designed to enhance the performance of ophthalmic lenses, independent of their power. This File is divided into three parts:

I - tinting (in the broadest sense of the word), including photochromism and special filters,

II - protection against abrasion,

III - antireflection coating and associated anti-tarnish coating.

Each part consists of an analysis of the specific function of each type of coating, and a description of the technology used to meet the given objectives.

It is important to retain a global view of the ophthalmic lens. Indeed, this is an increasingly complex product because of the combination of diverse Materials and Coatings, which are being more and more often integrated into the manufacturing process (figure 1). Consequently, coatings are gradually being considered not so much as optional “extras”, but rather as essential lens components. Indeed, the emphasis is on a greater interaction between the various components to obtain the final performance of the lens. For an overview of the general structure of modern lenses, we thus recommend reading of the Ophthalmic Optics File on “Materials”.
Figure 1: A coated plastic lens is a complex system.
The following description of Coatings draws on notions relating to the “structure of matter” presented in the Ophthalmic Optics File on “Materials”. It also refers to various aspects concerning the nature of light; the main characteristics of light are reviewed below.

At the end of the 19th century, the physicist Maxwell established that, in a general fashion, the material objects which exist in the Universe may exert electric and magnetic influences on each other. Since these influences are inversely proportional to the distance between the objects, they may be exerted over very long distances.

These phenomena have been attributed to an extremely fast oscillation of the electrons present in each atom. This oscillation, called an electromagnetic wave, is able to propagate in a vacuum or in a medium, and to exert electric and magnetic influences by exciting electrons present in the atoms of bodies located far from each other (this is why oscillations of electrons of the Pole Star still have enough influence to excite the electrons in our retina).

The sum of these two phenomena - the oscillation of electrons in atoms, and the propagation of electromagnetic waves over a long distance - is called electromagnetic radiation.

A wave is a perturbation of space which is characterized by the fact that it periodically resumes the same value during its displacement. Its essential values are as follows:
- wavelength $\lambda$ in m (or multiples): this is the distance covered between 2 identical successive states,
- frequency $\nu$ in Hertz (Hz): this is the number of times to the same state per second,
- velocity (in m.s$^{-1}$), in the case of electromagnetic waves, velocity - in a vacuum - is $c = 300000$ km/s = $3 \times 10^8$ m.s$^{-1}$; these 3 values are related by the basic formula : $\lambda = c/\nu$.

Matter which fills the Universe consists of atoms and their electrons which vibrate and continuously emit electromagnetic waves. The frequency of these waves varies enormously, depending on temperature (ratio of 1 to about $10^{20}$). This range of frequencies is called the electromagnetic spectrum, or the electromagnetic wave spectrum. It is made of zones which have been historically defined by their frequency/wavelength (figure 2).

The electromagnetic radiation emitted by the Sun is largely absorbed by the Earth’s atmosphere. Solar radiation which reaches the surface of the Earth is made up of the following rays:
- **ultraviolet rays**, called “UV-A” (315 to 380 nm), well-known for their tanning effect, and “UV-B” (280 to 315nm), which cause sunburn and ocular disorders (e.g. snow blindness). Ultraviolet radiation contains a third area called “UV-C” (200 to 280 nm); this very dangerous component is fortunately stopped by the Ozone layer surrounding the atmosphere.
- **visible light** made up of waves which, after going through the intra-ocular media, stimulate the retinal receptors; their wavelength ranges from $\lambda = 380$ nm (violet) to $\lambda = 780$ nm (red).
- **infrared rays** with wavelengths ranging between $\lambda = 780$ nm and $\lambda = 2000$ nm. Infrared radiation goes up to $\lambda = 1$ mm, but is stopped by the water vapor in the atmosphere.

Visible light is an area corresponding to a specific and remarkable band of waves within the vast electromagnetic spectrum which fills the Universe. These waves are remarkable in that they interact with our eye, and thus allow us to see the world.

Natural light emitted by the Sun, and perceived by the brain as white, is made of a continuous spectrum of radiations, each of which creates perception of a color. This range of colored rays can be seen in a rainbow, where each ray is characterized by its specific wavelength $\lambda$ (figure 2).
Figure 2: Electromagnetic waves and light.
A/ General remarks

1/ The principle underlying protection

The human eye possesses a number of natural anatomical or physiological defense mechanisms, ensuring protection against light. These mechanisms include the closing reflex movement of the eyelids, the reduction in pupillary diameter, the filtration of transparent media (tears, cornea, aqueous humor, lens), retinal adaptation to luminous intensity, etc. But this natural defense may be insufficient, in which case extra protection is obtained through the use of a filtering lens, either permanently, to improve wearer comfort, or specifically, to protect against harsh luminous radiation. The filtering lens has a twofold role: to reduce intensity of the light which reaches the eye, and to eliminate dangerous rays by absorbing them. It may have a permanent tint, i.e. present as a single color lens with a full or graduated tint, or its tint may be variable, i.e. photochromic.

2/ Lens classification as a function of luminous transmission

Any light filter can be characterized by its physical light transmission properties - transmission factor $\tau$, transmission curve and U.V. cutoff - and by its ensuing physiological properties: relative transmission factor in the visible $\tau_V$. The latter factor complies with a standardized international definition and is used to classify lenses into 5 categories based on their light transmission: from 0 for the lightest to 4 for the darkest lenses (table 1). The classification criteria do not only refer to the lens transmission properties in the visible range, but also in the UV-A and UV-B ranges. These criteria are established for 2.0 mm thick plano lenses and a normal light incidence.

Table 1: Lens classification as a function of luminous transmission.

<table>
<thead>
<tr>
<th>Filter category</th>
<th>Ultraviolet range of the spectrum</th>
<th>Visible range of the spectrum</th>
<th>Former French classification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum value of solar UV-B transmission $\tau_{SUVB}$</td>
<td>Maximum value of solar UV-A transmission $\tau_{SUVA}$</td>
<td>Light transmission interval</td>
</tr>
<tr>
<td></td>
<td>280 nm - 315 nm UV-B %</td>
<td>315 nm - 380 nm UV-A %</td>
<td>from %</td>
</tr>
<tr>
<td>0</td>
<td>$\tau_V$</td>
<td></td>
<td>80.0</td>
</tr>
<tr>
<td>1</td>
<td>$\tau_V$</td>
<td></td>
<td>43.0</td>
</tr>
<tr>
<td>2</td>
<td>0.125 $\tau_V$</td>
<td></td>
<td>18.0</td>
</tr>
<tr>
<td>3</td>
<td>0.5 $\tau_V$</td>
<td></td>
<td>8.0</td>
</tr>
<tr>
<td>4</td>
<td>1.0</td>
<td></td>
<td>3.0</td>
</tr>
</tbody>
</table>
The tint of a lens is determined by the chromatic composition of the light it transmits (except for mirrored lenses). It results from the summation of visible radiation by the receiving observer’s eye.

