17 OPTICAL MATERIAL

17.1 INTRODUCTION

17.1.1 General. The only properties of an optical material which are used in the actual design of a system are its indices of refraction, and the quantities derived therefrom (such as the ν-value). However, frequently the designer must select materials which meet requirements that are not concerned with the quality of imagery, but which are important with respect to satisfactory fabrication and performance of the instrument. Often he must make a compromise between desirable optical properties, and such characteristics as weight, availability, durability and cost.

17.1.2 Coverage. The following discussion of optical materials will involve the properties of refracting materials, and those of reflecting materials.

17.2 REFRACTING MATERIAL CHARACTERISTICS

17.2.1 Transmission. A refracting material, to be useful, obviously must transmit radiation in the wavelength region in which it is to be used, or it may be used to absorb the undesirable radiation of other wavelengths. In some instances, the refracting material transmits imperfectly in the region of use, and the designer must determine what thicknesses (if any) he can use without greatly impairing the performance of the instrument. The amount of light transmitted through a lens or plate is limited by surface reflection, by absorption within the medium, and by diffusion.

17.2.2 Surface reflection. When light is incident on the boundary surface between two refracting media, part of the light is transmitted into the second medium and part is reflected back into the first. The ratio of the reflected light to the incident light, sometimes called the reflection coefficient or reflectance or

$$R = \frac{1}{2}\left[\frac{\sin^2 (I - I')}{\sin^2 (I + I')} + \frac{\tan^2 (I - I')}{\tan^2 (I + I')}\right] , \qquad (1)$$

reflectivity, is where I is the angle of incidence and I' is the angle of refraction. If the light is incident normally, so that $I = 0$, and if one medium is air, or a vacuum with index of refraction $= 1$, then the

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

expression reduces to wherein n is the index of refraction of the other medium. This formula is the one most frequently used in estimating reflection losses. Since the reflection coefficient depends on the indices of refraction, and these in general depend on the wavelength, the reflection coefficient itself varies with wavelength. Thus for an extra dense flint, having a refractive index of 1.720 at the sodium D line and 1.673 at 2.5 microns, equation (2) yields reflection coefficients of 7.0% and 6.3% respectively at the two wavelengths. Whether the variation with wavelength is important depends on the application. Many times it is satisfactory to use a single value of the index throughout the range of wavelengths under consideration.

17.2.3 Absorption. When radiant energy passes through a medium other than a vacuum, a portion of it is usually converted into another form of energy. This phenomenon is called absorption, and the energy so absorbed is no longer available for image formation.

NOTE

> In this discussion a terminology will be used which is becoming standard. However, the reader is warned that in other publications on this subject the use of terms and symbols may vary considerably with those presented herein. In consulting other published data on optical materials be sure of the exact meaning given to the terms and symbols used, regardless of their apparent similarity to the terms and symbols in this handbook. The basic physical concepts are the same in all cases.

17.2.3.1 According to Bouguer's law, the amount of light not absorbed in the passage through a homogenous medium, i.e., the transmitted light, is a decreasing exponential function of the thickness. That is,

$$W = W_o \, e^{-\alpha t} \qquad (3)$$

In this equation W_o is the original flux. W is the amount remaining unabsorbed after passage through a thickness t of the medium; α is a quantity called the absorption coefficient of the medium. (Note that this equation refers to what happens within the medium - it is not complicated by the reflection losses which occur when the light passes through a boundary surface into or out of the medium.) In general, α is a function of the wavelength.

17.2.3.2 The extinction coefficient κ and the absorption constant k are also commonly used constants. These are related to the absorption coefficient by the equation

$$\kappa = \frac{k}{n} = \frac{\alpha\lambda}{4\pi n} , \qquad (4)$$

λ being the wavelength of light and n the index of refraction. For computation purposes it is sometimes convenient to replace the base e in equation (3) by base 10, and write

$$W = W_o \, 10^{-\beta t} \qquad (5)$$

This permits using tables of common logarithms. We shall call β the "absorption coefficient to base 10", when necessary for clarity, and simply the "absorption coefficient" when the distinction is clear from the context. Therefore, $\alpha = 2.303\beta$. The quantity,

$$T = \frac{W}{W_o} = e^{-\alpha t} = 10^{-\beta t} . \qquad (6)$$

is called the <u>internal transmittance</u> of the thickness t.

