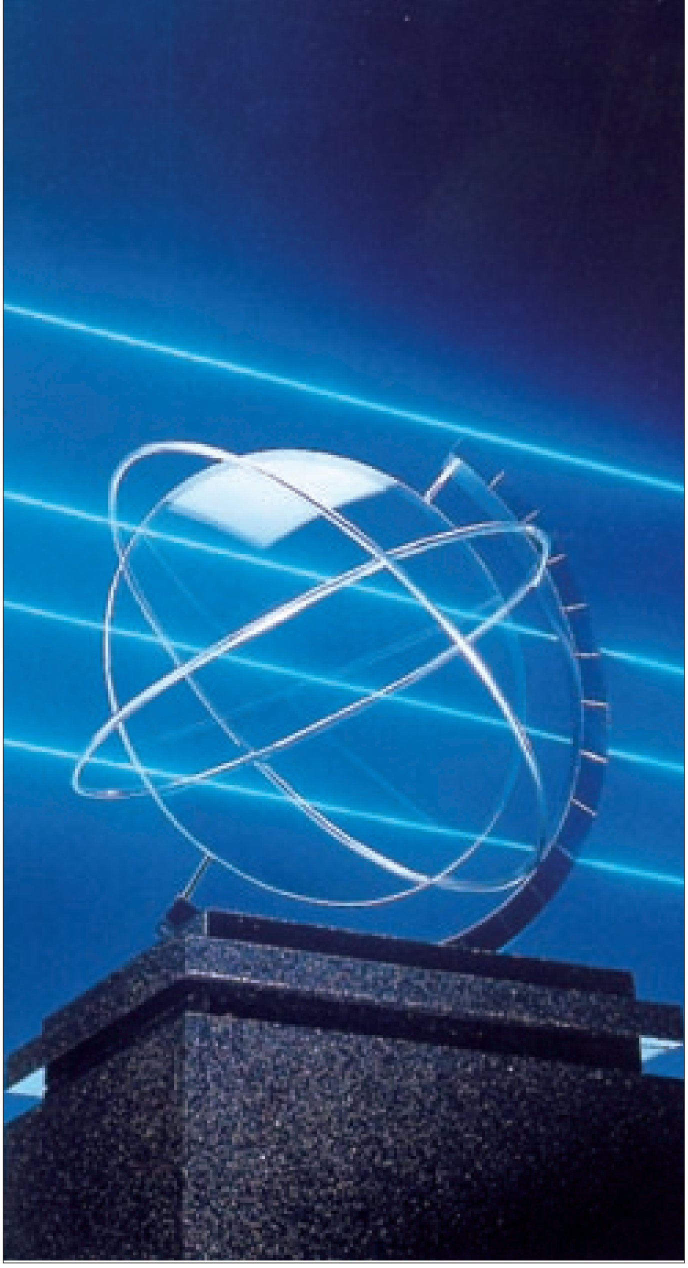


OPHTHALMIC
OPTICS
FILES

# *Materials*

ESSILOR

SUMMARY

# MATERIALS

This volume of the Ophthalmic Optics Files presents a study of the Materials used to manufacture ophthalmic lenses. "Materials" means "all materials used during manufacturing", i.e. all materials which enter into the composition of the basic ophthalmic lens and which, shaped to a specific geometry, give the lens its corrective function (function described in detail in other volumes of this series).

The present File is divided into three parts : the first part consists of an inventory of the physical and chemical properties used to describe materials, the second part presents a structural and functional analysis of the materials available, and the third part is a brief description of the techniques used to manufacture ophthalmic lenses.

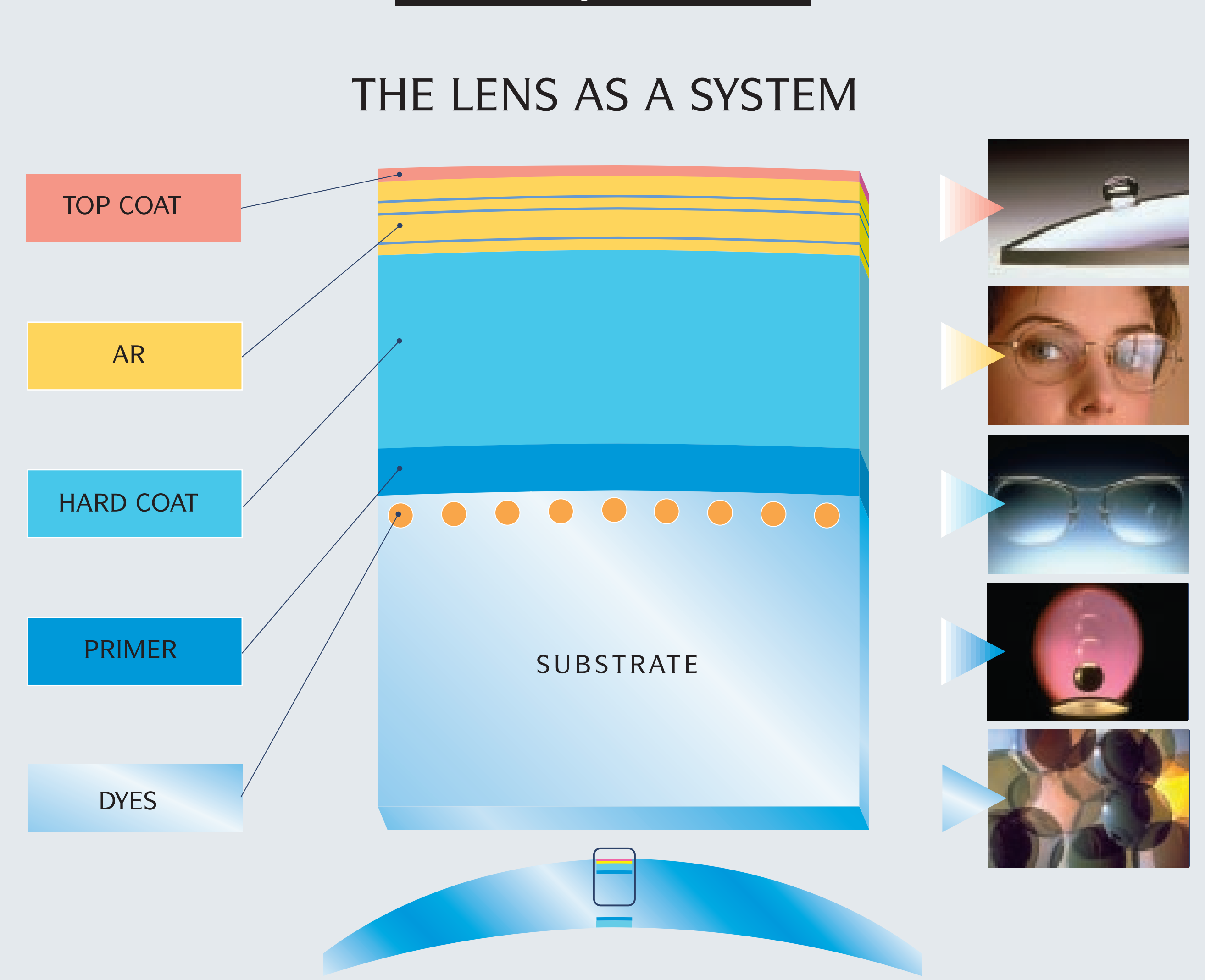
## *The ophthalmic lens is a complex system*

Before proceeding with an analytical description of materials, we should point out that today, an ophthalmic lens is a very complex product, resulting from the combination of various Materials and numerous Coatings which endow it with specific properties (figure 1).

Thus, the Material is just one of the lens components : its role consists not only of participating in producing the corrective function of the lens, but also of acting as a support for one or several coatings. The study of materials is therefore intimately linked with that of the coatings to be applied to those materials.

***Figure 1 :*** *A coated plastic lens is a complex system.*

***Figure 1***



# SUPPLEMENT
## REVIEW OF BASIC NOTIONS CONCERNING THE NATURE AND STRUCTURE OF MATTER

*The analysis of material structures calls upon some notions of Physics and Chemistry relating to the Nature of matter. A brief review of these notions is provided below.*

*Modern Physics is based on the fact that, throughout the Universe, any material body is made of atoms. These are corpuscles which are perpetually in movement. They are in turn made of related elementary particles called protons and neutrons, around which smaller particles called electrons follow a distant orbit.*

*The radius of an atom measures between 1 and 2.$10^{-10}$ m - i.e., approximately 1Å (Angström). Atoms are the basic building blocks of all material bodies ; physicists have discovered that there are no more than about a hundred types of atoms present throughout the Universe. Mendeleev ingeniously predicted the list of these materials, and classified them in a table even before they were actually discovered : this classification is known as the Periodic Table of the Elements (figure 2).*

***Figure 2 :*** *Periodic Table of the Elements - (Mendeleev's table ).*

***Figure 2***

| | I a | II a | III b | IV b | V b | VI b | VII b | VIII | VIII | VIII | i b | II b | III a | IV a | V a | VI a | VII a | O | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 H | | | | | | | | | | | | | | | | | 2 He | 1 |
| 2 | 3 Li | 4 Be | | | | | | | | | | | 5 B | 6 C | 7 N | 8 O | 9 F | 10 Ne | 2 |
| 3 | 11 Na | 12 Mg | | | | | | | | | | | 13 Al | 14 Si | 15 P | 16 S | 17 Cl | 18 Ar | 3 |
| 4 | 19 K | 20 Ca | 21 Sc | 22 Ti | 23 V | 24 Cr | 25 Mn | 26 Fe | 27 Co | 28 Ni | 29 Cu | 30 Zn | 31 Ga | 32 Ge | 33 As | 34 Se | 35 Br | 36 Kr | 4 |
| 5 | 37 Rb | 38 Sr | 39 Y | 40 Zr | 41 Nb | 42 Mo | 43 Tc | 44 Ru | 45 Rh | 46 Pd | 47 Ag | 48 Cd | 49 In | 50 Sn | 51 Sb | 52 Te | 53 I | 54 Xe | 5 |
| 6 | 55 Cs | 56 Ba | 57 La | 72 Hf | 73 Ta | 74 W | 75 Re | 76 Os | 77 Ir | 78 Pt | 79 Au | 80 Hg | 81 Ti | 82 Pb | 83 Bi | 84 Po | 85 At | 86 Rn | 6 |
| 7 | 87 Fr | 88 Ra | 89 Ac | | | | | | | | | | | | | | | | |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 58 Ce | 59 Pr | 60 Nd | 61 Pm | 62 Sm | 63 Eu | 64 Gd | 65 Tb | 66 Dy | 67 Ho | 68 Er | 69 Tm | 70 Yb | 71 Lu | 6 |
| 90 Th | 91 Pa | 92 U | 93 Np | 94 Pu | 95 Am | 96 Cm | 97 Bk | 98 Cf | 99 Es | 100 Fm | 101 Md | 102 No | 103 Lr | 7 |

*In material bodies, atoms are assembled in more or less complex structures, which chemists have described as follows :*

*- **Simple Bodies** made of a single type of atom : Hydrogen, Oxygen, Carbon, Iron, Silicon, Barium, Titanium, etc.*

