
CHAPTER 35

PROPERTIES OF METALS

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35.1 GLOSSARY

a	absorptance, absorptivity
a	plate radius (m)
B	support condition
C_{ij}	elastic stiffness constants (N/m ²)
C_p	specific heat (J/kg K)
CTE	coefficient of thermal expansion (K ⁻¹)
D	flexural rigidity (N m ²)
D	thermal diffusivity (m ² /s)
E	elastic modulus (Young's) (N/m ²)
\mathbf{E}	electromagnetic wave vector (J)
e	electron charge (C)
E_o	amplitude of electromagnetic wave at $x = 0$ (J)
G	load factor (N/kg)
G	shear modulus, modulus of rigidity (N/m ²)
g	acceleration due to gravity (m/s ²)
I	light intensity in medium (W/m ²)
i	$(-1)^{1/2}$
I_o	light intensity at interface (W/m ²)
I_o	section moment of inertia (m ⁴ /m)
K	bulk modulus (N/m ²)
k	extinction coefficient
k	thermal conductivity (W/m K)

L	length (m)
M	materials parameter (kg/N m)
m	electron mass (kg)
\mathbf{N}	complex index of refraction
N	number of dipoles per unit volume (m^{-3})
n	index of refraction
P	plate size (m^4)
q	load (N/m^2)
r	reflectance, reflectivity
R_I	intensity reflection coefficient
S	structural efficiency (m^{-2})
T	temperature (K)
t	time (s)
t	transmittance, transmissivity
V_0	volume per unit area of surface (m)
x	distance (m)
α	coefficient of thermal expansion (K^{-1})
α	absorption coefficient (m^{-1})
β	deflection coefficient
β	dynamic deflection coefficient
Γ	damping constant
δ	skin depth (nm)
δ	deflection (m)
δ_{DYN}	dynamic deflection (m)
ϵ	emittance, emissivity (W/m^2)
ϵ	complex dielectric constant
ϵ_0	permittivity of free space (F/m)
ϵ_1	real part of dielectric constant
ϵ_2	imaginary part of dielectric constant
$\ddot{\theta}$	angular acceleration (s^2)
λ	wavelength (m)
λ_0	wavelength in vacuum (m)
μ	magnetic susceptibility (H/m)
ν	frequency (s^{-1})
ν	Poisson's ratio

ρ	mass density (kg/m^3)
σ	conductivity (S/m)
ω	radian frequency (s^{-1})

35.2 INTRODUCTION

Metals are commonly used in optical systems in three forms: (1) structures, (2) mirrors, and (3) optical thin films. In this article, properties are given for metal mirror substrate and structural materials used in modern optical systems. Many other materials have not been included due to their limited applicability. Metal film properties are discussed in the context of thick films (claddings) rather than optical thin films that are covered in Chap. 42, *Optical and Physical Properties of Films and Coatings*, in Vol. I. Since mirrors are structural elements, the structural properties are equally important as the optical properties to the designer of an optical system. Therefore, the properties addressed here include physical, mechanical, and thermal properties in addition to optical properties. Mechanical and thermal properties of silicon (Si) and silicon carbide (SiC) are included, but not their optical properties since they are given in the article entitled “Optical Properties of Semiconductors,” Vol II, Chap. 36.

After brief discussions of optical properties, mirror design, and dimensional stability, curves and tables of properties are presented, as a function of temperature and wavelength, where available. For more complete discussions or listings, the reader should consult the references and/or one of the available databases.¹⁻³ A concise theoretical overview of the physical properties of materials is given by Lines.⁴

Nomenclature

The symbols and units used in this subsection are consistent with usage in other sections of this Handbook although there are some unavoidable duplications in the usage of symbols between categories of optical, physical, thermal, and mechanical properties. Definitions of symbols with the appropriate units are contained in the table at the beginning of this article.

Optical Properties

The definitions for optical properties given in this section are primarily in the geometric optics realm and do not go into the depth considered in many texts dealing with optical properties of solids.⁵⁻⁸

There is obviously a thickness continuum between thin films and bulk, but for this presentation, bulk is considered to be any thickness of material that has bulk properties. Typically, thin films have lower density, thermal conductivity, and refractive index than bulk; however, current deposition techniques are narrowing the differences. Optical properties of thin films are presented only when bulk properties have not been found in the literature.

The interaction between light and metals takes place between the optical electric field and the conduction band electrons of the metal.⁹ Some of the light energy can be

transferred to the lattice by collisions in the form of heat. The optical properties of metals are normally characterized by the two optical constants: index of refraction n and extinction coefficient k that make up the complex refractive index \mathbf{N} where:

$$\mathbf{N} = n + ik \quad (1)$$

The refractive index is defined as the ratio of phase velocity of light in vacuum to the phase velocity of light in the medium. The extinction coefficient is related to the exponential decay of the wave as it passes through the medium. Note, however, that these “constants” vary with wavelength and temperature. The expression for an electromagnetic wave in an absorbing medium contains both of these parameters:

$$\mathbf{E} = E_o e^{-2\pi kx/\lambda_0} e^{-i(2\pi nx/\lambda_0 - \omega t)} \quad (2)$$

where E_o is the amplitude of the wave measured at the point $x = 0$ in the medium, E is the instantaneous value of the electric vector measured at a distance x from the first point and at some time t , ω is the angular frequency of the source, and λ_0 is the wavelength in vacuum.