17.2.3.3 The absorption characteristics of a material are usually measured by placing a sample in the form of a polished, plane-parallel plate in the beam of a spectrophotometer, and determining what portion of the radiation incident on the first surface of the sample emerges from the second. This determination is made for as many wavelengths as desired. Most modern spectrophotometers automatically draw a curve of transmittance as a function of wavelength. It is evident that the results from the spectrophotometer include the effects of reflection loss and absorption loss. (They also include the effect of loss due to diffusion, but this is usually negligible in comparison with the others.) It is frequently necessary to be able to separate the two effects in order to predict the benefit to be gained by low-reflection coatings, or the absorption to be expected from other thicknesses. Of the light incident on the first surface of the sample, the fraction R is reflected and lost, and the fraction (1-R) passes into the sample. Of this, the fraction T passes through the sample without being absorbed and reaches the second surface. Here a fraction R is reflected and only (1-R) passes through the surface. That is, of the original radiation, the fraction

$$T_1 = T\,(1-R)^2 \qquad (7)$$

passes through the second surface. However, the radiation reflected at the second surface passes back through the medium toward the first surface, where a part of it is reflected back into the medium, and so on. Summing over all such passages one obtains for the total fraction T_∞ passing through the second surface of the sample,

$$T_\infty = \frac{(1-R)^2\,T}{1 - T^2 R^2} . \qquad (8)$$

It is the quantity T_∞ (usually expressed as a percent) which is measured by the spectrophotometer.

17.2.3.4 Since R can be determined from the refractive index, the value of T can be computed from equation (8) which can conveniently be rearranged as the quadratic equation:

$$T^2 + \left(\frac{1}{R} - 1\right)^2 \cdot \left(\frac{T}{T_\infty} - \frac{1}{R^2}\right) = 0 \qquad (9)$$

If R is not large, the amount of light contributed by the re-passages through the medium may be negligible, and it will then be simpler and satisfactory to use equation (7) for T, using the spectrophotometer reading for the value of T_1 . Having determined the value T for the sample and knowing its thickness, one can determine the absorption coefficient from equation (7) or equation (9). Then one may compute the fraction which will be transmitted through other thicknesses, with the same or different surface reflectivities.

17.2.3.5 Consider the following example. Spectrophotometer curves were run on a sample of ordinary plate glass, 6.18mm thick, and on a sample of "waterwhite" plate, 6.6mm thick. At the wavelength of 600mμ the former transmitted 88.3% and the latter, 91.4% (the measured transmittances are significant to a few tenths of a percent). Both glasses have an index of refraction of about 1.52 at this wavelength. How would their transmittances compare in thicknesses of 25.4mm, if the surfaces in use are to have low-reflection coatings with reflectivities of 1% ? For the ordinary plate glass

$$R = \left(\frac{0.52}{2.52}\right)^2 = 0.043 \quad .$$

Substituting in equation (7) yields

$$T = 0.964.$$

Use of the more precise equation (9) would give $T = 0.960$ but the difference is hardly significant in view of the limited precision of the initial data. Then,

$$\beta = \frac{-\log\ 0.964}{6.18\text{mm}} = 0.00257/\text{mm} \quad .$$

The internal transmittance of a 25.4mm thick piece would then be

$$\text{antilog}\ (-0.00257 \times 25.4) = 0.860 \quad .$$

Since the coated surfaces are to have reflectivities of 1%, substitution in equation (7) shows that 84% of the incident 600mμ radiation would pass through the plate. For the waterwhite plate the surface reflectivity is again 0.043. Substitution in equation (7) yields

$$T = 0.998 \ .$$

This value is so near unity that the difference is not reliable in view of the limited accuracy of the data from which it was computed. However, it is safe to assume that T_1 is no worse than 0.995 and that hence

$$\beta \leq \frac{-\log\ 0.995}{6.61\text{mm}} = 0.00033/\text{mm}.$$

Consequently the internal transmittance of the 25.4mm thickness will be at least 0.981 and with the surfaces coated at least 96% of the radiation will pass through the piece.