*- **Compound Bodies**, made of a single type of molecule, which is in turn a rigorously quantified assembly of predetermined atoms : water ($H_2O$), sodium chloride (NaCl), ethyl alcohol ($C_2H_6O$), silicon dioxide ($SiO_2$).*

*Simple and Compound Bodies are called Pure Bodies.*

*In particular, they are characterized by the rigorously precise temperatures at which they change state (Melting Point, Evaporation Point); these temperatures are in fact physical constants of the given material.*

*- **Mixtures**, consisting of a combination of Simple and Compound Bodies which is not strictly defined, and therefore cannot be represented by a precise chemical formula. Mixtures include air, steel, glass, rubber, honey, blood, petrol, etc. Their Melting and Evaporation Points are not precise, and vary depending on their composition.*

*In our terrestrial environment, it is also possible to define materials macroscopically, by referring to their essential atomic constituents. The following classifications can thus be distinguished :*

*- **mineral matter**, consisting of the Pure Bodies and Mixtures which form the rocks of the earth's crust - called "**SIAL**" and essentially made up of **SI**licon and **AL**uminum - and their derivatives. Their molecules consist of various combinations of a small number of atoms (from one to twenty) listed on the Periodic Table of the Elements. The main elements encountered in the field of Ophthalmic Optics are represented by the green area of figure 2.*

*- **organic matter**, consisting of the Pure Bodies and Mixtures which make up the basis of the plant and animal worlds and derivative bodies, fossil fuels, and synthetic materials obtained by Organic Chemistry. Organic materials, which are very numerous and complex ("the living organs are made of organic matter"), are made of molecules often comprised of a large number of atoms (as many as several thousand), although these atoms belong to a very limited number of species, i.e. basically to C, H, O and N (pink area on figure 2). Carbon, C, is a kind of skeleton for living matter, while H, O and N are the atmospheric elements which make life possible.*

## *The 3 states of Matter.*

*Imagine a drop of water : this consists of $H_2O$ molecules, which in turn consist of 2 atoms of Hydrogen combined with a single atom of Oxygen. At room temperature, these molecules are permanently in motion but stay together through the attraction they exert on each other, which maintains cohesion of the drop of water - this is the **LIQUID** state. The molecular agitation is proportional to temperature : if temperature rises, the motion accelerates and distances between the molecules increase. At a certain temperature, the forces of attraction are no longer enough to keep the molecules together, and they disperse in all directions - this is the **VAPOR** or **GAS** state. Although the drop can no longer be seen, the steam is nevertheless still made of $H_2O$ molecules. Conversely, if we cool the drop of water, the motion is slowed down until the molecules stop overlapping altogether and the system becomes static and literally frozen, producing ice, the **SOLID** state of water. Ice is characterized by a regular periodic structure called the crystalline network. It also exists another solid structure, called amorphous - or vitreous - state, which is characteristic of glass). The characteristic of the solid state is the fact that all molecules are in a fixed position with respect to each other, enabling solid matter to transmit forces and movement.*

***Figure 3 :*** *Liquid-to-gas change of state : evaporation of water.*
***Figure 4 :*** *Solid state : ice.*

***Figure 3***

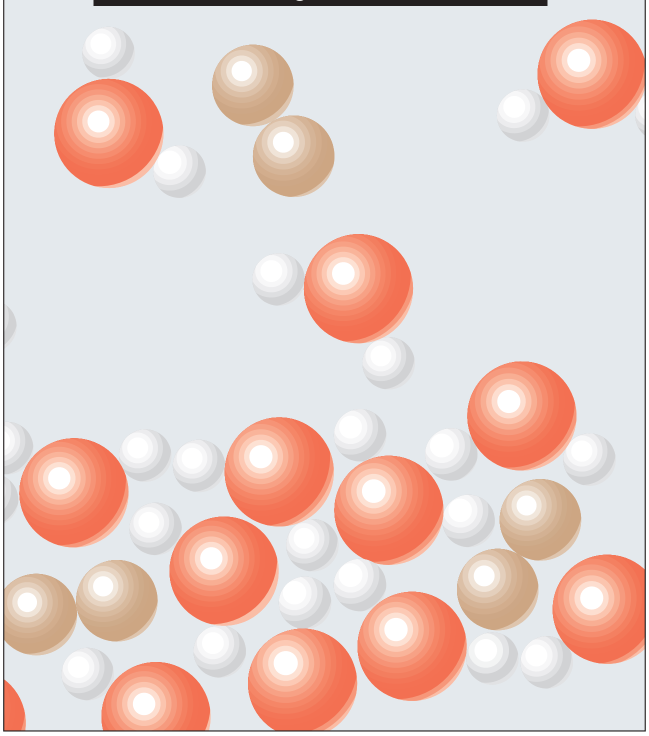
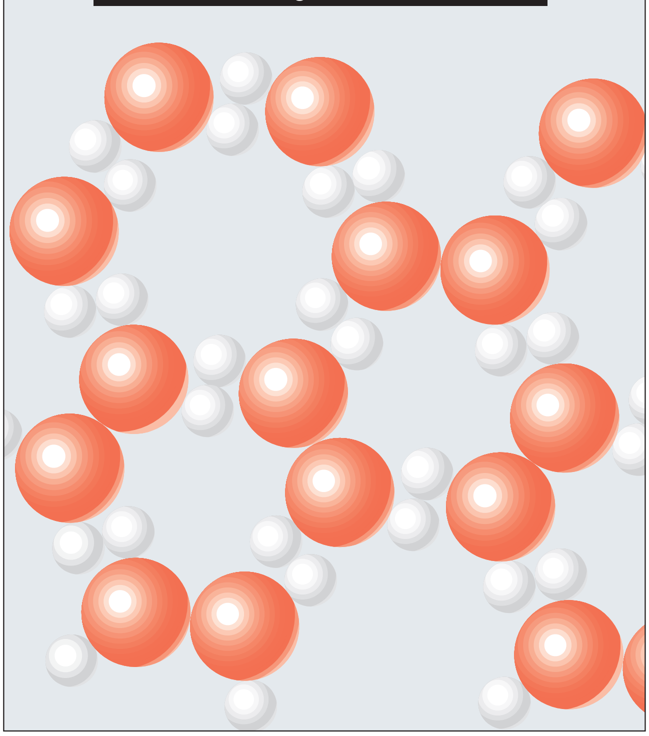


***Figure 4***



# CHARACTERIZATION OF MATERIALS

The aim of ophthalmic optics is to restore clear vision to an ametropic eye by placing a corrective lens between the viewed object and the eye. The dioptric function of the lens depends on :
- its geometric characteristics : radius of curvature, surface geometry, etc.
- the physicochemical characteristics of the material : refractive index, constringence, etc.

Research on Materials is chiefly aimed at obtaining and controlling these physicochemical characteristics. Furthermore, tools and techniques used to manufacture lenses require precise knowledge of the characteristics of the materials used. Extensive knowledge of these materials is therefore needed in the following areas :
- optical properties, to calculate the dioptric function and control of optical performances,
- mechanical and thermal properties, to describe dimensional aspects of lenses and their resistance to deformation,
- electrical properties, to physically characterize the materials,
- chemical properties, to account for behavior of materials with respect to external chemical agents.



## *A/ Optical properties*

These are the essential properties of the material. The optical properties act on light and, first and foremost, allow the sought corrective effect to be obtained. They correspond to various optical phenomena encountered at the level of the actual lens : light refraction through the surfaces, reflection on each side of the lens, possible absorption by the material, and also diffusion and diffraction. These phenomena will be described in detail, and material properties associated with each of them will be characterized.

***Figure 5***

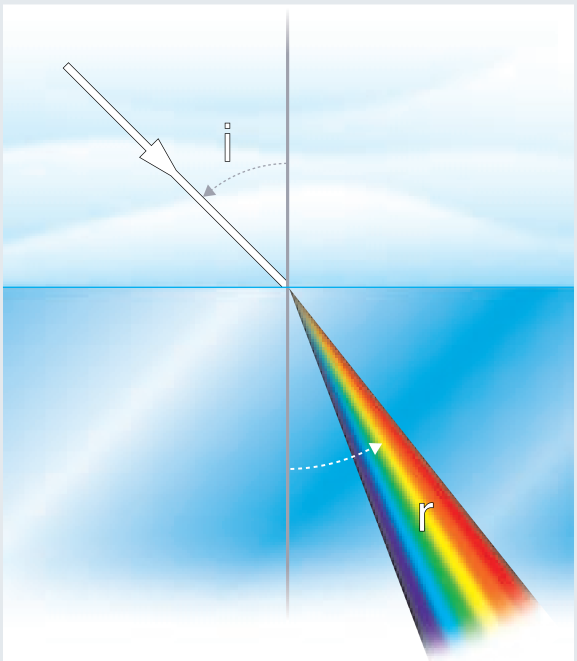



***Figure 5 :*** *Refraction and chromatic dispersion.*

## 1/ Refraction of light

The rays of light which cross the lens undergo refraction - or deviation - at the level of its front and back surfaces. Amplitude of these deviations is determined by the refractive power of the material, and by the incidence of the rays of light on each surface.

### a) Refractive index

The refractive index of a transparent medium is the ratio $n = c / v$ of the velocity of light in a vacuum (c) to the velocity of light in the given medium (v). This number, which has no unit and is always greater than 1, quantifies refractive power of the medium : the higher the refractive index, the more a beam of light entering this medium from air will be deviated.

At any point of a surface separating air from a transparent medium with refractive index n, the deviation or refraction is calculated according to Snell's - Descartes' law which stipulates that (figure 5) :
1 - the refracted ray lies in the plane formed by the incident ray and the perpendicular to the surface at the point of incidence
2 - angles of incidence i and refraction r, respectively formed by the incident and refracted rays with the perpendicular to the surface, are such that

$$\sin (i) = n \sin (r)$$

As the velocity of light in a transparent medium varies with wavelength, the value of the refractive index is always expressed for a reference wavelength : in Europe and in Japan, this reference is $\lambda_e$ = 546.07 nm (Mercury green spectral line), whereas in other countries like the U.S.A. it is $\lambda_d$ = 587.56 nm (Helium yellow spectral line) . This distinction has no real effect since it only changes the 3rd decimal of the value of the index.

Refractive indexes of materials currently used in ophthalmic optics range from approximately 1.5 for standard glass and plastic, up to 1.9 for the most recent glass materials.

### b) Chromatic dispersion : Constringence or Abbe number (*)

The variation of the refractive index with the wavelength of light causes the phenomenon of chromatic dispersion of white light upon refraction. Indeed, since the refractive index is higher for short wavelengths, refraction of visible light spreads from the red zone towards the blue zone of the spectrum (figure 5).