The absorption coefficient α is related to the extinction coefficient by:

$$\alpha = 4k/\lambda_0 \quad (3)$$

and for the general case, the absorption coefficient also appears in the absorption equation:

$$I = I_0 e^{-\alpha x} \quad (4)$$

However, this equation implies that the intensities I and I_0 are measured within the absorbing medium. The complex dielectric constant ϵ for such a material is:

$$\epsilon = \epsilon_1 + i\epsilon_2 \quad (5)$$

where the dielectric constants are related to the optical constants by:

$$\epsilon_1 = n^2 - k^2 \quad (6)$$

$$\epsilon_2 = 2nk \quad (7)$$

Two additional materials properties that influence the light-material interaction are magnetic susceptibility μ and conductivity σ that are further discussed later.

The equations describing the reflection phenomena, including polarization effects for metals, will not be presented here but are explained in detail elsewhere.^{5-8,10-11} After a brief description of Lorentz and Drude theories and their implications for metals, and particularly for absorption, the relationship among reflection, transmission, and absorption is discussed.⁹

The classical theory of absorption in dielectrics is due to H. A. Lorentz¹² and in metals to P. K. L. Drude.¹³ Both models treat the optically active electrons in a material as classical oscillators. In the Lorentz model, the electron is considered to be bound to the nucleus by a harmonic restoring force. In this manner, Lorentz's picture is that of the

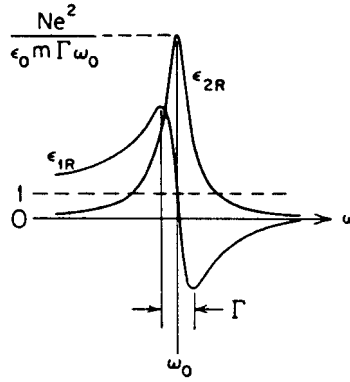


FIGURE 1 Frequency dependences of ϵ_{1R} and ϵ_{2R} .

nonconductive dielectric. Drude considered the electrons to be free, and set the restoring force in the Lorentz model equal to zero. Both models include a damping term in the electron's equation of motion that in more modern terms is recognized as a result of electron-phonon collisions.

These models solve for the electron's motion in the presence of the electromagnetic field as a driving force. From this, it is possible to write an expression for the polarization induced in the medium and from that to derive the dielectric constant. The Lorentz model for dielectrics gives the relative real and imaginary parts of the dielectric constant ϵ_{1R} and ϵ_{2R} in terms of N , the number of dipoles per unit volume; e and m , the electron charge and mass; Γ , the damping constant; ω and ω_0 , the radian frequencies of the field and the harmonically bound electron; and ϵ_0 , the permittivity of free space. These functions are shown in Fig. 1. The range of frequencies where ϵ_1 increases with frequency is referred to as the *range of normal dispersion*, and the region near $\omega = \omega_0$ where it decreases with frequency is called the *range of anomalous dispersion*.

Since the ionic polarizability is much smaller than the electronic polarizability at optical frequencies, only the electronic terms are considered when evaluating optical absorption using the Lorentz model for dielectrics. The Drude model for metals assumes that the electrons are free to move. This means that it is identical to the Lorentz model except that ω_0 is set equal to zero. The real and imaginary parts of the dielectric constant are then given by

$$\epsilon_{1R} = 1 - (Ne^2\epsilon_0 m) \frac{1}{\omega^2 + \Gamma^2} \quad (8)$$

$$\epsilon_{2R} = (Ne^2\epsilon_0 m) \frac{\Gamma}{\omega(\omega^2 + \Gamma^2)} \quad (9)$$

The quantity Γ is related to the mean time between electron collisions with lattice vibrations, and by considering electronic motion in an electric field \mathbf{E} having radian frequency ω , an expression for the average velocity can be obtained. An expression for the conductivity σ is then obtained and the parts of the dielectric constant can be restated. At electromagnetic field frequencies that are low, it can be shown that $\epsilon_2 \gg \epsilon_1$ and therefore it follows that:

$$\alpha = (\omega\mu\sigma/2)^{1/2} \quad (10)$$

In other words, the optical properties and the conductivity of a perfect metal are related

through the fact that each is determined by the motion of free electrons. At high frequencies, transitions involving bound or valence band electrons are possible and there will be a noticeable deviation from this simple result of the Drude model. However, the experimental data reported for most metals are in good agreement with the Drude prediction at wavelengths as short as 1 μm .