17.2.4 Diffusion. Some light, in passing through a medium is deviated from its path due to the presence of fine inhomogeneities in the medium. This effect is called diffusion. In extreme cases it causes the medium to be translucent rather than transparent. Some of the diffused light is lost from the optical system. That which remains is not image-forming but, being spread over the image area, reduces contrast. For this discussion it is not necessary to consider the physics of the phenomenon beyond remarking that the amount of scattering is a function of the ratio of the size of the inhomogeneity to the wavelength of light, the amount decreasing as the ratio decreases. (The effect can be noticed in a long line of automobile headlights at night, unless the air is very clear. Since more light is scattered from the blue end of the spectrum, the distant lights look more yellow or orange than the near ones.) As a result, inhomogeneities which would be bothersome in the visible region may be of negligible importance in infrared work.

17.3 REFRACTIVITY AND DISPERSION

17.3.1 Selection of materials.

17.3.1.1 From the available media which transmit satisfactorily in the wavelength region with which he is concerned, the designer must select those with index and dispersion characteristics best suited for his needs. In the visible region, it is usually sufficient for the designer to know the indices of refraction for a few conventionally specified wavelengths, and to do much of his calculations with the quantities derived from them, (such as the ν value and the partial dispersion ratios). Glass-makers' catalogs customarily describe the refractive properties of the glasses in terms of these standard quantities.

17.3.1.2 In the ultraviolet and infrared regions, procedures and requirements are not so well standardized. Use of standard wavelengths for index measurement, and of dispersion constants based on such measurements, has not become common. It is often necessary to work from such tables of values of refractive index as are available, and to interpolate for the wavelengths one wishes to consider in the design. To aid in selecting either the derivative $dn/d\lambda$ or the related quality

$$\frac{(n-1)}{\frac{dn}{d\lambda}} .$$

The latter is analogous to the ν-value; for achromatism of a thin doublet, the ratio of the powers of the two elements should be the negative of the ratio of the values of $(n-1)/(dn/d\lambda)$ of the two media. Use of the former is similar to the use in the visible region of $n_F - n_C$; the ratio of the total curvatures of the two elements of a thin achromatized doublet should equal the negative reciprocal of the ratio of the two derivatives. Some publications tabulate values of the derivative $dn/d\lambda$.

17.3.2 Optical homogeneity.

17.3.2.1 It is important that the refractive index of a lens or prism be constant throughout the piece. Usually the requirement for uniformity within the piece is more rigid than the requirement for uniformity from piece to piece. There are two principal causes of optical inhomogeneity: chemical inhomogeneity and improper annealing.

17.3.2.2 Since most glassy substances are complex mixtures, rather than precise chemical compounds, it is difficult to make them chemically homogeneous throughout. The presence of streaks of slightly varying composition results in striae. The harm done by striae depends on their loaction in a system. If they are so placed and oriented that all parts of each image-forming ray bundle pass through about the same optical path in the striae, the effect may be negligible. Thus a moderate amount of flat striae, approximately parallel to the plane of a weak lens, may be tolerable. On the other hand, in a reflecting prism in which the beams pass through the same volume in at least two different directions, it is impossible to meet this condition, and material for such prisms should be free of striae.

17.3.3 Mechanical strain. The thermal history of the piece of material may also cause optical inhomogeneity. If it has been such as to result in the presence of mechanical strains, the material becomes locally polarizing. The presence of this defect can be observed by examining the piece between crossed polarizers. However, even if there is no detectable strain, the material still may be optically inhomogeneous, and a more careful fine annealing of the glass, to accomplish the effect known as compacting, is necessary. (The fine annealing is also necessary to bring the index of the glass to its maximum value. Melt sheets supplied by manufacturers generally give index and dispersion measurements made on fine-annealed samples). Heating the glass to softening for making molded blanks, slumpings, etc. cancels out its previous thermal history and necessitates re-annealing to ensure the quality desired.

17.3.4 Optical isotropy and anisotropy.

17.3.4.1 In most cases the designer requires that his materials be optically isotropic - that is, the index of refraction at any point must be constant, regardless of the direction in which the radiation is passing the point. Only occasionally does he want anisotropic or polarizing media. Optical glasses are isotropic, except as made locally anisotropic by improper annealing. Many crystalline materials with otherwise attractive characteristics are anisotropic and hence unsuitable for making lenses and non-polarizing prisms. However, crystals belonging to the cubic system, when free from mechanical strain, are optically isotropic, and some such are noted below.

17.3.4.2 Occasionally a weakly anisotropic material such as sapphire can be used satisfactorily, by orienting its optic axis parallel to the optic axis of the system.