To characterize the dispersive power of a material, a quantity called constringence or the Abbe number is used (*). In Europe and Japan this is defined by $\nu_e$ , and in other countries like the U.S.A. it is defined by $\nu_d$ , with the following respective formulae :

$$\nu_e = \frac{n_e - 1}{n_{f'} - n_{c'}} \quad \text{or} \quad \nu_d = \frac{n_d - 1}{n_f - n_c}$$

where :
$n_e$ : index for $\lambda_e$ = 546.07 nm (green Hg)
$n_d$ : index for $\lambda_d$ = 587.56 nm (yellow He)

$n_{f'}$ : ................. $\lambda_{f'}$ = 479.99 nm (blue Cd)
$n_f$ : ................. $\lambda_f$ = 486.13 nm (blue H)

$n_{c'}$ : ................. $\lambda_{c'}$ = 643.85 nm (red Cd)
$n_c$ : ................. $\lambda_c$ = 656.27 nm (red H)

The Abbe number is inversely proportional to chromatic dispersion of the material, and generally varies in ophthalmic optics between 60 for the least chromatic and 30 for the most chromatic materials. Generally speaking, although there are some exceptions, the higher a refractive index, the greater the chromatic dispersion, thus, the lower the Abbe number (see table 2).

Chromatic dispersion is an important but not an essential characteristic in ophthalmic optics. Although it exists in all lenses, this factor is always negligible at the center, and is only really discernible at the periphery of lenses manufactured with highly dispersive materials. In this case, dispersion is seen as color fringes at the edges of off-axis objects. Experience has shown that chromatism of ophthalmic lenses has no perceptible effects for the majority of corrective lens wearers.

*(*) See " Supplement " section below*

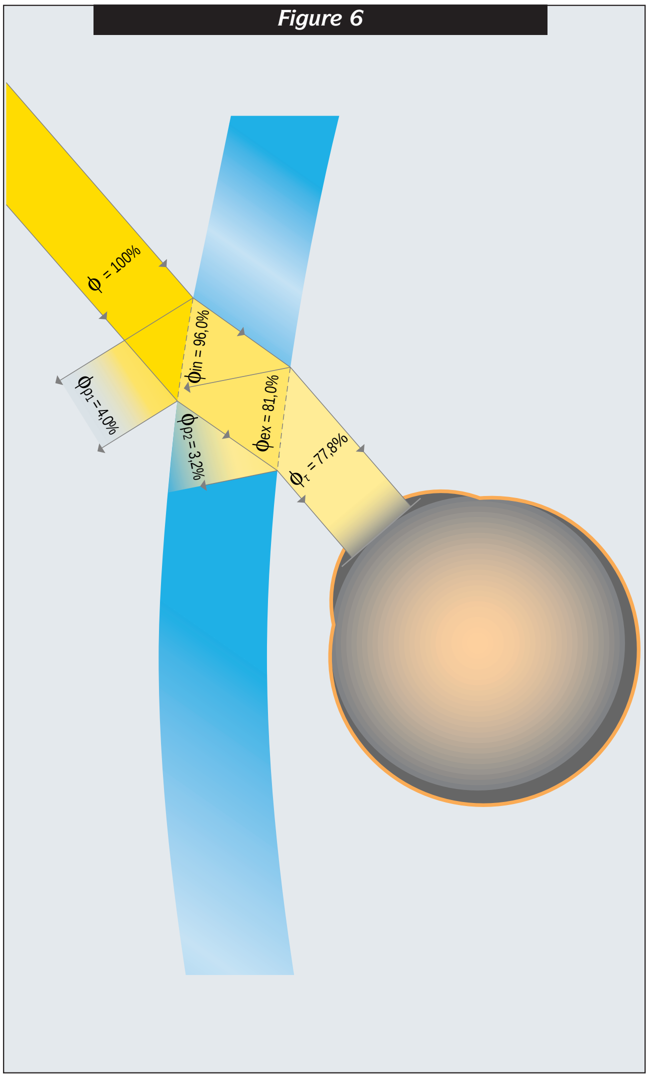



***Figure 6 :*** *Refraction, reflection and absorption of light in an ophthalmic lens (1.5 index lens with 15 % absorption).*

## 2/ Reflection of light

At the same time as refraction, a phenomenon of light reflection also occurs at each of the lens surfaces. This results, for the wearer, in a loss of lens transparency, and in undesirable reflections on the lens surfaces. The higher the refractive index of the lens material, the more light is lost through reflection :

| Index : | | | | |
|---|---|---|---|---|
| 1.5 | 1.6 | 1.7 | 1.8 | 1.9 |

| Total reflected light : | | | | |
|---|---|---|---|---|
| 7.8 % | 10.4 % | 12.3 % | 15.7 % | 18.3 % |

This unwanted reflection can be almost completely eliminated by applying an efficient antireflective coating (see Ophthalmic Optics File on Coatings).

## 3/ Absorption of light

The amount of light which goes through a lens can be reduced because of absorption by the material : this is negligible for an untinted ophthalmic lens, but constitutes an intrinsic function of a tinted or photochromic lens. Absorption of an ophthalmic lens generally refers to its internal absorption, i.e. to the percentage of light absorbed between the front and rear lens surfaces. For example, 30 % absorption corresponds to a 30 % internal reduction in luminous flux, which should be added to the loss already caused by the reflection on both surfaces of the untinted lens. Lens absorption occurs according to Lambert's law, and varies exponentially as a function of lens thickness (see "Supplement" section below).

### Light transmitted by an ophthalmic lens

The light transmitted by a lens is simply the amount of light that is neither reflected nor absorbed by the lens. Luminous flux $\phi_\tau$ , which reaches the eye, corresponds to incident flux $\phi$ at the front surface of the lens, attenuated by flux $\phi_\rho$ reflected by the 2 surfaces, and by flux $\phi_\alpha$ , possibly absorbed by the material, such that $\phi_\tau + \phi_\rho + \phi_\alpha = \phi$. Furthermore, the wearer's perception results from the combination of 3 elements : intensity and spectral composition of the incident light, absorption and spectral selectivity of the lens, and sensitivity of the eye to the different visible wavelengths (see figures 6 and 7 and "Supplement" section below).

**Figure 7**

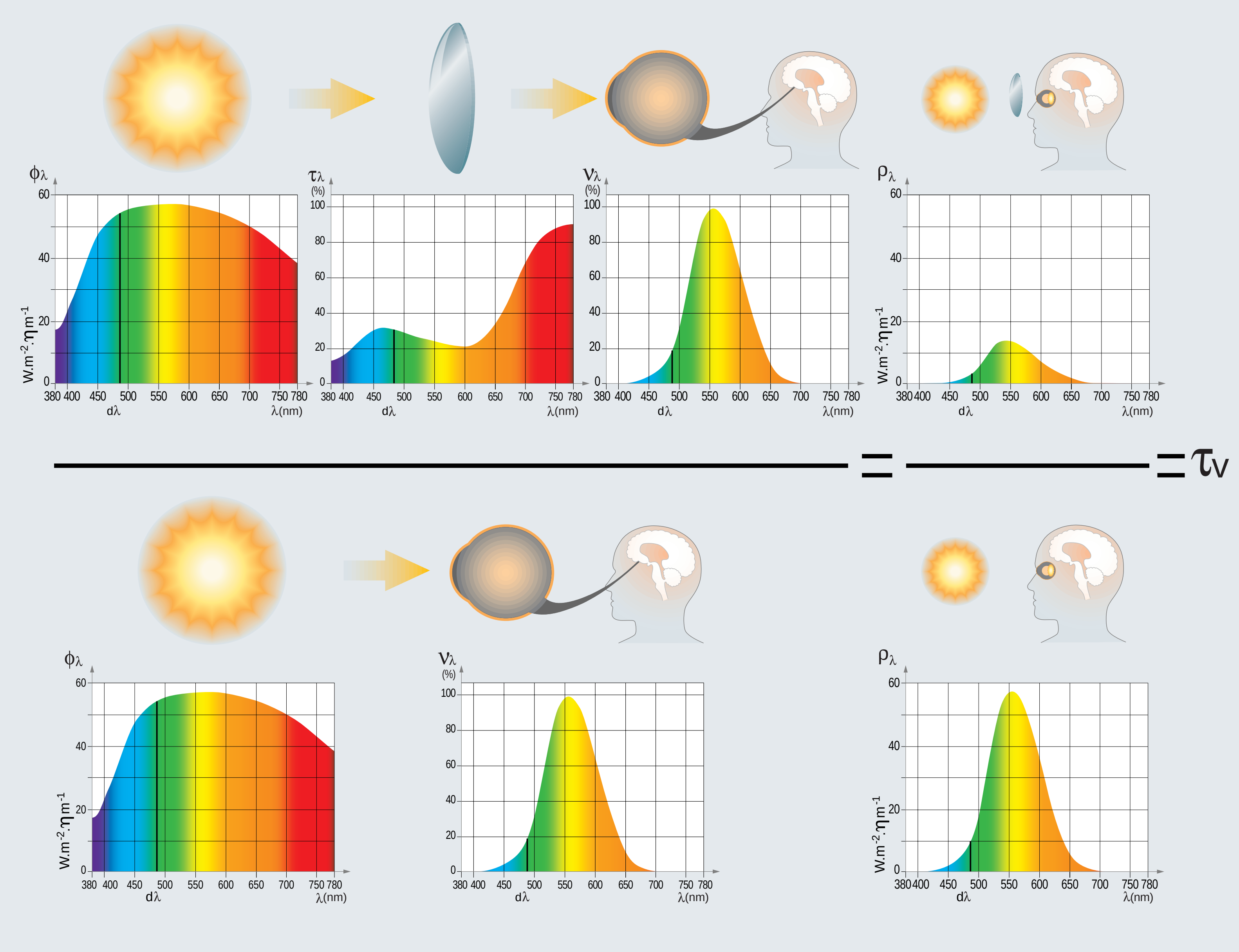



***Figure 7 :*** *Transmission of an ophthalmic lens.*

## 4/ Diffusion and diffraction of light

a) Diffusion

Diffusion is a phenomenon which can be described as a scattering of light in all directions. It occurs at the surface of all solids, and inside transparent materials. In an ophthalmic lens, there is theoretically no surface diffusion since lens surfacing processes (particularly polishing) are performed to eliminate this phenomenon. It does occur, however, when the lens is soiled by external pollution or when its surface is smeared with oil. Diffusion within the actual lens is also very limited, but in some cases, may give lenses a yellow or milky appearance. Overall, though, an ophthalmic lens diffuses only a very small quantity of light, generally considered as negligible.

b) Diffraction

Diffraction is a phenomenon consisting of a change in the direction of a light wave when it encounters a small obstacle (measuring only a few wavelengths). This phenomenon is important in ophthalmic optics, since it can reveal irregularities on lens surfaces, and in particular scratches resulting from wear and tear.