It is difficult to precisely assess lens transmission properties based on tint alone. Nevertheless, certain general principles hold good (see figure 3):
- a grey tint transmits visible radiation more evenly,
- a brown tint is more absorbent in the blue-green range of the spectrum than in the orange-red range,
- a green tint is more absorbent in the orange-red range than in the blue-green range,
- the tint intensity shows the extent of absorption in the visible range,
- tint provides no indication of absorption in the ultraviolet or infrared ranges.

Conversely, it is difficult to predict the color of a lens from its transmission curve. The choice of tint is a function of absorption properties required, and may be determined by the wearer’s ametropic tendency (a myope may prefer brown, and a hyperope may prefer green), but is also a function of the wearer’s own taste.

**Figure 3:** Transmission curves.
B/ Fixed tint lenses

The filtering properties and characteristics of the various tints have been described above. This section will focus on the techniques used to tint glass and plastic lenses, and on their respective properties.

1/ Fixed tint glass lenses

Solid tinting

Solid tint glass lenses are manufactured directly from rough blanks of tinted material supplied by the glass-making industry. The drawback of this method is that powerful lenses present an uneven tint. Indeed, since absorption is exponentially proportional to thickness of the material (Lambert’s law), minus lenses are darker at the edge than at the center and, conversely, plus lenses are darker at the center than at the edge. This major drawback has been the downfall of such lenses, which have now practically disappeared from the market. The only area where solid tint glass is still widely used is for making plano sun lenses.

Tinting by vacuum coating

Vacuum tinting of glass lenses consists of depositing a layer of light-absorbent metallic compounds on one side of the lens. The lenses are heated to 200-300 °C/440-570 °F, and the coating is applied under vacuum by evaporation ($10^{-5}$ mbar) of materials such as Chromium, Molybdenum or Titanium oxides mixed with silica, Silicium monoxide, or Magnesium fluoride. Depending on the materials used and the required color, the coating may consist of a single, thick, continuous layer, or a stack of various alternating thin layers producing total thickness of the order of a micron ($10^{-6}$ m). Tint intensity is determined by thickness of the applied layer, and color is determined by the materials used: oxides generally produce brown tints, while the grey tint is obtained from a combination of metals and transparent compounds such as silica. The applied layers are intrinsically of equal thickness, thus ensuring that the lens tint remains constantly even. The range of available tints is relatively limited. The technology used to vacuum tint glass lenses is very sophisticated, and is similar to that used to apply antireflection coating, described in Part III of this File.
Solid tinting

The only solid tint plastic lenses are plano sun lenses. They are obtained by polymerization of a monomer which contains colored dyes. Moreover, an ultraviolet blocking agent is added to the monomer formulation to reinforce protection against this harmful radiation.

Tinting by surface treatment

Plastic lenses are tinted by impregnating their surfaces with colored dyes. The lenses are immersed in a solution containing the dyes and various additives to promote the coloring process. The dyes penetrate the material to a depth of 6 to 10 microns. Tinting is performed before or after application of a scratch-resistant coating, depending on whether the hard coating can absorb the colored dyes.

Tint intensity is determined by the nature and concentration of the dyes, and by the duration of immersion of the lens, which is about 1 minute for the lightest tints, and may last as long as 2 hours for the darkest tints. As the tint is determined by relative concentrations of the 3 primary pigments (blue, yellow, red), it is possible to obtain an infinite range of shades. Moreover, an even, full tint can be applied to the entire lens, a color gradient can be obtained by making tint intensity vary from top to bottom, a double gradient can be obtained by simultaneously varying tint from both the top and bottom of the lens, or a “rainbow” effect can be obtained by applying a double gradient tint onto a full tint lens. Graduated tints are obtained by slowly removing the lens from the color bath: the lens is held in a lens holder and totally immersed (top section downmost) then very slowly removed: the lower part, which is immersed longest in the bath, is therefore more strongly impregnated with the dyes than the upper part.

There are numerous possibilities for tinting plastic lenses. The procedures are relatively simple: lenses may be tinted individually, in pairs, or in batches where reference lens tints are copied. The operator’s sensitivity to colors and visual skills are very important: tinting plastic lenses calls for real craftsmanship!

Figure 4: Solid tinting vs tinting by surface treatment.
C/ Variable tint lenses

The basic principles of glass and plastic photochromic materials have been described in the Ophthalmic Optics File on "Materials". This section will therefore focus on an analysis of the properties of glass and plastic photochromic lenses.

1/ Transmission in clear and dark states

The light transmission properties of a photochromic lens are precisely described by its transmission curves and $\tau_v$ coefficients measured in the clear and dark states. The examples in figure 5 show transmission graphs for glass and plastic lenses measured before activation and after exposure to light for 15 minutes. The variation in transmission caused by the photochromic property is clearly visible. Moreover, the U.V. cutoff of the plastic lens (390 nm) is significantly higher than that of the glass lens (345 nm).

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Figure 5: Transmission graphs in the clear and dark states.
Photochromic properties of a lens are generally represented with graphs showing the lens darkening and fading kinetics. These graphs show the change in the lens transmission factor $\tau_v$ as a function of time during the darkening and fading phases. On the examples shown in figure 6 a) and b), the left-hand side of each graph shows the lens darkening over a period of 15 minutes, and the right-hand side shows the lens fading over a period of 20 minutes. The value of $\tau_v$ can be seen to decrease, at a temperature of $2^\circ C / 68^\circ F$, from a value close to 90 % to about 30 % after darkening for 15 minutes. Similarly, $\tau_v$ subsequently rises to about 75 % after fading for 20 minutes. The curve slope shows that darkening is significantly faster than fading. Furthermore, the photochromic performance of current glass and plastic lenses can be seen to be practically the same.

**Figure 6**: Darkening and fading kinetics.
The photochromism of a lens is obtained by introducing U.V. light-sensitive substances into the glass or plastic material. For glass lenses, a single substance is used and the lens color remains relatively constant throughout the photochromic process. For plastic photochromic lenses, several photosensitive substances are used, each absorbing a specific part of the visible spectrum. Since these substances do not necessarily react at the same rate, the resultant color combination may change during the photochromic process. This accounts for the marked color variation sometimes observed in early plastic photochromic lenses. Nevertheless, such variations have been largely eliminated from materials of the latest generation.