17.3.4.3 A crystal which is isotropic optically is not necessarily so in all mechanical properties, and it may be desirable to have blanks for lens making cut with preferred orientation with respect to the cleavage planes. This will ensure uniform grinding or minimize losses from fracture along the cleavage planes.

17.4 INCLUSIONS

17.4.1 Imperfections in optical materials. Optical materials may have imperfections in the form of tiny opaque or refracting inclusions. In ordinary optical glass the most common of these are called, according to their nature, bubbles, seeds or stones. Other refracting media may have similar imperfections. The harm done by such defects depends on their position in the optical system. An inclusion near an image plane, as in a field lens or in the plane-parallel plate on which a reticle is formed, will appear as a bothersome out-of-focus object in a visual system, or may give a false signal in an infrared system. The same inclusion in an objective lens may have negligible effect on the performance. Tolerances on such imperfections should be set with the specific use of the part in mind.

17.5 ENVIRONMENTAL CHARACTERISTICS

17.5.1 Optical system requirements. Withing recent years, requirements for the performance of optical systems under extreme environmental conditions, such as in airborned equipment or under exposure to desert, jungle and artic conditions, and also the necessity of using available refracting materials other than ordinary optical glass outside the visible spectrum, have made it necessary for the designer to be conscious of the thermal, mechanical and chemical characteristics of the materials he proposes to use. The most important of these are the following:

(1) Softening characteristics - cold flow. A lens or window obviously should hold its shape, including the figure of its refracting surfaces, under storage and service conditions. The softening temperature of the material should be high enough to ensure that this will be the case. A few materials exhibit the phenomenon of cold flow, a tendency to deform even at ordinary temperatures.

(2) Resistance to thermal shock. Materials vary in their ability to undergo rapid changes in temperature without fracture. Some media, unless precautions are taken, are likely to crack during ordinary grinding and polishing. Others can withstand the changes involved in exposure on the exterior of supersonic airframes. The larger the piece of material, the more subject it is to damage from this cause.

(3) Coefficient of thermal expansion. This characteristic, while related to the ability of a material to withstand thermal shock, is also important if the instrument must withstand a wide range of temperatures. The coefficient material should be matched with that of the cell in which it is to be held or to which it is to be cemented.

(4) Specific gravity. Especially in airborne equipment, weight is an important factor. Hence knowledge of the specific gravity of the material is useful. However, the significance of the specific gravity depends on the effect of the optical characteristics of the design of the system. If, for example, a material of higher density permits using a single lens instead of two, there still may be a weight advantage with the dense material.

(5) Hardness. The hardness of the material is important both during fabrication and in service. A very hard material, such as fuzed quartz, is difficult and time-consuming to grind. On the other hand, a very soft material is likely to develop scratches or sleeks during polishing. Soft materials should be avoided in locations where they will be exposed to surface abrasion, as in exposed domes in airborne equipment.

(6) Surface deterioration. Polished optical surfaces may deteriorate from a number of causes, the susceptibility depending on the material. Staining due to the action of atmospheric moisture and carbon diozide is known as weathering. Closely related to weathering is susceptibility to tarnish or etching by weak acids, which may frequently occur in the atmospheres encountered. In hot, humid climates mold may grow on the surface, leaving marks which cannot be removed except by re-polishing.

(7) Devitrification. Some glassy materials have a tendency to devitrify, and the tiny crystals formed make the glass diffusing. Glasses for instruments which must be stored for long periods should be chosen with this in mind.

17.6 REFRACTIVE MATERIALS FOR SPECIFIC WAVELENGTH RANGES

17.6.1 Classifications. It is convenient to discuss materials under the following classifications:

(a) for the visible region including the near ultraviolet and the near infrared, from about 0.36μ to about 2.20μ.

(b) for the ultraviolet region at wavelengths shorter than 0.36µ.

(c) for the infrared at wavelengths longer than 2.2µ.

17.6.2 Applicable materials for visible spectrum. Most optical design work is done in the visible spectrum and more types of media have been developed for it than for the others. These may be classified as ordinary optical glasses (including rare earth glasses), crystals (natural or synthetic), and plastics. Some of the media used mainly for the other wavelength ranges are transparent in this region and could be used here, but their disadvantages make them unattractive as compared with optical glass.