## Characterization of chromatism : Constringence or the Abbe number ?

*Improper use of terminology often leads to use of the term "Abbe number" to designate constringence, whereas in fact definitions of these two factors are slightly different. While the Abbe number uses the same formula as constringence - $\nu_d$ - the reference yellow spectral line is the D medium of the sodium doublet with wavelength $\lambda_D$ = 589.29 nm, instead of the yellow Helium spectral line d, with wavelength $\lambda_d$ = 587.56 nm. However, differences between $\nu_d$ and $\nu_D$ (and even $\nu_e$ ) are small and relatively insignificant in ophthalmic optics, since they affect only the first decimal of the constringence value.*

## Characterization of transmission of an ophthalmic lens :

### Transmission factor :

*The transmission properties of a lens are characterized by its transmission factor $\tau = \phi_\tau / \phi$ ratio of the luminous flux $\phi_\tau$ which exits from its back surface to the luminous flux $\phi$ incident reaching its front surface (figure 6). Since transmission varies with wavelength, the spectral transmission factor $\tau_\lambda$ of the lens is determined for each wavelength $\lambda$ of the incident light.*

### Transmission curve

*The transmission curve describes the physical properties of the light filter comprised by the lens, presenting the variation of its spectral transmission factor $\tau_\lambda$ as a function of wavelength (figure 7). This curve allows spectral selectivity of the filter to be observed, and the physical transmission factor $\tau$ of the lens to be determined throughout the wavelengths ranging from $\lambda_1$ to $\lambda_2$ , using the formula :*

$$\tau_\lambda = \frac{\int_{\lambda_1}^{\lambda_2} \phi_\lambda . \tau_\lambda \, d\lambda}{\int_{\lambda_1}^{\lambda_2} \phi_\lambda . \, d\lambda}$$

*where $\phi_\lambda$ = incident spectral flux.*

### Relative transmission factor in the visible range $\tau_V$

*This factor is specific to ophthalmic optics, and summarizes the physiological properties of the filter as a single number : the ratio of the luminous flux emerging from the lens and of the luminous flux incident upon the entrance surface, as perceived by the eye, i.e. weighted for each wavelength by relative spectral luminous efficiency $V_\lambda$ of the eye. This factor is calculated using the following formula :*

$$\tau_V = \frac{\int_{380}^{780} \phi_\lambda . \tau_\lambda \, V_\lambda \, d\lambda}{\int_{380}^{780} \phi_\lambda . V_\lambda \, d\lambda}$$

*where $\tau_\lambda$ = spectral transmission factor, $\phi_\lambda$ = incident spectral flux, $V_\lambda$ = relative photopic spectral luminous efficiency of the eye (see detailed illustration, figure 7). This coefficient, $\tau_\lambda$ , is used to describe and classify sunglasses.*

### U.V. cutoff :

*In ophthalmic optics, ultraviolet absorption properties are of particular interest : to characterize the "UV cutoff" of a lens, the wavelength up to which the lens transmits less than 1% light is determined on the lens transmission curve.*

*NB : Transmission characteristics of ophthalmic lenses are usually established for lenses of 2.0 mm thickness, under normal incidence.*

### *Characterization of reflection of an ophthalmic lens :*

#### *Reflection factor :*

*Reflection at the interface of two media is characterized by the reflection factor* $\rho = \phi_\rho / \phi$ *ratio of reflected luminous flux* $\phi_\rho$ *and of incident luminous flux* $\phi$ *(figure 6). Since reflection varies with wavelength, the spectral reflection factor* $\rho_\lambda$ *is generally determined for each wavelength* $\lambda$ *of the incident light.*

*At the level of one surface separating air from a transparent medium of refractive index n, the reflection factor is obtained using the following formula, established by Fresnel :*

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

*assuming that the light incidence is normal. This factor represents the curbing of luminous flux through the surface, and is used as an attenuator coefficient, applied to the incident flux of light : thus luminous flux* $\phi$ *crossing one surface of reflection factor* $\rho$ *loses a fraction of intensity* $\phi_\rho$ *to become* $\phi.(1-\rho)$ *after traversing the surface. For an ophthalmic lens, the reflection phenomenon occurs at both the front and back sides of the lens, such that the total reflected flux is calculated with the formula* $\phi_\rho = \phi \,.\, \rho \,.(2-\rho)$ *, when there is no absorption.*

#### *Relative reflection factor in the visible range* $\rho_V$

*This factor is used in ophthalmic optics to characterize the visual effect of reflection by the ratio of reflected light flux* $\phi_\rho$ *to incident light flux* $\phi$ *as perceived by the eye, i.e. weighted for each wavelength by the relative spectral luminous efficiency of the eye,* $V_\lambda$*. This factor is calculated with the following formula :*

$$\rho_V = \frac{\int_{380}^{780} \rho_\lambda \, \phi_\lambda \, V_\lambda \, d\lambda}{\int_{380}^{780} \phi_\lambda \, V_\lambda \, d\lambda}$$

*where* $\rho_\lambda$ = *spectral reflection factor,* $\phi_\lambda$ = *incident spectral flux,* $V_\lambda$ = *relative photopic spectral luminous efficiency of the eye.*

### *Characterization of absorption of an ophthalmic lens :*

#### *Absorption factor*

*Absorption of a lens is characterized by its internal absorption factor* $\alpha_i = \phi_\alpha / \phi_{in}$ *, the ratio of luminous flux* $\phi_\alpha = \phi_{in} - \phi_{ex}$ *which is absorbed between entrance and exit surfaces to luminous flux* $\phi_{in}$ *which has passed through the entrance surface (see figure 6). As lens absorption varies with wavelength, the internal spectral absorption factor* $\alpha_{i\,\lambda}$ *of the lens is determined for each wavelength* $\lambda$ *of incident light.*

*The quantity of light absorbed during traversal of a material is given by Lambert's law, which stipulates that layers of material of equal thickness produce equal light absorption (expressed as %), irrespective of light intensity. It is thus possible to deduce that luminous flow* $\phi_{ex}$ *reaching the lens exit surface is given by the formula* $\phi_{ex} = \phi_{in} \,.\, e^{-k.x}$ *where k is the specific coefficient of extinction of the material, and x is thickness of the material traversed by the light. The internal absorption factor is calculated using the formula* $\alpha_i = 1 - e^{-k.x}$*; and is applied as an attenuating coefficient such that* $\phi_{ex} = \phi_{in} \cdot (1-\alpha_i)$*.*

### *Application : calculation of the luminous flux transmitted by a lens*

*Given an incident luminous flux* $\phi$ *which reaches the surface of a lens :*
*- after partial reflection on the first surface, the flux which enters the lens is :* $\phi \,.\, (1-\rho)$*,*
*- this flux is attenuated upon traversing the lens, and becomes :* $\phi.\,(1-\rho)(1-\alpha_i)$ *when it reaches the second lens surface*
*- reflection occurs again, such that the flux emerging from the lens is :* $\phi_\tau = \phi \;(1-\rho)^2 \,.(1-\alpha_i)$*.*

## *B/ Mechanical properties*

Mechanical properties are the characteristic properties of the solid and massive state of materials. They define values relative to mass, volume and dimensions, and resistance to deformation and shock. The following characteristics are generally used :

- specific gravity is the ratio of the density of 1 $m^3$ of a given substance to the density of 1 $m^3$ of water, the usual standard of reference for solids under normal conditions. It is expressed by a number without a unit,
- hardness measured in clearly defined systems using precision instruments, such as the Knoop, Rockwell, and Barcol hardness tests,
- modulus of elasticity E (or Young's modulus) : ratio between a stress and the corresponding deformation where the material resumes its initial shape upon removal of the stress (in Pascal : Pa),
- impact resistance : compliance with the test consisting of dropping a 0.56 ounce (16 g) steel ball from a height of 50 inches (1.27 m) - test established in the USA by the Food & Drug Administration (FDA),
- breaking-point resistance : compliance with the “100 Newton” CEN static deformation test - which consists of exerting increasing pressure at a constant rate up to a value of 100 Newtons (procedure being reviewed by the European Standardization Committee),
- breaking-point in traction, compression, and deflection (Pa),

## C/ Thermal properties

Thermal properties characterize changes of state and the effect of temperature on materials. The main thermal properties are as follows :
- thermal conductance (W.m$^{-1}$.°K$^{-1}$)
- specific heat : the ratio of the quantity of heat required to raise the temperature of a body by one degree to that required to raise the temperature of an equal mass of water by one degree (J.Kg$^{-1}$.°K$^{-1}$)
- linear dilatation coefficient : given for a predefined temperature range ($10^{-7}$/°K)
- melting point (d°C) - a physical constant for Pure Bodies - for glass, melting point is defined by the temperature at which it has a viscosity of $10^{2,5}$ poises
- evaporation point (d°C) at a given pressure - e.g. for materials used for Antireflection Coatings, the evaporation point may be specified under low pressure (~ $10^{-6}$ mbar),
- stress temperature $T_C$ (for the lens) : the temperature at which viscosity reaches the value of $10^{14,5}$ poises,
- vitreous transition temperature $T_G$, at which lens viscosity presents a value of $10^{13,3}$poises.

## D/ Electrical properties

Electrical properties characterize effects of electro-magnetic waves and electricity on materials. They are governed by complex laws of physics. Some link the optical properties of solids to their electrical properties. For this reason, manufacturers of materials mention the following parameters :
- dielectric strength (V.m$^{-1}$),
- dielectric loss factor (tg $\delta$ x $10^4$), at predefined frequencies.

## E/ Chemical properties

Chemical properties characterize the reaction of materials to the chemical substances usually found during lens manufacture, in everyday life, or to certain extreme conditions to which materials can be subjected, such as accelerated ageing in order to test their reliability. These substances are usually water - hot and cold, salty and fresh - acids, bases, and various organic solvents. Finally, international standards also require testing to determine fire resistance of materials used to manufacture ophthalmic lenses.

# THE BASIC OPHTHALMIC LENS



## *A/ Glass materials*

Glass is a solid, amorphous material, which is hard and breakable at ambient temperature, and becomes viscous at high temperatures. It is obtained by melting a mixture of oxides of elements such as Silicon, Calcium, Sodium, Potassium, Lead, Barium, Titanium, and Lanthanum at a temperature of about 1500 °C / 2700 °F. Glass does not have a homogeneous chemical structure. Consequently, there is no precise melting point at which it abruptly changes from the solid to the liquid state. Furthermore, as temperature rises, glass softens, its viscosity decreases, and it very gradually goes from solid to liquid, this very gradual change being characteristic of the so-called “vitreous” state. This unique feature means that glass can be worked while hot, and molded. It is valuable for ophthalmic optics for two reasons : it transmits visible light, and its surface can be polished and therefore made transparent.

### 1/ Standard glass materials (1.5 and 1.6)

Glass of index 1.5 is the traditional material used in ophthalmic optics. It is made of 60 to 70 % Silicon dioxide, the remainder consisting of various compounds such as Calcium, Sodium and Boron oxides.
Glass of index 1.6 is currently becoming the new standard in ophthalmic optics. Its higher index is obtained by adding a significant proportion of Titanium dioxide to the mixture.

Materials are usually grouped into 2 categories depending on their chemical composition (see table 1) :
- “Sodium-Calcium” glass, containing significant proportions of Sodium and Calcium : this is the traditional material used in optics : its refractive index is relatively low ($n_e$ = 1.525 / $n_d$ = 1.523), as is its chromatic dispersion (constringence of about 60).
- “Borosilicate” glass, with a high Boron content : this is the most recent material used to manufacture photochromic and medium-index glass lenses ($n_e$ = 1.604 / $n_d$ = 1.600).

### 2/ Solid tint glass materials

Glass can be mass tinted by incorporating metal salts with specific absorption properties into its composition : for example, salts of Nickel and Cobalt (purple), Cobalt and Copper (blue), Chromium (green), Iron, Cadmium (yellow), Gold, Copper, Selenium (red), etc. These solid tint materials are mainly used for mass production of plano sun lenses or protective spectacles. A few faintly tinted materials (brown, grey, green or pink colors), with specific filtering properties are also used to manufacture corrective lenses, but such lenses are in far less demand today, a major drawback being that darkness of the tint varies with lens thickness.