Heat is the main factor which triggers lens fading and ensures reversibility of the photochromic process. Consequently, ambient temperature influences the photochromic performance of a lens, which tends to darken less at high temperatures than at low temperatures. To describe this discrepancy, the darkening performance of lenses is measured in different simulated climatic conditions. On figure 6, the lower graph simulates a harsh winter (Montreal in winter, at -11 °C/12 °F), the middle graph simulates a temperate summer (Paris at +20 °C/68 °F), and the upper graph simulates a tropical summer (Miami at +35 °C/95 °F). The difference between these 3 graphs shows the effect of climatic conditions on the photochromic process for glass and plastic lenses.

The performance of photochromic lenses is measured in laboratory conditions using sophisticated apparatus which artificially recreates the real climatic conditions in which the lenses are used. The apparatus (figure 7) consists of two arc lamps (A) which reproduce the spectrum of sunlight, a climatic chamber (B) which reproduces temperature conditions, a spectrophotometer (C) which permanently measures the intensity and chromaticity of the light transmitted by the lens, and a computer (D) to process the collected data.

Figure 7: Apparatus for measuring photochromic performance.
D/ Special filters

These filters are designed to selectively transmit certain types of radiation and partially or totally absorb others. They may play two different roles:
- a protective role, by reducing or eliminating the noxious effects of certain wavelengths, and/or attenuating luminous energy which enters the eye,
- an enhancing role, by selectively transmitting certain wavelengths likely to improve wearer perception.

There are many kinds of filters, including the following:

1/ Ultraviolet light filters Filters improving natural U.V. absorption provided by clear glass and plastic materials can be used to improve protection against this radiation. To allow these lenses to be worn permanently, the protective mechanism should only slightly attenuate transmission of the visible spectrum. With glass, solid tint materials are used because of their better U.V. cutoff: for example, a filtering material with a slight solid brown tint (figure 8a) raises UV cutoff for 1.5 index glass from 280 nm for traditional materials or from 330 nm for the most recent materials, up to 350 nm. With plastics, U.V. cutoff of CR 39 (1) (at about 350 nm) can be reinforced by a coating: for example, “UVX” coating (figure 8b) is a U.V. blocker combined with a pink amber tint, allowing all U.V-B and U.V-A to be eliminated by cutting off radiations up to 400 nm. Generally speaking, plastics are clearly better U.V. filters than glass materials. Among the former, photochromic high-index plastics, including polycarbonates, are better U.V. filters than CR 39.

2/ Contrast enhancing filters These filters absorb ultraviolet and blue radiations, and specifically transmit the central part of the visible spectrum. For example, the “Kiros” filter (figure 8c), which has a light yellow tint, stops the transmission of blue light and specifically transmits wavelengths close to maximum sensitivity of the eye. It enhances contrast perception in cloudy conditions, and is therefore useful for drivers, mountaineers, and hunters. Similarly, Essilor “Lumior”, which is a darker tinted orange-yellow filter, specifically transmits the central zone of the visible spectrum and filters all U.V. and blue radiation up to 400 nm. It is used to improve vision and visual comfort of amblyopic and aphakic patients. These filters are obtained by treating Orma® (2) plastic lenses.

3/ High absorption filters These filters absorb U.V. light and the lower part of the visible spectrum, and only transmit its upper part. For example, “Extreme” coating (figure 8d), which has a dark yellowish-brown tint, cuts off all wavelengths up to 530 nm, thus eliminating all U.V. and the most active part of the visible spectrum. Its yellow component improves contrast. It is designed to be used in strong lighting conditions, such as on sunlit snow.

The Essilor “RT” coating, which cuts off all U.V. rays and the visible spectrum up to 420 nm, allows a reduction in retinal rod cell stimulation and rests the scotopic system, while maintaining central visual acuity. These filters are obtained by treating Orma® lenses.

4/ Polarized filters Polarization of light: when a light beam is reflected by a polished surface, the vibration of the wave becomes strictly confined to a plane, which is perpendicular to the light incident plane. Certain substances can be arranged in optical filters such that they absorb the ray of polarized light if correctly oriented with reference to the polarization plane. The effect of these filters is to cancel glare emitted by reflecting surfaces. One particular application consists of orienting filters of this type so that they absorb polarized light reflected by water in the natural environment. These polarized filters are useful for water sports and fishing, since the wearer can observe water without being dazzled by reflections and disturbed by glare (see Figure 8d).

Figure 8: Transmission graphs for some of the Essilor special filters.

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1/ CR 39 is a registered trademark of PPG Industries.
2/ Orma® is a registered trademark of Essilor International.
A/ Why protect lenses against abrasion?

Among the everyday enemies of spectacle lenses, the damage caused by the rubbing of various objects and by abrasive dust particles (chiefly made of silica) wiped across the lenses is certainly one of the worst. This goes for all lenses, glass or plastic, although glass lenses are generally considered much more scratch resistant than plastic materials. This chapter therefore deals mainly with the abrasion resistance of plastic lenses.

A preliminary observation of "scratched" plastic lenses suggests that two phenomena are at work:
- abrasion by the rubbing of “fine” particles, responsible for small, fine scratches which are practically invisible to the wearer,
- scratching by "large" particles, causing visible splintering which is a source of wearer discomfort.

Nevertheless, physical analysis of abrasion and scratching phenomena reveals more complex mechanisms, governed by mechanical properties of hardness and deformation response of the analyzed materials.

The general aim of the present File is to describe, from the wearer’s viewpoint, the reasons for developing various coating techniques. However, we felt it would be useful to provide an additional, more detailed description of one of the basic mechanisms which cause scratches in the supplement below.

B/ What if the lens has an antireflection coating?

The basic phenomenon remains the same, but the effects of the abrasive particles are considerably amplified by the structure of the antireflection coating. Indeed, materials used for antireflection coating are mineral materials applied in very thin layers (less than a micron) to the plastic lens surface. The thinness of the applied layers certainly does not give them the rigidity of a glass lens; under the local pressure of a grain of dust, these layers undergo deformations which are characteristic for the dominant material in terms of volume, i.e. the polymer substrate. At the same time, however, these thin layers continue to behave mechanically as mineral materials: when the polymer is subjected to substantial deflection, making the mineral layers deform beyond their breaking point, they will crack abruptly, creating a rather uneven groove on the lens surface (figure 9).

This effect is obviously catastrophic for a plastic lens without a scratch protective coating. Even a plastic lens coated with traditional polysiloxane varnish will show considerably lower resistance to abrasion and scratches if it has also been antireflection coated, since deformations of the lens/ varnish combination go beyond the breaking point threshold of the antireflection coatings.

This phenomenon is moreover amplified by greater visibility of scratches: the contrast between the brilliant, deepest point of a scratch, and the matte antireflection coating, is stronger than on an uncoated lens (it should be pointed out that this phenomenon is also noticeable, although to a lesser extent, on glass lenses).