17.6.2.1 Optical glass. The properties of the ordinary optical glasses are well catalogued, and the designer should obtain the catalogs of several manufacturers for reference. These lists vary widely in the amount of information provided. The most elaborate lists gives indices of refraction for a number of wavelengths distributed through the visible region, the Abbe or ν-value, and several partial dispersions and dispersion ratios, along with information on specific gravity, weathering characteristics, amount of internal imperfections, and thermal characteristics. There is much similarity between the glasses of various manufacturers. However, if a catalog does not give the desired information on a characteristic which is critical for a special application, it is well to inquire of the manufacturer rather than to take data from another manufacturer's catalog.

17.6.2.1.1 Figure 17.1 shows the range of index values and ν-values within which most of the commercially available glasses fall. However, manufacturers' lists vary widely in the variety offered. The available varieties are adequate for most purposes. If the importance of the project warrants the expense, melts of glasses with properties intermediate between those listed can sometimes be arranged for.

17.6.2.1.2 As pointed out elsewhere in this handbook, complete chromatic correction of a simple system puts a condition on the partial dispersion ratios of the glasses involved, as well as on the ν-values. Thus, in a doublet, to bring light of three wavelengths to a single focus, the ν values of the two glasses should differ, but the partial dispersion ratios should be equal. Unfortunately the partial dispersion ratio for most glasses (and other substances as well) is practically a function of the ν-value, so this requirement cannot be met. However, a few manufacturers offer a small number of glasses which depart from the rule sufficiently to be useful.

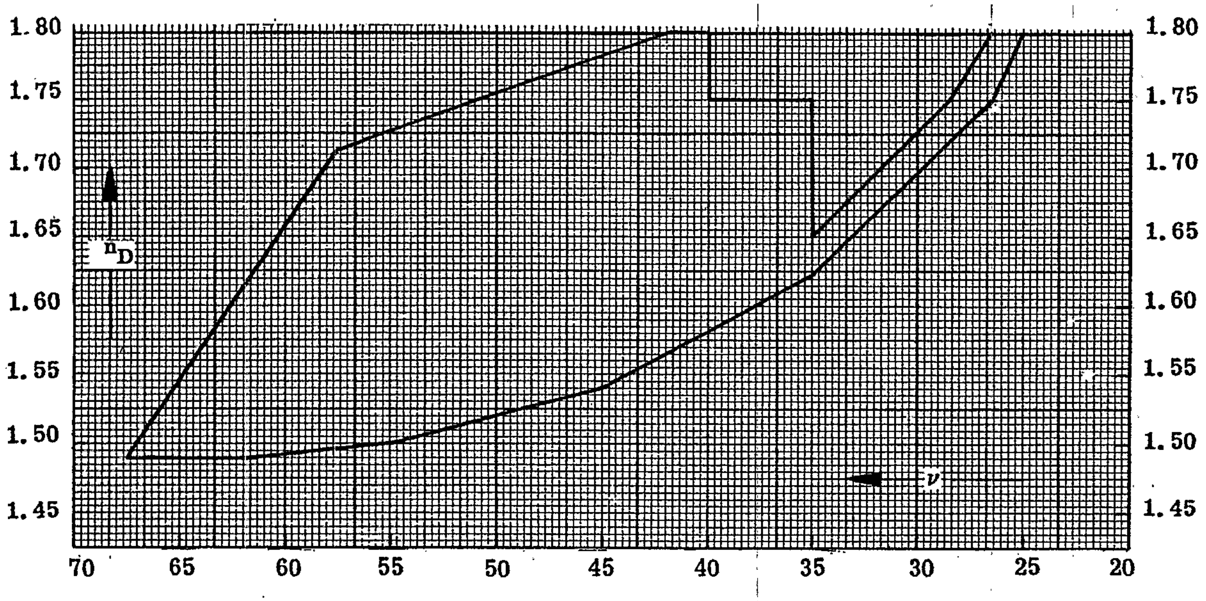

Figure 17.1- The range of commercially available glass, with respect to index and ν values.