## 3/ Photochromic glass materials

Photochromism is the property of a material to react to the intensity of sunlight by a modification of its light absorption properties. Its basic principle - which is common to glass and plastic photochromic materials - is to darken under the effects of U.V. radiation, and to fade under the effects of ambient heat ; these two actions are reversible, and may occur indefinitely. This result is achieved by the activation of molecules of photochromic substances incorporated into the material. Light absorption is determined at all times by the equilibrium between the number of photosensitive molecules activated by U.V. stimulation, and the number of molecules deactivated by heat.

The first photochromic glass materials appeared around 1962, and have been constantly improved with each successive generation of lenses. They are obtained by introducing silver halide crystals into the material. These crystals react to ultraviolet radiation, such that the lens darkens. At the atomic level, the basic mechanism of photochromism is an electron exchange between the Silver atom - present as Silver Chloride (figure 9) - and its environment. In the absence of light, the Silver-Chloride bond is ionic, and the Silver ion is transparent ; the lens is clear. In the presence of U.V. radiation, the unstable electron leaves the Chloride ion to join the Silver ion which becomes metallic and absorbs light : the lens darkens. When the U.V. radiation diminishes, the mobile electron leaves the Silver atom and returns to the Chloride atom, and the lens gradually returns to its original clear state.

***Figure 8 :*** *General principle of photochromism.*

***Figure 9 :*** *Principle of glass photochromism.*

***Figure 8***

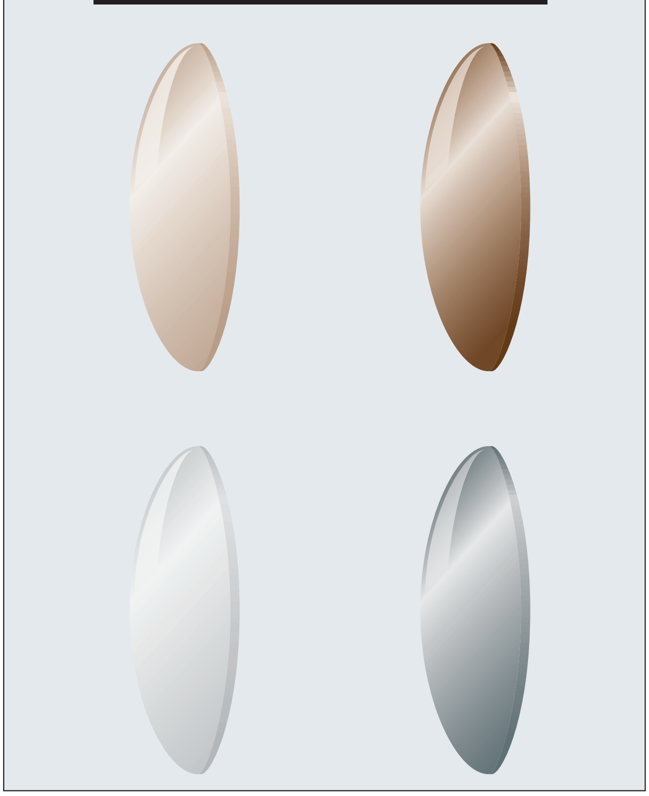
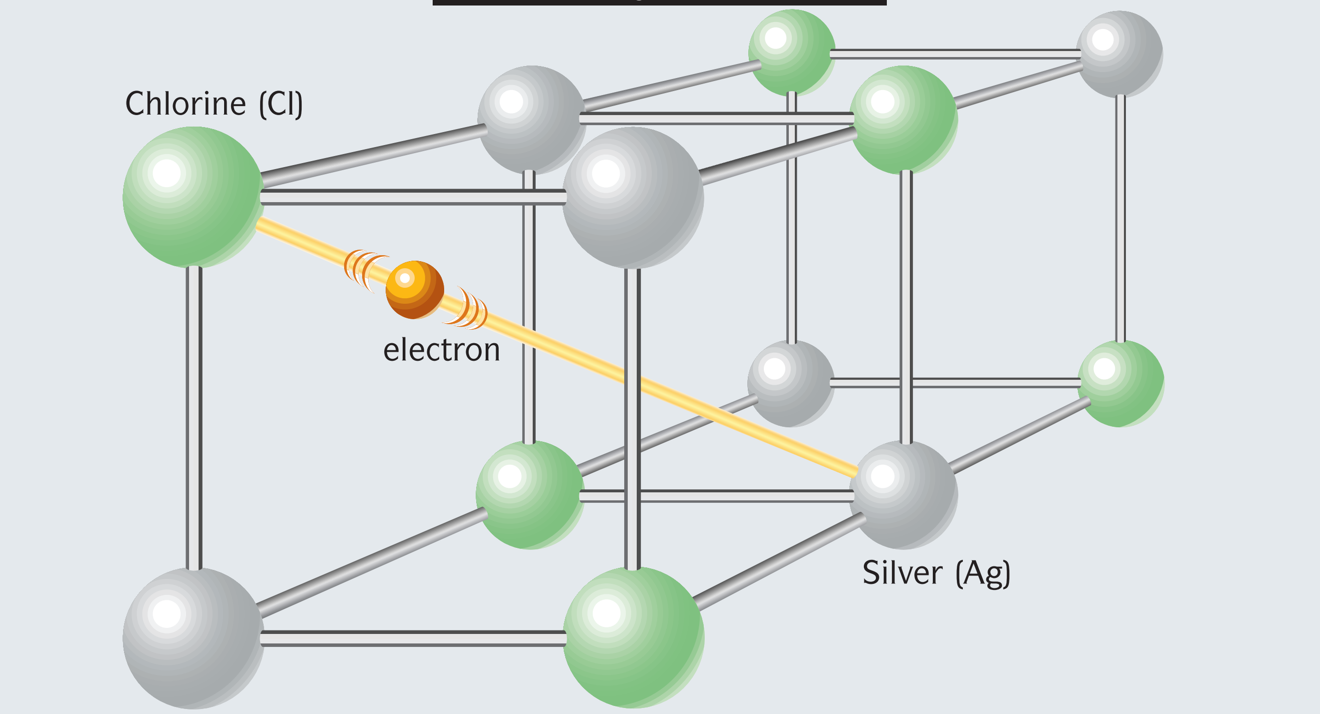


***Figure 9***



### 4/ High index glass materials (1.7, 1.8 et 1.9)

For many years, glassmakers have sought to raise the refractive index of their materials, while maintaining low chromatism values. To do so, they have regularly introduced new chemical elements into the composition of glass. Thus, around 1975, lenses containing Titanium with a 1.7 index and constringence of 41 were manufactured ; these were followed approximately fifteen years later by lenses containing Lanthanum with a 1.8 index and constringence of 34 and, finally, around 1995, by lenses containing Niobium with index 1.9 and constringence of 30. These materials allow thinner lenses to be manufactured, but do not achieve a significant reduction in weight. Indeed, the increased refractive index of the material goes together with an increase in density, which counteracts any reduction in weight one might have expected from the reduction in lens volume .

**Table 1 : Indicative chemical composition of the main glass materials (in weight)**

| Component | Oxide | GLASS MATERIAL TYPES | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Sodium-Calcium | | Borosilicate | | Titanium | Titanium/ Lanthanum | Lanthanum/Niobium | |
| | | 1.5 clear | 1.5 tinted | 1.5 photo | 1.6 photo | 1.6 clear | 1.7 clear | 1.8 clear | 1.9 clear |
| Silicium | $SiO_2$ | 70 | 71 | 57 | 48 | 56 | 36 | 29 | 7 |
| Aluminum | $Al_2O_3$ | 1 | - | 6 | - | 1 | - | - | - |
| Boron | $B_2O_3$ | 1 | - | 18 | 15 | 6 | 10 | 2 | 17 |
| Sodium | $Na_2O$ | 11 | 12 | 4 | 1 | 9 | 2 | - | - |
| Potassium | $K_2O$ | 5 | 6 | 6 | 5 | 8 | - | - | - |
| Lithium | $Li_2O$ | - | - | 2 | 2 | 4 | 6 | 4 | - |
| Magnesium | $MgO$ | 1 | - | - | - | - | - | - | - |
| Calcium | $CaO$ | 9 | 11 | - | - | - | 9 | 15 | 14 |
| Barium | $BaO$ | 2 | - | - | 6 | - | - | - | - |
| Zirconium | $ZrO_2$ | - | - | 5 | 7 | 1 | 5 | 5 | 8 |
| Titanium | $TiO_2$ | - | - | 2 | 6 | 15 | 6 | 9 | 9 |
| Niobium | $Nb_2O_5$ | - | - | - | 8 | - | 9 | 15 | 21 |
| Lanthanum | $La_2O_3$ | - | - | - | - | - | 14 | 21 | 24 |
| Strontium | $SrO$ | - | - | - | 2 | - | 3 | - | - |
| Iron | $Fe_2O_3$ | - | 1 | - | - | - | - | - | - |

## Table 2 : Characteristics of the main materials

| | GLASS MATERIALS | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Standard index** | | | **Medium index** | | | **High index** | |
| | clear | photochromic grey | photochromic brown | clear | photochromic grey | photochromic brown | clear | clear |
| Essilor brand name | 15 clear | 15 Isorapid grey | 15 Isorapid brown | 16 clear | 16 Isorapid grey | 16 Isorapid brown | 17 | 18 |
| Refractive index $n_e$ | 1.525 | 1.525 | 1.525 | 1.604 | 1.604 | 1.604 | 1.705 | 1.807 |
| $n_d$ | 1.523 | 1.523 | 1.523 | 1.600 | 1.600 | 1.600 | 1.701 | 1.802 |
| Constringence $\nu_e$ | 59 | 57 | 56 | 41 | 42 | 42 | 41 | 34 |
| $\nu_d$ | 59 | 57 | 56 | 42 | 42 | 42 | 42 | 35 |
| Specific gravity | 2.61 | 2.41 | 2.41 | 2.63 | 2.70 | 2.73 | 3.21 | 3.65 |
| U.V. cut off | 330 nm | 335 nm | 335 nm | 335 nm | 345 nm | 345 nm | 335 nm | 330 nm |

| | PLASTIC MATERIALS | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Thermosetting** | | | | | | | **Thermo-plastic** |
| | **Standard index** | | | **Medium index** | | | **High index** | **High index** |
| | clear | photochromic grey | photochromic brown | clear | photochromic grey | photochromic brown | clear | polycarbonate |
| Essilor brand name | Orma | Orma Transitions Plus | Orma Transitions Eurobrown | Ormex | Ormex Transitions III | Ormex Transitions III | Ormil | |
| Refractive index $n_e$ | 1.502 | 1.502 | 1.502 | 1.561 | 1.559 | 1.559 | 1.599 | 1.591 |
| $n_d$ | 1.500 | 1.500 | 1.500 | 1.557 | 1.557 | 1.557 | 1.595 | 1.586 |
| Constringence $\nu_e$ | 58 | 58 | 58 | 37 | 37 | 37 | 36 | 31 |
| $\nu_d$ | 59 | 59 | 59 | 37 | 38 | 38 | 36 | 30 |
| Specific gravity | 1.32 | 1.28 | 1.28 | 1.23 | 1.20 | 1.20 | 1.36 | 1,20 |
| U.V. cut off | 355 nm | 370 nm | 370 nm | 370 nm | 390 nm | 390 nm | 380 nm | 380 nm |

## *B/ Plastic materials*

Plastic materials can be divided into 2 groups :
- thermosetting resins which have the property of hardening under the action of heat, without the possibility of subsequent reshaping under heat ; most of the resins used in ophthalmic optics are of this type, particularly CR 39,
- thermoplastic resins which have the property of softening under the action of heat, and are particularly suitable for shaping under heat or injection molding : polycarbonate is such a material.