However, this complex problem has prompted the development of a new generation of specific hard coatings. These nanocomposite varnishes endow antireflection coated plastic lenses with extraordinary performance.
Characterization of the phenomenon of scratching and abrasion

The implemented mechanism can be described by considering an abrasive particle as a point which exerts a pressure - called stress - locally, at the lens surface. This surface reacts to the stress as a function of its mechanical characteristics. When the stress is eliminated, there is a remnant imprint, the shape of which varies, and which constitutes a kind of signature of the interaction between the abrasive grain and the lens surface. This mechanism simultaneously calls on two mechanical properties - hardness and deformation - which are specific for a given material. Hence, one can imagine applying identical stress with the same abrasive point:

- on a block of rubber: this will deform in a completely elastic fashion, and resume its initial state upon removal of the point
- on a block of glass: this will show very little deformation, then fracture if the stress exceeds a certain threshold, yielding a very visible remnant imprint
- on a block of aluminum: this will show greater deformation than glass because of the nature of the material (plastic behavior), and the print will retain the shape acquired at the time of maximum deformation, without any fracture or splintering.

Thus, one can refer to a “law of behavior” specific for each material. In mechanical physics, this is represented on a graph, plotted as follows:

- on the abscissa: % deformation with respect to the initial state,
- on the ordinate: the value \( \sigma \) of the applied stress (expressed in Pascals, meaning that a stress is considered as a pressure).

For any material, the law of behavior is represented by a curve which originates at 0 and terminates at a point \( R \), where breaking point occurs. Abscissa \( x_R \) of \( R \) is called breaking point deformation. Ordinate \( \sigma_R \) of \( R \) is called breaking point pressure. Slope of the curve may be constant (straight line) - indicating a material with purely elastic behavior: resumption of initial shape after elimination of the stress. Slope of the curve may alternatively be variable - indicating a material with plastic behavior, more precisely termed “visco-elastic” behavior: there is a remnant imprint after elimination of the stress.

Figure 10 shows the laws of behavior for glass and a polymer (type CR 39).

The polymer may be scratched subsequent to rupture, for far weaker stresses than those withstood by the glass. Similarly, before attaining its breaking point deformation threshold, the polymer may undergo major permanent deformation, without any rupture or splintering.

To verify these theoretical explanations, it is imperative to observe numerous lenses which are effectively worn. This can be done using a “scanning electron microscope”, which allows the observation of scratches with tearing of material and splintering, i.e. the causal factors in diffraction leading to wearer discomfort (figure 11).

Figure 10: Laws of behavior for glass and polymer materials.
Analysis of the scratch phenomenon provides researchers with clues as to the development of abrasion-resistant coating prototypes. It must be possible to characterize performance of such prototypes.

Characterization consists of performing precision measurement of hardness and deformation-resistance of the coated lens as a whole, but also of the actual coating. For example, this can be done with an instrument which ensures "indentation" of the test surface: a diamond point of known dimensions is applied to the surface, implementing determined load "P", and residual imprint "A" is measured (Figure 13).

The diamond tip can also be displaced to inscribe a scratch with a variable load, and at a set displacement rate.

Figure 12 shows indentation imprints obtained with a load of 300 mN, for a thick evaporated silica-based subcoat on the left, and for a "nanocomposite" varnish on the right.

Figure 14: Indentation photos - mineral hardening layer on the left - nanocomposite layer on the right.
C/ How do anti-abrasion coatings work?

1/ The principle of anti-abrasion coatings

The first generation of coatings (1970) was exclusively based on the notion of hardness: plastic lenses scratch easily because of the softness of the material, whereas glass lenses are almost “unscratchable” because they are hard. Hence, the principle for increasing the abrasion resistance of a lens consisted of applying a mineral coating to the polymer surface by vacuum evaporation. The coating was made of silica, and the procedure was commonly referred to as “quartzing.”

From 1975, finer analysis of the behavior of materials revealed interworkings of the relation between “hardness” and “deformation.” At the same time, progress in Chemistry allowed harder plastic materials, capable of following deformations without breaking, to be applied to the polymer surface. This led to the generation of hard varnishes - polysiloxane or acrylic compounds applied in the liquid phase; this second generation of coatings is still widely used today.

Finally, as mentioned earlier, the specific problem caused by antireflection coated lenses gave rise to a new generation of hard layers. The solution in this case consisted of compensating for the difference between mechanical properties of the polymers and those of the thin antireflection layers, by interposing between these two substances a structure characterized by an intermediate behavior. A new generation of coatings, nanocomposite varnishes, appeared in the early nineties, and proved to be capable of fulfilling this function. Indeed, their new structure offered a good mechanical transition - a kind of “shock absorber” effect - between the hard, brittle antireflection coating, and the flexible, deformable polymer.

Furthermore, new forms of mineral hardening layers have been introduced to the market: they are based on vacuum evaporated silica compounds. As their mechanical behavior is similar to glass, they still remain brittle when subjected to strong loads.

2/ Quartzing

The Quartzing procedure, first used in the seventies, consists of applying silica (“Quartz”) to a plastic lens by vacuum evaporation (this method will be described in part III, on antireflection coatings). It is difficult to combine Quartz and the CR 39 polymer, since the latter’s dilatation coefficient is almost 20 times that of Quartz. This induces stress which leads to fracture of the layer in the event of thermal shock. When wiping the lens, if a speck of dust exerts a strong local pressure on the quartzed surface, the layer may break, and very visible scratches may appear. These drawbacks account for the relatively limited success of the “quartzing” process.
3/ Varnishing

a) Traditional varnishes

The advent of polysiloxane varnishes represents one of the numerous applications of Silicon chemistry. It has already been stated that organic matter is chiefly comprised of C, H, O and N elements, whereas mineral matter consists of various elements, particularly Silicium. The chemistry of Silicons, which is a branch of organic chemistry, has developed thanks to the extraordinary properties of chemical compounds where the Carbon atom has been replaced by a Silicium atom. Thanks to Silicium, these Silicon compounds form a bridge between organic and mineral matter (figure 15).

Thus, polysiloxane varnishes provide extraordinary performance in terms of their reinforcement of the surface hardness of organic materials:
- thanks to the presence of Silicium, which ensures an intermediate hardness value, between that of silica and that of the pure polymer materials, and
- thanks to the existence of long hydrocarbon chains, which maintain the elasticity and dilatation coefficient necessary to ensure cohesion of the "layer/polymer" system.

These varnishes are applied by two specific methods (described in the supplement, see below):
- varnishing by "dip coating",
- varnishing by centrifugation or "spin coating".

b) Nanocomposite varnishes

As seen above, the application of a polysiloxane varnish under an antireflection coating does not provide enough mechanical support to prevent cracking. Hence, the underlying structure on which the antireflection coating is applied must be stiffened, from the core to the outer layers.