17.6.2.1.3 Although one foreign manufacturer's catalog has recently begun listing index values for the wavelengths 0.365μ in the ultraviolet and 1.014μ in the near infrared, most manufacturers give only values in the visible region and to 0.405μ in the ultraviolet. In selecting glass types for the ultraviolet or the infrared without resorting to actual measurement it is necessary to resort to some sort of extrapolation. Kingslake and Conrady* measured the indices of 17 glasses at various wavelengths from 0.365μ to 2.5μ. An approximate value of the index of another glass can usually be derived by interpolation between the values for glasses with similar n_D and ν in Kingslake and Conrady's list. A number of formulae for demonstrating the refractive index as a function of wavelength have been proposed, the constants of the formula being determined from the indices of the glass in the visible region. A fairly recent formula has been proposed by Herzberger.**

17.6.2.2 Crystals. Crystals, natural or synthetic, are rarely used for this wavelength region. The principal application is in the reduction, or elimination, of secondary spectrum in apochromatic systems. Fluorite (CaF) has been used for many years for this purpose since it has an index $n_D = 1.434$, and a $\nu = 95.4$. The partial dispersion ratio

$$\tilde{P} = \frac{n_D - n_C}{n_F - n_C} = 0.293$$

which is equal to that of an ordinary glass with $\nu = 57$ to 59. Synthetic crystals, with diameters up to 7.5 inches are available. Synthetic alum crystals ($KAl(SO_4)_2 \cdot 12H_2O$) has also been used. For this material $n = 1.456$, $\nu = 58.2$, $\tilde{P} = 0.315$. Since alum is highly water soluble, the material cannot be used in exposed locations. It has usually been made the central member of a cemented triplet.

17.6.2.3 Plastics. In recent years there has been considerable interest in some of the synthetic resins which can be made transparent and colorless. These materials have a number of attractive features, foremost of which are its lightweight, and the possibility of fabricating elaborate forms quite inexpensively by casting.

17.6.2.3.1 Specific gravities of typical optical plastics are 1.05 to 1.19, compared with 2.48 for crown glass and 3.41 for dense flint. The weight savings are obvious.

17.6.2.3.2 Since the optical elements can be fabricated by casting or molding (processes which are not practical with glass for any, except crude optical elements) it is possible to aspherize mold inserts in order to aspherize lenses, and to cast optical elements complete with mounting flanges, or other mechanically convenient additions.

17.6.2.3.3 Counterbalancing these advantages, available plastics have a number of disadvantages which so far have worked against their use in any but very simple and non-critical systems. They are quite soft, and scratch easily. Many attempts have been made to improve this defect, such as coating the lenses with harder materials, but low scratch resistance remains an important defect. They are quite subject to change of index with humidity, and to significant change of index and surface figure with temperature. They also deform easily under mechanical force, and some tend to turn yellow with age.

17.6.2.3.4 The principal injection-molding materials now used are acrylics, with $n_D = 1.49$, $\nu = 58$, and styrenes with $n_D = 1.59$, and $\nu = 31$. Allyl-diglycol carbonate is used for casting.

17.6.2.3.5 Cast spectacle lenses have some popularity because they are light weight, but the principle defect preventing their wider acceptance is that they scratch easily.

17.6.2.3.6 Large cast blocks are used in unit-power, tank periscopes to shorten the optical path through the periscope, but the end prisms, which ideally should be cast in a single piece with the block, are still made of glass.

17.6.2.3.7 Acrylic lenses have been used in large numbers in simple one and two lens slide viewers, and in inexpensive camera viewfinders. Their quality is adequate for these applications, and their lightness and cheapness are attractive. An additional advantage in the view finders is the aspherization of one lens surface to obtain the elimination of barrel distortion. Injection-molded acrylics are also widely used as singlet meniscus objective lenses in box cameras. One camera manufacturer has introduced a plastic f/8 triplet. It is possible that more applications of this sort will be made as fabrication processes are developed and improved.

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* R. Kingslake and H. G. Conrady, J. Opt. Soc. Am. 27; 257 (1937).
** M. Herzberger, J. Opt. Am. 32; 70 (1942).

17.6.3 Materials suitable for wavelengths longer than 2.2μ.

17.6.3.1 For application reasons, optical systems in the infrared have been designed mainly for three wavelength regions: the region near 1μ, for use with image converter tubes and infrared photography; the region from 2 to 3μ, for use with lead sulphide cells; and the region near 4.2μ. (Some applications have called for coverage of longer ranges.) Current activity shows an interest in longer wavelengths. As noted above, ordinary optical glasses are satisfactory for the region near 1μ. However, they begin to absorb strongly at about 2.5μ, and their usefulness in the 2 to 3 micron region depends on the requirements of the application, and on the thicknesses needed. For longer wavelengths, other materials must be used.