### 1/ Standard plastic material (CR 39)

Diethylene Glycol bis (Allyl Carbonate), better known as CR 39 (1), is the material most widely used to manufacture currently marketed plastic lenses. It was discovered during the forties by chemists from the “Columbia Corporation” (division of the American **PPG** - **P**ittsburg **P**late **G**lass company), hence its name, since it was the “**C**olumbia **R**esin” # 39 of a series of polymers studied by chemists for the US Air Force. It was used to manufacture corrective lenses between 1955 and 1960 (by the firm called **LOS** - **L**entilles **O**phtalmiques **S**péciales - , one of the Essilor founding companies), which led to the introduction of Orma® lenses (2), the first lightweight, impact-resistant lenses.

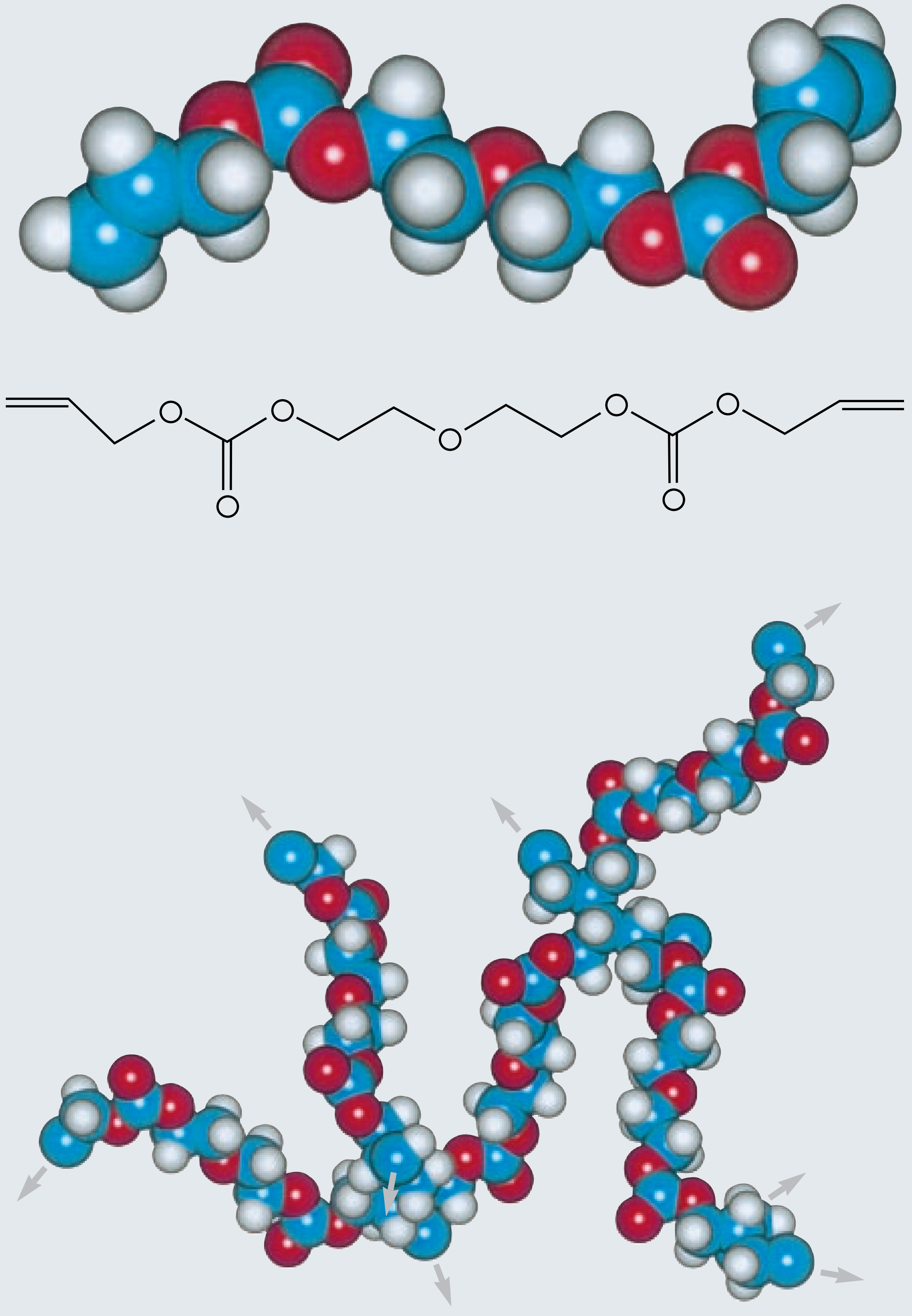
CR 39 is a polymerizable thermosetting resin, i.e. in its basic form it is a liquid (the monomer), which is hardened by polymerization under the effect of heat and a catalyst. Polymerization is a chemical reaction whereby several identical molecules of monomer create a new molecule of polymer, with different dimensions and properties. In the case of CR 39, the polymer thus obtained is reticulated (i.e. comprised of a three-dimensional network), making it unmeltable, insoluble, resistant to solvents, and dimensionally stable.

For ophthalmic optics, CR 39 features a number of properties which account for its success : a refractive index of 1.5 (close to that of standard glass), a density of 1.32 (almost half that of glass) and a constringence of 58-59 (thus a very low chromatism), high impact resistance, excellent transparency, and multiple tinting and coating possibilities. Its major drawback is its limited resistance to abrasion relative to glass.

*(1) CR 39 is a registered trade mark of PPG Industries.*
*(2) Orma® is a registered trade mark of Essilor International.*

***Figure 10 :*** *CR 39 molecule : monomer and polymer.*

**Figure 10**



## 2/ Tinted plastic materials

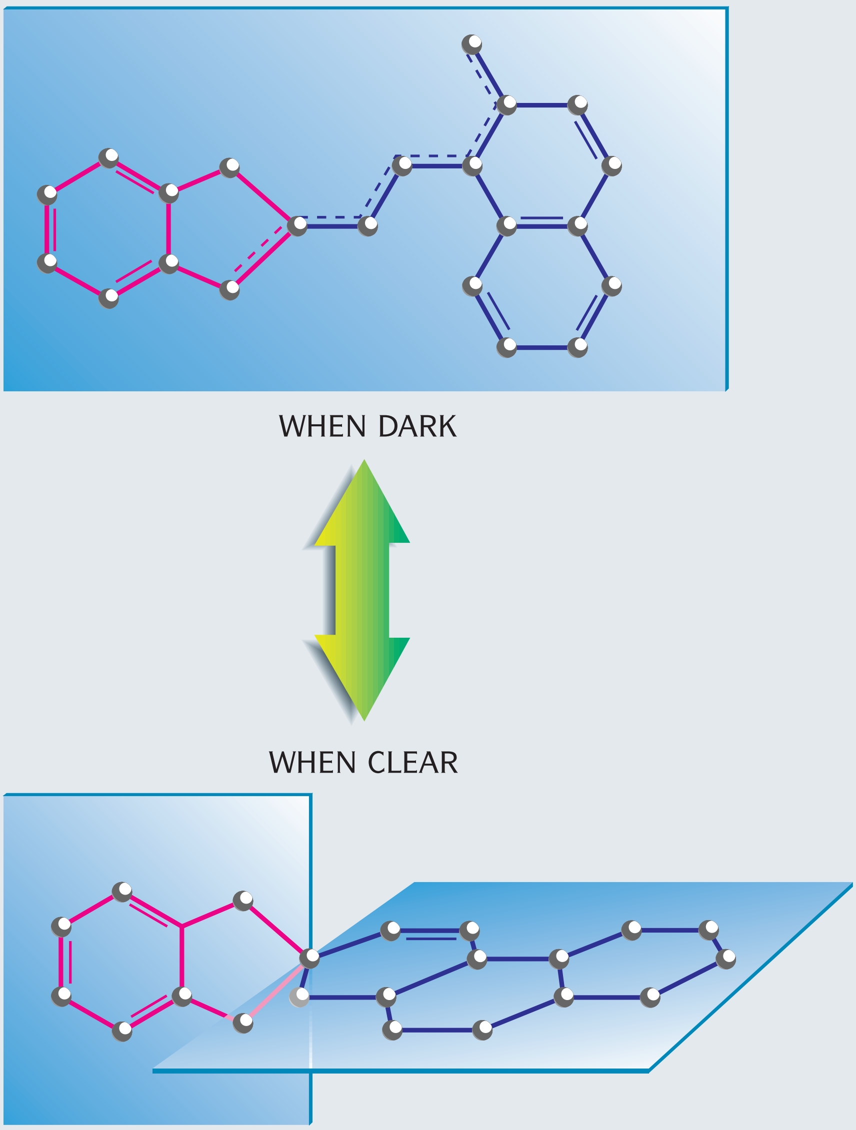
Solid tint plastics are exclusively used to manufacture sun lenses. They are obtained by adding dyes before polymerization, and are particularly suitable for the mass production of plano sun lenses, with a wide variety of tints and absorptions. U.V. absorbers are generally added to these materials, to improve protection against U.V. radiation.

## 3/ Photochromic plastic materials

The first photochromic plastics appeared briefly around 1986, but they only really started to develop in 1990, when the first Transitions® lenses were introduced (3). The photochromic effect is obtained by introducing photosensitive compounds into the material. Under the action of specific band of ultraviolet radiation, these compounds undergo structural changes, which modify absorption properties of the material. The compounds are incorporated using two main procedures : either they are mixed with the liquid monomer before polymerization, or they are applied by imbibing after polymerization (the latter procedure is used for Transitions lenses). Several families of molecules are used to create photochromism, and these families are subject to several types of structural modifications. Figure 11 shows the case of a Spiro-Oxazine molecule :

***Figure 11 :*** *Principle of photochromism in plastic material (example of a Spiro-Oxazine molecule).*

**Figure 11**




*(3) Transitions® is a registered trade mark of Transitions Optical Inc.*

the right part of the molecule rotates under the effect of ultraviolet light, causing the lens to darken. Photochromism of plastic lenses is generally obtained by using several dyes, and the final product combines respective photochromic effects of each of these agents.

## 4/ Medium and high index plastic materials

The use of medium index ($n \leqslant 1.56$) and high index ($n > 1.56$) plastics has greatly increased over recent years. Compared with traditional CR 39, they allow manufacture of even thinner, lighter lenses. Their density is generally similar to that of CR 39 (between 1.20 and 1.40), although their chromatism is generally greater (constringence $\leqslant 45$), as is their sensitivity to heat and, generally, they offer better U.V. protection (see table 2). The main drawback of these materials is that they are easily scratched, and a protective coating must thus be applied systematically. They can also be tinted and antireflection coated. These materials are currently undergoing intensive development, and hold much promise for the future.