Certain manufacturers have modernized the quartzing principle to manufacture hard, silica-based mineral type coatings, even though they still present a risk of cracking beyond a certain load.

Other manufacturers have focused on research to develop composite materials called nanocomposites, which are transparent to visible light. These materials consist of an organo-silicon matrix in which nanoparticles have been dispersed, i.e. sub-microscopic particles measuring 10 to 20 nm, which are therefore smaller than the wavelength of light. This rules out the risk of diffusion. These composite materials generally use very stable particles of colloidal silica.

Thus, the principle of building a bridge between mineral and organic matter thanks to Silicium atoms is once more operational here, though at an entirely different scale: whereas polysiloxane varnish molecules contain a small percentage (in mass) of Si-O radicals, nanocomposite molecules are made of about 50% silica.

The silica nanoparticles are suspended in a liquid with a similar structure to that of polysiloxanes to form a homogenous mixture which has the properties of a varnish, and is applied to the lenses either by dip coating or by spin coating (see supplement). The liquid film is then polymerized by baking at about 100°C/200 °F, to become an organo-silicon polymer in which mineral nanoparticles “float” in an organic matrix. This nanocomposite coating has remarkable properties:
- high resistance to deep scratching, preventing the superimposed antireflection coating from being deformed beyond breaking point,
- relatively high flexibility, to follow deformations of the polymer without separating,
- an extremely low friction coefficient, with a resultant increase in abrasion resistance: angular particles cannot “get a grip” on this kind of surface.

Figure 15: Mineral structure (lower left) - organic structure (upper left) - silicon (right).
Varnishing by dip coating

This is a dipping process where the lenses simultaneously receive a layer of varnish on each surface. The lenses are cleaned using ultrasonic activated chemistry, then immersed in the liquid varnish bath from which they are removed at a constant rate to control thickness of the final coating, which is likewise dependent on viscosity of the liquid. The varnish is then polymerized by baking at a temperature of about 100°C/200°F. It then turns into a hard, solid film which endows the coated lens with resistance to scratching, its performance being a function of composition and thickness.

All these operations are performed in controlled atmospheric conditions (clean room), with monitored temperature and humidity.

Varnishing by centrifugation or spin coating

This procedure is simple, and its principle makes it particularly suitable for small items which rotate symmetrically: the lens is attached to a rotary support at a controllable speed, a drop of the liquid varnish to be spread is applied to the lens center, then rotation speed is accelerated until a uniform film covering is obtained by centrifugation.

This method is readily adaptable to the manufacturing of small series of lenses; since the actual varnishing operation is performed very fast, it can be used to apply less stable, more complex varnishes than the dip coating procedure.

Moreover, because of its simplicity and speed, it is used to varnish concave surfaces in US surfacing laboratories (where polymerization is often achieved by a few minutes’ exposure to ultraviolet radiation). On the other hand, the resulting coatings often show poor abrasion resistance.

Figure 16: Principle of varnishing by dip coating.

Figure 17: Principle of varnishing by centrifugation.
This procedure uses an entirely different technology to those described above. A plasma, i.e. an electric discharge in a gas at low pressure (as in a neon tube), is created in a vacuum chamber, before introduction of a gaseous monomer (of the “HMDS” - “hexamethyldisilazane” family), rich in siloxanes. The monomer polymerizes under the effect of the energy provided by the plasma, and by condensation, forms a solid film on the lenses in the chamber. There are several ways to generate the plasma: direct current, microwaves and radio-frequency, etc.

Plasma polymerization is expensive, and the manufacturing control involved is complex. Furthermore, this type of treatment shows up surface defects. Some manufacturers use this procedure to coat plastic bifocals. Others have tried to combine it with standard vacuum coating to create a hard sublayer, or a water-repellent layer for an antireflection-coated lens. For the time being, reliability is still apparently not easy to master.

It is difficult to check the abrasion resistance of a coated lens. Such control must be quick to implement, and easy to interpret. Manufacturers have developed methods of testing which consist of subjecting samples of a manufactured batch to abrasion or scratch simulations.

Here are a few of the most commonly used tests:
- **Bayer test**: the lens is moved back and forth in a recipient containing an abrasive powder (sand) with a precisely defined grain. Diffusion of a control lens and the test sample is measured “before” and “after” this action, and results are compared;
- **abrasimeter test**: a ribbon encrusted with fine abrasive particles (e.g. carborundum) is rubbed on the test lens a certain number of times, with a predetermined load. Diffusion of transmitted light is then compared with that diffused by a control lens;
- **steel wool test**: there are several ways of rubbing a test lens with a fine steel wool pad: using a standard mechanical device for reproducibility, or simply manually, by way of demonstration. In the latter case, a lens is rubbed by hand with a fine steel wool pad. The test and control lenses are compared visually or with a standard apparatus for measuring diffusion;
- **“Taber” test**: a “Taber” type rubber wheel, shaped to match the lens curvature, is applied to the lens with a predetermined load. Diffusion is measured and compared with that of a CR 39 control lens;
- **barrel test**: there are several similar tests of this type: the lenses are set in rotation in a barrel filled with various precisely calibrated items, and diffusion of transmitted light is measured at regular intervals.

One of the most marked trends in the ophthalmic lens market at the end of the 20th century is the gradual and inevitable substitution of glass lenses by plastic lenses. This has accelerated research to improve performance of the already large family of plastic materials. In particular, impressive progress has been made with medium-index polymers ($n \leq 1.56$) and high-index polymers ($n > 1.56$): these allow substantial reductions in lens thickness, making the lenses more cosmetically pleasing. On the other hand, the abrasion resistance of medium- and high-index plastics is lower than that of CR 39. Consequently, **ALL** plastic lenses made with these materials must be protected with an abrasion-resistant coating. Hence, we can reasonably expect rapid progress to be made in this area!
A/ Why antireflection coating?

1/ The effects of reflected light

The parasite effects due to the reflection of light on both surfaces of a lens are varied and well known (see figure 19).

The most obvious effect is the “mirror” effect observed by the person looking at a spectacle wearer: light reflections on uncoated lenses make it impossible to see the other person’s eyes, and are considered annoying and unattractive (see figure 20). Yet this effect is negligible compared with the very real visual drawbacks that parasite reflections represent for the wearer of the spectacles.

Figure 19: Lens surface reflections.

Figure 20: “Mirror” effect of an uncoated lens (on the left).
Let us look at what happens when images are formed on the retina. Like any optical system, the eye presents imperfections, and the image the eye gives of a point on the retina is not a point, but a blur spot (figure 21-1). Thus, the perception of two close points results from the juxtaposition of two more or less overlapping blur spots. As long as the distance between these two points is big enough, the images formed on the retina result in the perception of two points (figure 21-2), but if the points are too close, the two blur spots tend to merge, and are wrongly perceived as a single point (figure 21-3).