17.6.3.2 The search for satisfactory infrared transmitting materials has been active and is continuing vigorously. The situation is complicated by the fact that many of the applications, for airborne equipment and especially for windows for such equipment, require excellent mechanical characteristics, and large pieces of material.

17.6.3.3 The properties of approximately fifty materials which are of potential usefulness in the infrared, and which constitute nearly all such materials which had been investigated up to the end of 1958, have been gathered and tabulated by Ballard et al* and the designer should provide himself with a copy of this reference. It lists for each material, to the extent to which information was available at the time of publication, the composition, molecular or atomic weight, specific gravity, crystal class, transmission, reflection loss, refractive index, dispersion, dielectric constant, melting temperature, thermal conductivity, thermal expansion, specific heat, hardness, solubility and elastic moduli. The transmission is usually presented as a curve showing external transmittance as a function of wavelength. Refractive index as a function of wavelength is given in tabular form. The dispersion (which is, of course, implicitly contained in the refractive index table) is for many substances plotted as a curve showing the derivative of index with respect to wavelength as a function of wavelength. One chapter is devoted to tables each listing the substances arranged in order with respect to a single characteristic such as thermal conductivity or coefficient of linear expansion, thus permitting easy comparison. The last chapter is devoted to a brief discussion of glasses and plastics.

17.6.4 Materials suitable for wavelengths shorter than 0.36μ. Work in ultraviolet optics is much less active than in infrared, and the existing applications for the most part impose much less stringent requirements on non-optical characteristics of the materials, and in size of pieces required. A modest number of suitable materials is available, some of them synthetic crystals. Important ones are listed in Table 17.1 together with some of their properties. Index and dispersion in the visible region are given to show the general optical position of the material. Literature references to ultraviolet index and transmission information are included.

Material	N_D	ν	Cutoff	Max. Piece Diameter	Remarks
Sodium Chloride	1.544	42.8	0.25μ	7.5 in.	Highly water soluble
Potassium Bromide	1.560	33.4	0.21μ	7.5 in.	"
Potassium Iodide	1.667	23.2	0.25μ	7.5 in.	"
Lithium Fluoride	1.392	99.3	0.11μ	6.0 in.	
Calcium Fluoride	1.434	95.1	0.125μ	6.0 in.	
Fused Quartz	1.458	67.8	0.22μ	several in.	
Barium Fluoride	1.474	81.8	0.145μ		

Table 17.1 - Materials suitable for ultraviolet beyond 0.36 μ.

17.7 REFLECTING MATERIALS

17.7.1 Thin films. Nearly all reflecting surfaces in optical instrumentation are made by forming thin films, usually by evaporation but sometimes by chemical means, on glass or some other appropriate substrate. Most frequently simple metal films are used. For special purposes, multilayer films are sometimes provided, which give enhanced reflectance in a particular wavelength region, or may serve as

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* Stanley S. Ballard, Kathryn A. McCarthy, William L. Wolfe: Optical Materials for Infrared Instrumentation; IRIA Report #2389-11-S, L'. of Michigan, Ann Arbor, 1959.

filters, reflecting in one region and transmitting in others.

17.7.2 First surface versus second surface coatings. Depending on the application, the radiation may be incident on the surface either on the side in contact with the glass, or in the side exposed to the air on a vacuum. The latter use is commonly called a "first-surface" reflection; the former, "second surface." When used as a second surface reflector the film can be protected by such means as plating and painting. For use as a first surface reflector, any protecting coating must be transparent. A film of silicon monoxide is frequently employed. Such a film is so thin as to have very little effect on the reflectance in the visible and in the infrared out to 9 or 10μ. However, the thickness required for protection of the surface is sufficiently large to produce interference effects which may decrease the reflectance at various ultraviolet wavelengths.