### a/ Thermosetting resins

Most medium and high index plastics available today are thermosetting resins. Their refractive index is increased using one of the two following techniques :
- modification of the electronic structure of the initial molecule, for example, by introducing aromatic structures,
- introduction in the initial molecule of heavy atoms such as halogens (Chlorine, Bromine, etc.) or Sulfur.

The manufacturing process for lenses made of these materials is similar in principle to that described above for CR 39.

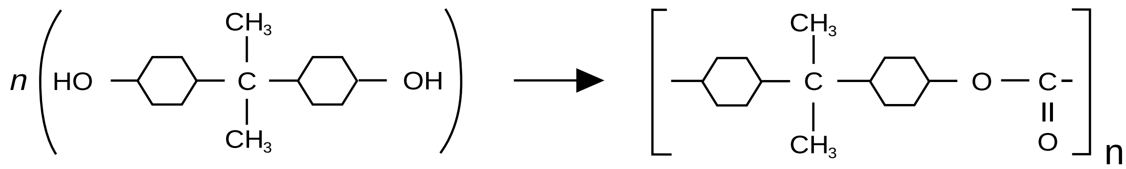
### b/ Thermoplastic resins : Polycarbonate

Thermoplastics like Plexiglas or PMMA were used during the fifties to manufacture the first plastic lenses, but proved too sensitive to abrasion, and were therefore rapidly replaced by CR 39. Today, however, the development of polycarbonate is bringing thermoplastics back onto the scene.

Polycarbonate is a relatively old material - discovered in about 1955 - but its use in ophthalmic optics has really grown over the past few years. It has undergone numerous improvements, particularly for use in the compact disk industry, and now offers optical quality which is equivalent to that of the other plastics.

In chemical terms, polycarbonate is a linear polymer thermoplastic with an amorphous structure, its carbonated skeleton being made of a succession of Carbonate radicals (-$CO_3$) and Phenol (-$C_6H_5OH$) (figure 12). It is most often manufactured in solution, according to the following chemical reaction :

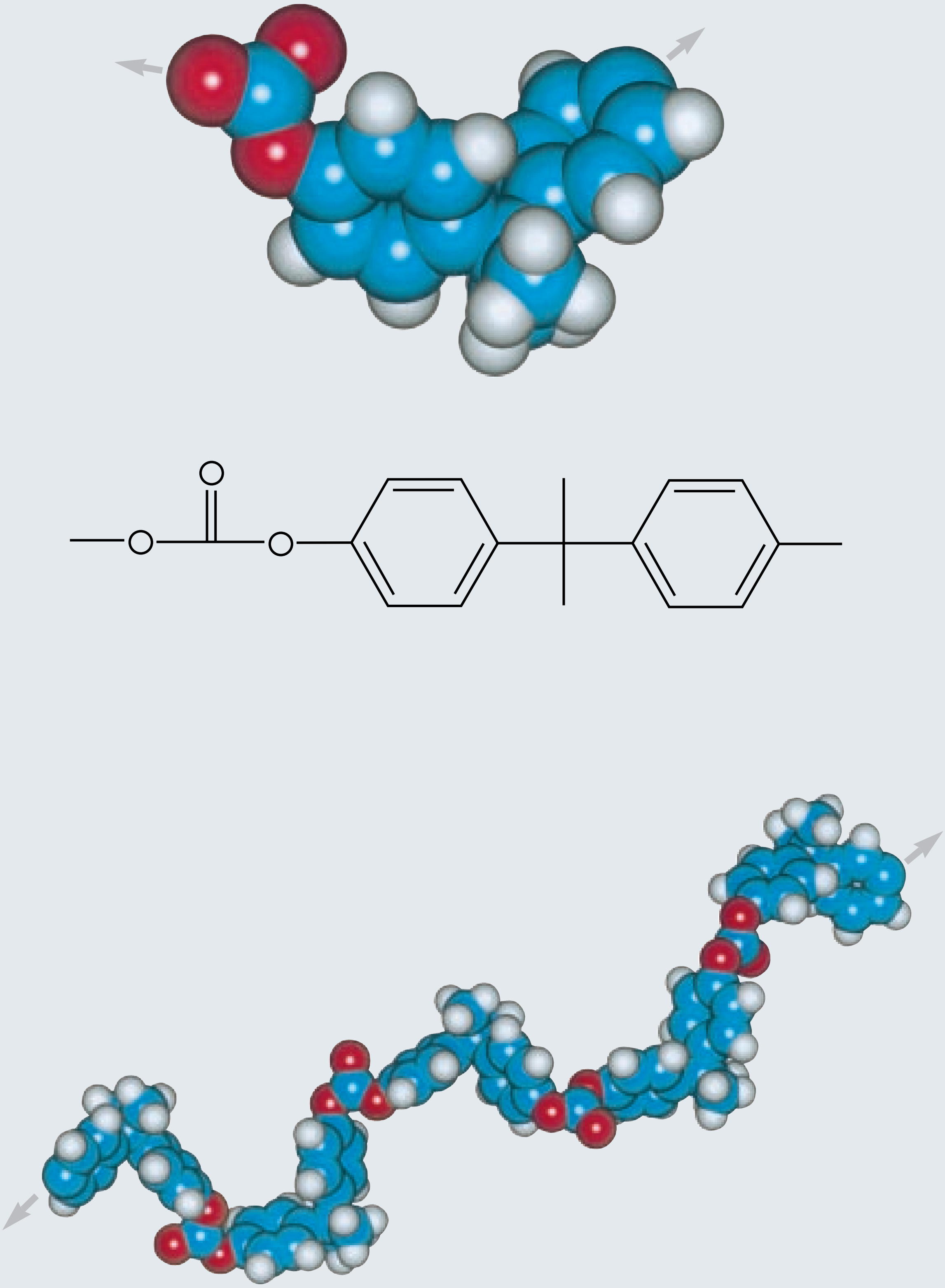





Polycarbonate presents a number of particularly useful benefits for ophthalmic optics : excellent impact resistance (more than 10 times that of CR 39), a high refractive index ($n_e$ = 1.591, $n_d$ = 1.586), very light weight (specific gravity = 1.20 g/cm$^3$), efficient protection against ultraviolet rays (U.V. cutoff at 380 nm) , and high resistance to heat (softening point exceeding 140 °C / 280 °F). Like all high index plastics, polycarbonate is a soft material which must systematically be protected with a scratch-resistant coating. Its constringence is relatively low ($\nu_e$= 31, $\nu_d$= 30), but in practice, this does not noticeably affect wearers. In terms of tinting and antireflection coating, the current possibilities of polycarbonate are rather close to those of other plastics : since the material itself is difficult to tint, tinting is generally obtained by impregnating a tintable scratch-resistant coating applied to the lens back side. Antireflection coatings are applied in the same way as for other materials.

***Figure 12 :*** *Polycarbonate Molecule : monomer and polymer.*

*Figure 12*



# LENS MANUFACTURE

Depending on the materials considered, the basic lens manufacturing technique differs substantially, but the overall principle remains constant : either the lens is directly manufactured as a “finished” product, or as a so-called intermediate “semi-finished” product, which is a thick lens with a completed front surface, but a back surface which still needs to be worked so as to obtain prescription specifications.

## *A/ Manufacture of glass lenses*

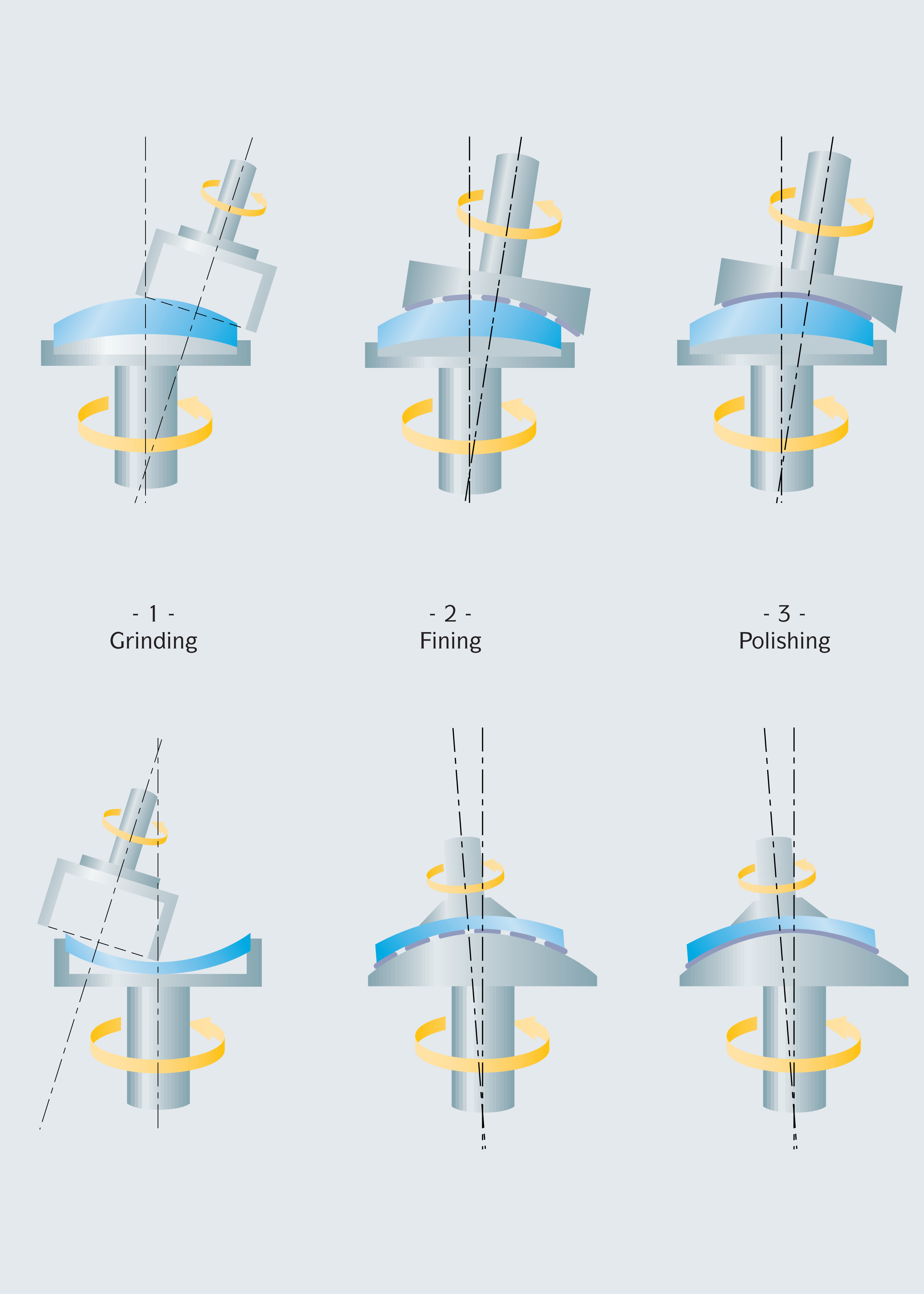
Whatever the material used, glass lens manufacture consists of surfacing the front and back surfaces of a rough blank supplied by the glass-making industry. This blank is manufactured by molding still incandescent glass, immediately after removal from the oven in which it is made by melting its various components. The blank is a very thick lens with uneven surfaces, but a perfectly homogeneous inner composition. Its front and rear surfaces are then generated to obtain the correct curves, yielding the finished lens.