This phenomenon can be quantified by using the relation determining contrast, based on the maximum and minimum illumination values of the spot formed on the retina (figure 21: segments “a” and “b”), and defined as follows:

\[
C = \frac{a - b}{a + b}
\]

This ratio must exceed a certain value (detection threshold, corresponding to an angle of 1 to 2°) for the eye to be able to separate the two neighboring points.

Figure 21: Formation of retinal images of separate points.

Figure 22: Effect of a parasite reflection.
Let us now take the following situation: a driver wearing spectacles is driving his/her car at night and, in the distance, the wearer clearly sees two cyclists coming toward his/her vehicle. Let us now suppose that the headlights of a car behind the first car reflect on the rear surface of the driver’s spectacles: this parasite reflection creates an image on the retina (figure 22) which is added to the intensity of the two observed points (i.e. the cyclists’ lamps). Consequently, length of segments “a” and “b” increases, causing a reduction in the value of C since the denominator (a+b) has increased, while the numerator (a-b) has remained constant. This results in a reduction in contrast, which may go so far as to merge as a single image the driver’s initial perception of two cyclists, exactly as though the angle separating them were suddenly reduced!

Clinical studies in this area consist of having wearers of spectacles with uncoated and antireflection-coated lenses observe contrast gratings, and of measuring their contrast sensitivity. Figure 23 shows normal sensitivity (red line) without dazzling, the loss of contrast caused by dazzling with uncoated lenses (purple line), and restored contrast obtained in identical dazzling conditions when lenses with antireflection coating are worn (blue line).

Similarly, under predetermined dazzling conditions, it has been possible to ascertain that the visual field of a subject wearing antireflection-coated lenses is considerably larger than that of the wearer of uncoated lenses.

Another source of disturbance is “phantom images” generated by the double reflection on both surfaces of a corrective lens (figure 24).

This effect is illustrated by the night scene in figure 25, observed through an uncoated lens (upper photo), then through an antireflection-coated lens (lower photo): the double parasite image of the light bulbs is clearly visible on photo (a).

Studies in night driving conditions have shown that, compared with uncoated lenses, antireflection-coated lenses cut down the time necessary to recover normal vision after dazzling by 2 to 5 seconds.

**Figure 23**: Contrast sensitivity in dazzling conditions, with and without antireflection coating.

**Figure 24**: Phantom image generated by the double reflection on both the lens surfaces.
2/ Principle of antireflection coating

Antireflection coatings are based on the undulating nature of light and on the phenomenon of light interference. Let us take two sine waves and calculate the sum of their amplitudes (segment AB) in the following two cases: on the left, the amplitudes add up: “constructive” interference occurs when waves have the same position on the x axis - they are said to be in phase; on the right, the amplitudes cancel each other out: “destructive” interference occurs, and the waves are said to be in phase opposition.

The principle of antireflection coating consists of applying a layer to the uncoated lens surface such that the reflected waves on the layer and at the “layer/lens” interface are in phase opposition, thus suppressing light waves reflected by destructive interference (figure 26).

For this, the 2 waves must be out of phase by \( \frac{\lambda}{2} \) after reflection: it is easy to deduce that the thickness of the layer must be \( \frac{\lambda}{4} \) in relation to wavelength. But real layer thickness must be calculated by taking into account the change in velocity of the wave when it goes from air to the antireflection coating; this introduces the refractive index which is the ratio between these two velocities, and gives the following formula:

\[
e = \frac{\lambda}{4n_1},
\]

\( n_1 \) = refractive index of the antireflection coating, otherwise expressed as

\[
n_1 = \frac{c, \text{ light velocity in vacuum}}{v, \text{ light velocity in the layer}}
\]
Moreover, for extinction to be total, amplitudes (segment AB above) of the two reflected waves must be equal. The calculation based on so-called “Maxwell’s equations stipulates a further condition, which defines the refractive index of the layer:

\[ n_1 = \sqrt{n}, \quad n = \text{refractive index of the lens.} \]

**Example: Single-layer antireflection coating on a crown glass lens:**

The index of crown glass is \( n = 1.523 \); calculation defines the index for the layer as \( n_1 = 1.235 \), but no solid material has this index. Hence, the material which comes closest to this value is used, i.e. magnesium fluoride, MgF\(_2\), which has an index of \( n_1 = 1.38 \).

As antireflection coatings are generally calculated for the central wavelength of the visible spectrum, \( \lambda = 550 \text{ nm} \), the real thickness of the layer becomes \( e = 100 \text{ nm} \).

**Note:** according to the principle of energy conservation, if intensity of the light reflected on the two surfaces of a coated lens is less than on the surfaces of an uncoated lens, then transmitted intensity \( T \) will be increased by the same amount. The transmission value for a lens where each surface presents reflection \( \rho \), is equal to \( T = 100 \cdot (1 - \rho)^2 \). Hence, for example, the above-mentioned crown glass, with uncoated reflection factor \( \rho = 4.3\% \), presents total transmission \( T = 91.6\% \) - with single-layer antireflection coating reflection drops to \( \rho' = 1.6\% \) and transmission becomes \( T = 97\% \).

**Figure 26: Diagram showing the principle of antireflection coating.**
3/ Specification and performance of antireflection coatings

a) Specification of the antireflection effect

The antireflection function is represented by a graph showing intensity of reflected light (ordinate) as a function of wavelength (abscissa). This set of data is called a “reflection graph” or “spectrogram R (λ)”. The reflection graph of an uncoated lens is the reference, and allows the antireflection efficiency factor to be calculated as the ratio of the areas located under each of the two curves.

b) Optimization of performance

The antireflection coating represented in figure 27 does not cancel out reflections completely. It allows some luminous reflection, depending on the wavelength: while this is minimal at about 460 nm, it is much greater at the two extremities of the spectrum. To improve the efficiency of antireflection coatings, physicists have refined the principle of light interference described above by calculating the thickness and refractive index of several stacked layers (up to 7 or 8), such that multiple interferences of the waves reflected on these layers taken two by two substantially reduce reflection at different points of the visible spectrum.