17.7.3 Simple metal coatings. The situation with respect to simple metal coatings has been summarized by Haas*. Aluminum, silver, gold, copper, and rhodium are considered to be the most important mirror metals. The only material that has a high reflectance in all useful regions, the ultraviolet, visible and infrared, is aluminum. The reflectance of all other metals drops rapidly in the visible or ultraviolet. In the near infrared between 1 and 2μ the average reflectance of silver, gold, copper, and aluminum is higher than 95% but the reflectance of aluminum is about 2% to 3% lower than that of the other three materials. In the far infrared at 10μ all four metals have a reflectance of 98% to 99% and even rhodium reflects about 96%. Today, the most frequently used high reflecting coating for first surface mirrors is vacuum deposited aluminum. It adheres better to glass and other substrates than the other high reflecting materials, it does not tarnish in normal air, and it is very easy to evaporate. Obviously, aluminum coatings are especially important for astronomical mirrors and reflection gratings where high reflectance in the ultraviolet is required. Figure 17.2 of Haas (loc cit) shows the reflectance of freshly deposited films of Ag, Al, Au, Cu and Rh as functions of the wavelength from 0.22 to 10μ. For second-surface reflectors in the visible and near infrared silver is frequently used. As a second-surface reflector it can be adequately protected by copper-plating and painting.

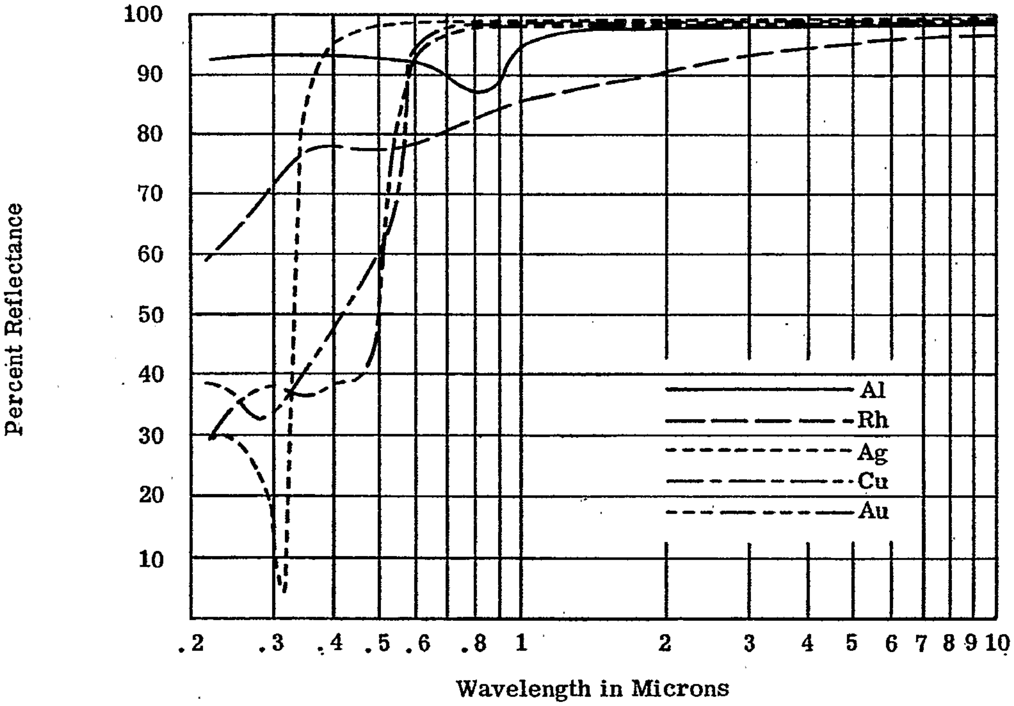

Figure 17.2- Reflectance of freshly deposited films of Ag, Al, Au, Cu, and Rh as function of wavelength from 0.22 to 10μ. (From Jour. Optical Soc. America, G. Haas 945; 945, 1955)

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* Haas, George: Filmed Surfaces for Reflecting Optics; JOS 945-945, November, 1955.

17.7.4 Reference. The subject of reflective and anti-reflective coatings is treated extensively in Sections 20 and 21 of this handbook.

17.8 AVAILABILITY; COST; EASE OF WORKING

17.8.1 General. Materials with attractive optical properties are sometimes unsuited to particular applications because of unavailability, either in quantity or in size of pieces required, because of high cost, or because of the difficulty of working the material satisfactorily. Even in cases in which the cost itself is not an objection, the designer of military instruments should as far as possible avoid the use of materials which would be in critical supply, or cause excessive demands on manpower in times of national emergency.