Surfacing of each of the two lens surfaces can be divided into three distinct phases (figure 13) :
- phase 1 : **grinding** which consists of milling the lens with a diamond wheel to give it its thickness and radii of curvature. After grinding, the lens has acquired its almost definitive shape, but still has a rough, translucent surface.
- phase 2 : **fining** or smoothing which consists of refining the grain of the lens surface without modifying its radii of curvature. For this, the firmly held lens is brought into contact with a tool which has been fitted with an abrasive pad or disk, the radius of curvature of the tool being strictly identical to that of the sought lens. The lens and tool are set in motion and cooled down with a lubricant solution. At the end of this operation, which lasts a few minutes, the lens has the exact thickness and curvature required, but the surface is not yet perfectly polished.
- phase 3 : **polishing** is the finishing operation which gives the lens its transparency. This stage is similar to the previous operation, but with a softer polishing disk and abrasive solution with a very fine grain.

Industrially, surfacing of the front lens surfaces (whether their designs are spherical, aspherical, bifocal, or progressive) is a mass production process, whereas surfacing of the back surfaces (which are only spherical or toric) is done individually or in series, depending on the quantity.

***Figure 13 :*** *Surfacing principle.*

Figure 13



- 1 -
Grinding

- 2 -
Fining

- 3 -
Polishing

## B/ Manufacture of plastic lenses

The following sections successively cover manufacture of thermosetting and thermoplastic lenses, since very different techniques are used.

### 1/ Thermosetting resins

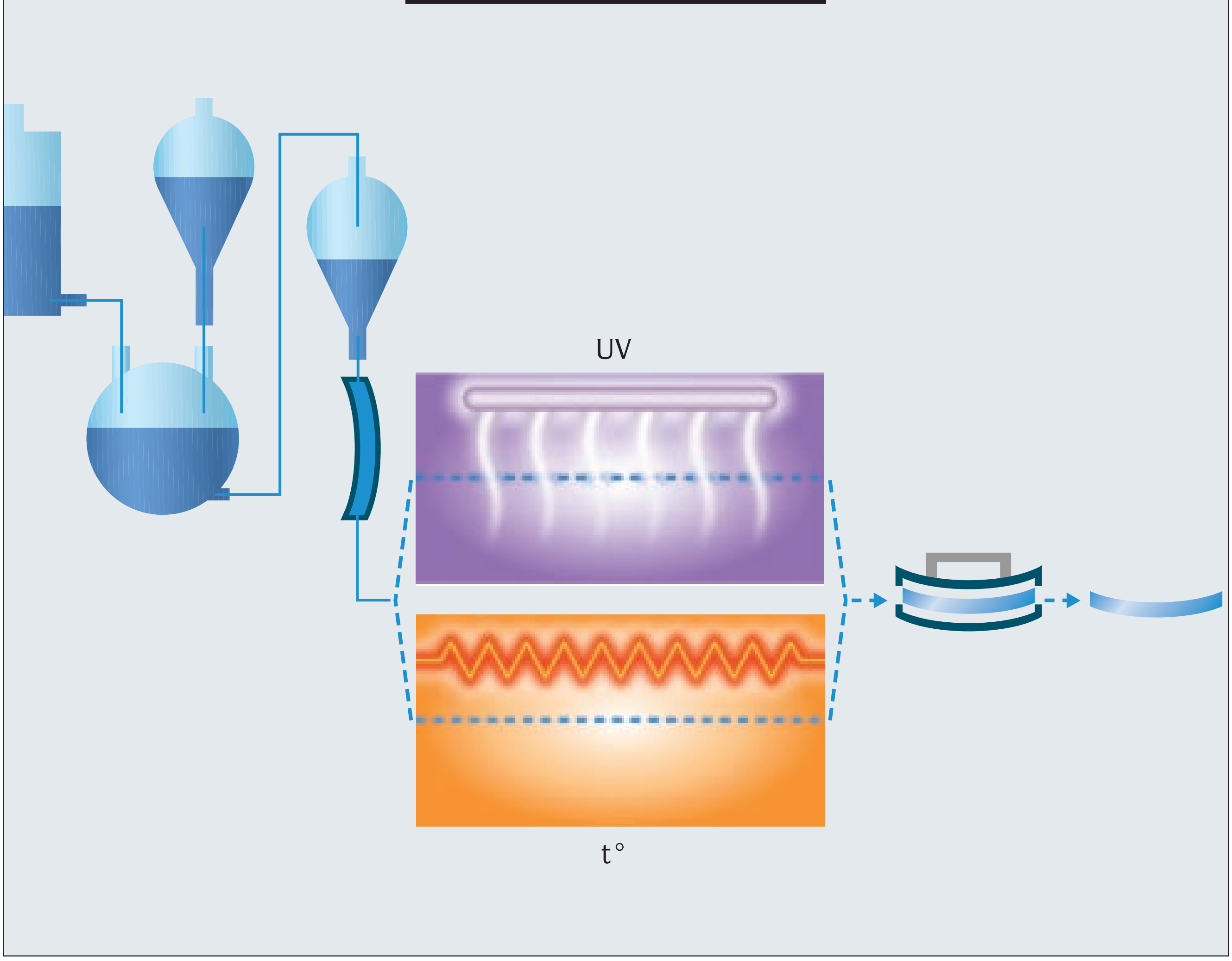
Let us take CR 39 as an example of a thermosetting resin. The monomer supplied in liquid form by industrial chemicals suppliers undergoes the following manufacturing steps :

- **preparation of the monomer** : filtering, degassing, and addition of a catalyst ;
- **mold assembly** : the molds consist of two glass or metal parts, assembled either by pressing against a circular ring (the gasket) and tightening with a clip, or by using special adhesive tape ;
- **filling** : the empty space created between the two parts of the mold is filled with the liquid monomer ;
- **polymerization** : the filled molds are placed in an oven where they undergo a heat cycle for several hours - or, for certain materials, are exposed to ultraviolet radiation for a few minutes - to provoke gradual hardening of the resin ;
- **demolding** : the clip or tape is removed and the mold parts are separated to release the lens.

This procedure is used to manufacture both “finished” and “semi-finished” lenses, the only difference being in the mold shape. This remains more or less the same for most thermosetting resins currently used in ophthalmic optics.

***Figure 14 :** Manufacturing principle for CR 39 lenses.*

**Figure 14**



## 2/ Thermoplastic materials

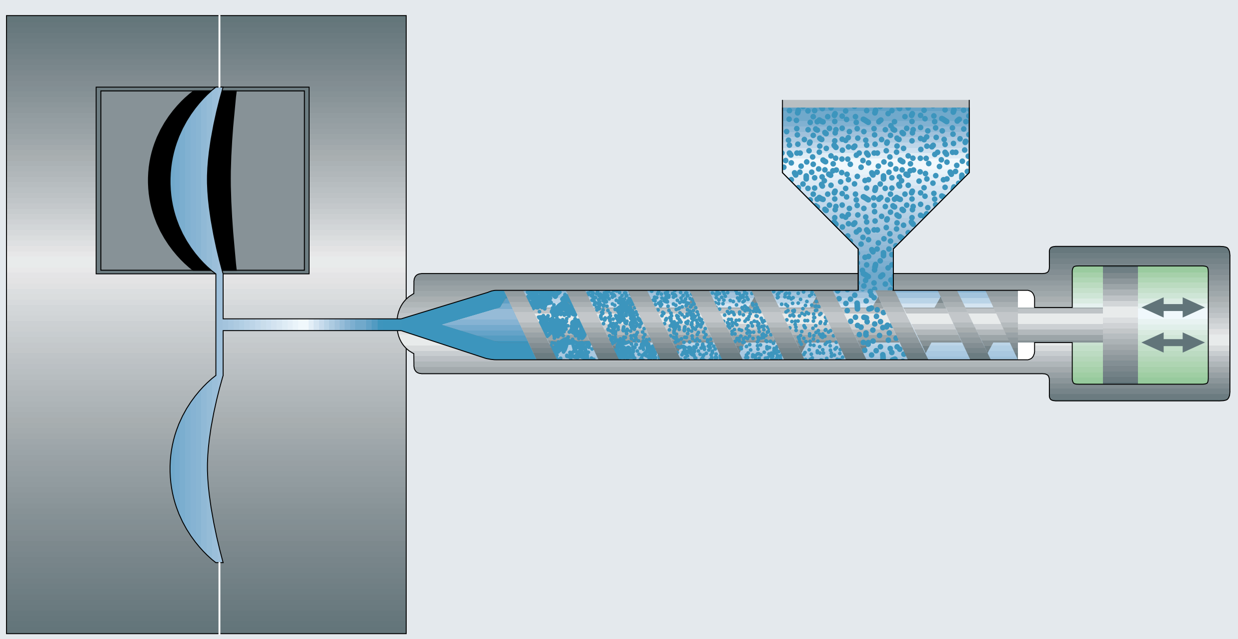
Let us take polycarbonate as an example : the raw material is made of transparent granules which melt upon heating, and are then injected into lens-shaped molds. The technology consists of liquifying the raw material through heating and, using a piston, pushing it into metal or glass molds. An extrusion screw ensures plastification of the material in the injection cylinder, as well as playing the role of a piston, pushing the hot material into the mold cavities via several channels. After injection and cooling time, the two-part molds are opened to release the lenses (figure 15).

The various manufacturing steps are as follows:
- **preparation of the material** : drying the granules with hot air and feeding them into the press ;
- **setting the press** : laying out the molds, setting pressure, mold temperature, injection and cooling time, and heating of the material (to about 300°C / 570 °F) ;
- **injection** : pushing the molten material under pressure into the molds ;
- **cooling** : solidification of the material by conduction through the molds ;
- **demolding** : opening the press and molds and releasing the lenses.

This technology allows lenses of any design to be manufactured, by simply filling different molds in the press. These lenses are either “finished” lenses ready for coating, or “semi-finished” lenses which require subsequent surfacing of the back surface, using techniques similar to those adopted for other materials.

***Figure 15 :*** *Manufacturing principle for polycarbonate lenses.*

**Figure 15**



## CONCLUSION

Since they first appeared in the sixties, plastic materials have constantly developed and gradually replaced glass materials. Today, they account for most lenses sold in the industrialized countries. Their success is essentially due to their main advantages : lightness and impact resistance. These have been reinforced by breakthroughs in a number of areas where they previously presented drawbacks : efficient scratch resistance, development of plastic photochromic materials, higher refractive index materials, and wider range of tinting and antireflection coatings. With these enhanced features, today's plastic lenses will continue to take over the international ophthalmic lens market. Yet glass lenses, with better scratch resistance and higher refractive indexes, will continue to offer a useful alternative to plastic materials, to ensure constantly improved visual comfort for the entire wearer community.

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