The efficiency of these multilayer stacks is spectacular (see figure 28), and their application is developing fast, despite the complexity of designing such systems. Generally speaking, antireflection coatings available on the market can be classified into three categories:

<table>
<thead>
<tr>
<th>Type of antireflection coating</th>
<th>Reflection per surface, ( \rho )</th>
<th>Total transmission, ( \tau )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard efficiency</td>
<td>1.6 to 2.5 %</td>
<td>95 to 97 %</td>
</tr>
<tr>
<td>Medium efficiency</td>
<td>1.0 to 1.8 %</td>
<td>96 to 98 %</td>
</tr>
<tr>
<td>High efficiency</td>
<td>0.3 to 0.8 %</td>
<td>98 to 99 %</td>
</tr>
</tbody>
</table>

c) Antireflection coating residual color

Figure 27 shows that the amount of reflected light is higher with wavelengths in the blue (400 nm) and red (700 nm) part of the spectrum. This residual colored reflection, essentially consisting of blue and red light, gives the lens a well-known “purple” appearance.

Figure 28 shows two graphs which do not have exactly the same shape throughout the spectrum, but which are characterized by a very low amount of reflected intensity: one might therefore expect the residual color to be fairly similar. In fact, this is far from true: the lenses corresponding to these two real curves were fitted to a pair of spectacles (figure 29) which proved unacceptable for cosmetic reasons. Indeed, the two lenses could under no circumstances constitute a pair.
In conclusion, residual color represents one of the important characteristics of antireflection coating, as it affects perception of the product quality, and the wearer’s final choice. It is therefore necessary to be able to control this phenomenon, both at the design phase, and during manufacturing. For this reason, scientific tools have been developed to allow the calculation of residual color to be deduced from a spectrogram $R(\lambda)$. This measurement has been defined in the “CIE L*a*b*” colorimetric system for instance (see supplement section p. 28).

**B/ The technology of antireflection coating**

1/ Vacuum evaporation: the reasons for this choice

The manufacturing technology for antireflection coatings consists of stacking thin layers with specific characteristics to achieve the overall result. These characteristics are:
- specified refractive index,
- absolute transparency,
and the method implemented to obtain the required configuration:
- high precision layers of even thickness,
- excellent adherence to the lens,
- outer surface coating as polished as the uncoated lens,
- optical qualities equal to that of the substrate: no isolated defects caused by dust ("pinholes"), no "haze" effect due to scattering, no pitting due to a material deficit ("bubbles"), etc.

Only one technology currently provides a satisfactory solution to all these requirements. This is vacuum evaporation. Why?
- evaporation allows very pure materials to be applied to lenses by condensation; the chemical composition of these materials can be rigorously controlled;
- vacuum evaporation allows layers to be built up with the required accuracy, however thin they may be ($\pm 5\,\text{Å}$);
- the vacuum technique guarantees optimal adherence, as the lens-layer interface is free from any residual contamination.

**Figure 28**: Reflection graph for two high efficiency multilayer coatings.

**Figure 29**: Difference in appearance of two multilayer AR coated lenses (right lens = red line, left lens = green line).
“CIE L*a*b*” Colorimetric system

An x axis called "a*" is plotted in a plane from point O, and serves to measure the variation from red to green. A y axis called "b*" measures the variation from yellow to blue. A color is defined by a point P from coordinates "a*, b*": hue "h*" is the angle formed by OP with the a* axis, and saturation "C*" is equal to the length of segment OP.

- hue "h*" translates the sensation of color,
- saturation "C*", or Chroma, expresses the sensation of chromatic purity, i.e. the position on a scale going from “achromatic” black/white, devoid of any tonality, to “monochromatic” saturated color, of completely pure tonality.

Figure 30 : Colorimetric system L*a*b*
a) Procedure

Vacuum evaporation consists of bringing a material to a gaseous state by heating it in a rarefied atmosphere. The evaporation rate depends on the temperature reached by the material. Materials used for antireflection coating must be heated to 1000°C/1800°F to 2200°C/4000°F, to obtain good quality coatings. To reach these temperatures, the materials are placed in a crucible where heat can be generated in two very different ways:

- heating by the Joule effect
  this is the effect governed by Ohm’s law $U = RI$ (electric heaters operate according to this law). A “boat” made of refractory metal (tungsten or tantalum) or carbon is filled in solid material which reaches a high temperature when a strong current passes into it: the material melts, then evaporates toward the lenses;

- electronic bombardment
  an “electron gun” is used, based on the same principle as the cathode tube of TV monitors. The gun emits an electron beam which is electromagnetically focused on the material to be evaporated, placed in a refractory crucible. The electrons are blocked by the target material, and give up their energy as heat, thus raising the temperature of the material to be evaporated (see figure 31).

b) Measurement and control of the evaporated thin layers

The thickness of the layer building up on the lenses must be measured in real time: one of the most common methods consists of weighing the deposited coating with a microbalance.

A piezo-electric quartz is a quartz crystal capable of vibrating with a very precise frequency (like the crystal used in a quartz watch). This frequency can be modified by applying a mass to one of the surfaces of the quartz. Hence, the thin layer is applied to a quartz crystal placed in the vacuum chamber with the lenses to be coated. Thanks to electronic processing, the variation in frequency is converted into a precise measurement of the thickness and rate of application of the thin layer.

Figure 31: Diagram of a vacuum evaporation chamber.
What is a vacuum?

In a container full of gas, molecules are subject to constant movement, consisting of rectilinear trajectories and collisions (with the other molecules or container walls). The mean free path designates the mean distance covered by any molecule between two successive collisions.

The kinetic energy due to velocity of the molecules is responsible for pressure exerted on the container walls.

Atmospheric pressure at the Earth’s surface, resulting from the action of gravity on the layer of atmospheric air, corresponds to the presence of \(2.5 \times 10^{13}\) molecules of nitrogen and oxygen per cm\(^3\).

A vacuum has no real physical existence, but is simply a term used to designate low pressure. For example, one generally speaks of a vacuum at the surface of the Moon, whereas in fact this designates a rarefied atmosphere where there are only \(3 \times 10^5\) molecules per cm\(^3\)!

Let us take the gas container example once more: if we reduce the number of molecules present in the container (by “emptying” it), from a certain point in time, they will collide only with the walls, and no longer with other molecules. At this moment, the mean free path exceeds dimensions of the container.

A vacuum evaporation jar is a sealed chamber in which vacuum pumps reduce the number of gas molecules to a value such that the mean free path exceeds dimensions of the jar (“secondary” vacuum). The molecules present thus propagate without colliding with other molecules, until they meet a wall or, in the present case, a lens. This is what happens to molecules of the evaporated material, which condense directly on the lens surface, thus creating the thin layer. Antireflection coatings are elaborated in chambers measuring approximately 1 m\(^3\), evacuated to ensure a vacuum of about \(1 \times 10^{-6}\) mbar, corresponding to 32000 molecules per cm\(^3\). The mean free path is 50 m.

Pumping time before evaporation lasts about half an hour, and a total evaporation cycle about one hour.

New developments for plastic lenses

Progress in the nineties in the electronic industry, in the area of ion beam bombardment, has allowed antireflection coating manufacturing cycles to integrate additional operations likely to improve adherence of the thin films (between the films themselves, and between the films and substrate), to increase their density, and to modify their refractive index. For example, such operations consist of optimizing lens surface properties by “ionic bombardment” - which somewhat resembles the use of high pressure hoses to scour a wall - just before undertaking antireflection coating (“IPC” or Ion Pre-Cleaning procedure). Another operation consists of “packing” the thin layer with heavy ions while it is being applied, to increase its density (“IAD” or Ion Aided Deposition).

These operations are performed with an ion gun set up in the vacuum chamber - ions are particles comprised of atoms of gas (e.g. Argon) from which an electron has been extracted.

At another level, namely that of the chemistry of the materials, progress in the manufacture of ultrapure mineral compounds makes it possible to elaborate stacks with better resistance to chemical corrosion and thermal shock. Such compounds include Tantalum pentoxide \((\text{Ta}_2\text{O}_5)\), Zirconium dioxide \((\text{ZrO}_2)\), Titanium dioxide \((\text{TiO}_2)\), mixtures of Neodymium and Praseodymium oxides \((\text{Nd}_2\text{O}_5 \text{ et Pr}_2\text{O}_3)\).
Properties of the thin films depend essentially on those of the substrate to which they are applied, and several polymers with specific characteristics have required the development of specific coatings for plastic lenses. This is clearly illustrated by the following two examples:

- Glass can be heated up to 300°C/570°F, but plastics heated above 100°C/210°F turn yellow, then decompose very fast. Magnesium fluoride (MgF₂), which is an ideal material because of its very low refractive index, and is universally used to coat glass, becomes brittle and has no adherence if applied below 200°C/400°F. Coating plastic lenses thus calls for more complex stacking procedures with low index layers made of silica. This means longer manufacturing times;

- The heat expansion coefficient for plastic lenses, which is about 20 times that of the materials used to make the thin layers, is such that shearing stress appears at the contact surface; this may result in cracking, and even peeling of the layer, when the coated lens undergoes a thermal shock (for example, in a frame heater when the spectacles are being glazed, or on the dashboard of a car left in the sun). The lens surface temperature must be more precisely controlled than that of glass lenses, for example using an infrared thermometer (“optical pyrometer”).

The final cleaning then takes place under vacuum, just before coating, thanks to a “glow discharge” phase (electric discharge in gas under low pressure), or ionic bombardment (“Ion Pre - Cleaning” or “IPC” - see insert “New developments for plastic lenses”).

This is an essential aspect of ophthalmic lenses, since they are treated roughly even during normal use:
- abrasion (wiping, placing face downwards on furniture, rubbing inside a handbag, etc.),
- corrosion (sweat, humidity, sea air, cleaning products, etc.),
- thermal shock (car in the sun).

Contrary to the uncoated lens, which remains stable over time, coatings may appear perfect at the time they are manufactured, then show defects after a period of several months. Coating procedures must therefore include accelerated aging tests, results of which should be correlated with actual wearer tests. Although there are many different artificial and accelerated aging tests, which are specific for each manufacturer, they generally consist of subjecting sample lenses to the physico-chemical tests employed in the optics industry:
- boiling salty water,
- cold salty water,
- steam,
- deionized cold water,
- deionized boiling water,
- abrasion by a felt pen, steel wool, rubber, etc.,
- immersion in alcohol and other solvents,
- thermal shock,
- UV climatic chamber - humidity,
- etc.

The highest elaborated technologies are now put into service of anti-reflection coating development in order to procure an optimal and durable transparency to corrective lenses wearers.
Figure 33: Artist's impression of a vacuum chamber in operation.

Antireflection coating
C/ Anti-tarnish coatings

1/ Principle  Multilayer antireflection coatings can be easily soiled: for example, an oily smear forms an additional layer which interferes with performance of the antireflection layers.

How can this drawback be countered?

Analysis of the microscopic structure of the thin layers shows that they are relatively porous (at the microscopic scale); it is thus possible for greasy pollutants and impurities deposited on the coated lens to become encrusted in the porosities of the outermost layer, making it difficult to clean the lens. Researchers have therefore implemented techniques used in the manufacture of compounds in the electronics industry. These techniques consist of coating the surface with an extra layer, giving the lens oil and water-repellent properties. Consequently, adherence of oily matter and water is considerably reduced. This coating is ultrathin (a few nanometers), and has no effect on antireflection performance.

Figure 34: Diagram showing the structure of an anti-tarnish coating.
This coating is prepared from chemical compounds containing fluorinated or hydrocarbonated chains. For example, these may consist of fluorinated polysilazanes, which have a relatively complex molecular structure (figure 34). These compounds possess radicals which act as "hooks" ensuring very good adherence to silica, the outermost layer of the antireflection coating. Moreover, these compounds possess Fluorine-rich radicals which manifest strong chemical repulsion of water and greases. These coatings can be applied in two different ways.

- by "dip coating", using a similar process to that described for abrasion resistant coating, although it is much lighter in this case,

- by vacuum evaporation using a crucible heated by the Joule effect, placed in the vacuum chamber used for antireflection coating. Application of this extra layer by evaporation is performed immediately after evaporation of the last layer of the antireflection stack.

The outer layer acts in two complementary ways:

- it prevents grease deposits from settling and remaining on the lens surface, by clogging surface porosities;

- the layer is composed in such a way that it modifies the shape of water and grease droplets, reducing their contact surface by a factor of 2.5; this makes it easier to wipe them off the lens.

Thanks to the specific properties of this extra layer, lenses with an antireflection coating are easily cleaned with a dry cloth. However, regular cleaning with soap and water maintains optimal transparency of the spectacles, and is still recommended.

Figure 35: Contact angle of a drop of water on a lens treated with an "anti-tarnish" coating.
CONCLUSION

Market surveys carried out in several countries clearly show the interest for lenses with “all-in-one” coatings or “integrated coatings”; such lenses correspond best to the wearer’s expectations, as they offer multiple advantages without raising the awkward question of options.

Antireflection coatings are recognized by consumers as a determinant factor for comfort and appearance. Similarly, anti-tarnish coatings have brought about a dramatic improvement in the cleaning of coated lenses, even though further research is required to definitively rule out this problem. Finally, the increased market share for high-index lenses implies substantial future growth in the area of anti-abrasion coatings.

These different needs allow us to conclude that coatings have a bright future. They are becoming fully fledged lens constituents, and their success has been proved throughout the world. Although their use varies from one country to the next, there is however a clear overall upswing. Hence, lens coatings are bound to assume an increasingly important place within the general economy of ophthalmic lenses.