From Eq. (10) it is clear that a field propagating in a metal will be attenuated by a factor of $1/e$ when it has traveled a distance:

$$\delta = (2/\omega\mu\sigma)^{1/2} \quad (11)$$

This quantity is called the *skin depth*, and at optical frequencies for most metals it is ~ 50 nm. After a light beam has propagated one skin depth into a metal, its intensity is reduced to 0.135 of its value at the surface.

Another aspect of the absorption of light energy by metals that should be noted is the fact that it increases with temperature. This is important because during laser irradiation the temperature of a metal will increase and so will the absorption. The coupling of energy into the metal is therefore dependent on the temperature dependence of the absorption. For most metals, all the light that gets into the metal is absorbed. If the Fresnel expression for the electric field reflectance is applied to the real and imaginary parts of the complex index for a metal-air interface, the field reflectivity can be obtained. When multiplied by its complex conjugate, the expression for the intensity reflection coefficient is obtained:

$$R_I = 1 - 2\mu\epsilon_0\omega/\sigma \quad (12)$$

Since the conductivity σ decreases with increasing temperature, R_I decreases with increasing temperature, and at higher temperatures more of the incident energy is absorbed.

Since reflection methods are used in determining the optical constants, they are strongly dependent on the characteristics of the metallic surface. These characteristics vary considerably with chemical and mechanical treatment, and these treatments have not always been accurately defined. Not all measurements have been made on freshly polished surfaces but in many cases on freshly deposited thin films. The best available data are presented in the tables and figures, and the reader is advised to consult the appropriate references for specifics.

In this article, an ending of *-ance* denotes a property of a specific sample (i.e., including effects of surface finish), while the ending *-ivity* refers to an intrinsic material property. For most of the discussion, the endings are interchangeable.

Reflectance r is the ratio of radiant flux reflected from a surface to the total incident radiant flux. Since r is a function of the optical constants, it varies with wavelength and temperature. The relationship between reflectance and optical constants is:⁵

$$r = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2} \quad (13)$$

The reflectance of a good, freshly deposited mirror coating is almost always higher than that of a polished or electroplated surface of the same material. The reflectance is normally less than unity—some transmission and absorption, no matter how small, are always present. The relationship between these three properties is:

$$r + t + a = 1 \quad (14)$$

Transmittance t is the ratio of radiant flux transmitted through a surface to the total incident radiant flux and absorptance a is the ratio of the radiant flux lost by absorption to the total incident radiant flux. Since t and a are functions of the optical constants, they

vary with wavelength and temperature. Transmittance is normally very small for metals except in special cases (e.g., beryllium at x-ray wavelengths). Absorptance is affected by surface condition as well as the intrinsic contribution of the material.

The thermal radiative properties are descriptive of a radiant energy-matter interaction that can be described by other properties such as the optical constants and/or complex dielectric constant, each of which is especially convenient for studying various aspects of the interaction. However, the thermal radiative properties are particularly useful since metallic materials are strongly influenced by surface effects, particularly oxide films, and therefore in many cases they are not readily calculated by simple means from the other properties.

For opaque materials, the transmission is near zero, so Eq. (14) becomes:

$$r + a = 1 \quad (15)$$

but since Kirchhoff's law states that absorptance equals emittance, ϵ , this becomes:

$$r + \epsilon = 1 \quad (16)$$

and the thermal radiative properties of an opaque body are fully described by either the reflectance or the emittance. Emittance is the ratio of radiated emitted power (in W/m^2) of a surface to the emissive power of a blackbody at the same temperature. Emittance can therefore be expressed as either *spectral* (emittance as a function of wavelength at constant temperature) or *total* (the integrated emittance over all wavelengths as a function of temperature).

Physical Properties

The physical properties of interest for metals in optical applications include density, electrical conductivity, and electrical resistivity (the reciprocal of conductivity), as well as crystal structure. Chemical composition of alloys is also included with physical properties.

For density, mass density is reported with units of kg/m^3 . Electrical conductivity is related to electrical resistivity, but for some materials, one or the other is normally reported. Both properties vary with temperature.

Crystal structure is extremely important for stability since anisotropy of the elastic, electric, and magnetic properties and thermal expansion depend on the type of structure.¹⁴ Single crystals of cubic metals have completely isotropic coefficient of thermal expansion (CTE), but are anisotropic in elastic properties—modulus and Poisson's ratio. Materials with hexagonal structures have anisotropic expansion and elastic properties. While polycrystalline metals with randomly oriented small grains do not exhibit these anisotropies they can easily have local areas that are inhomogeneous or can have overall oriented crystal structure induced by fabrication methods.

The combined influence of physical, thermal, and mechanical properties on optical system performance is described under "Properties Important in Mirror Design," later in this article.

Thermal Properties

Thermal properties of metals that are important in optical systems design include: coefficient of thermal expansion α , referred to in this section as CTE; thermal conductivity k ; and specific heat C_p . All of these properties vary with temperature; usually they tend to decrease with decreasing temperature. Although not strictly a thermal property, the maximum usable temperature is also included as a guide for the optical designer.

Thermal expansion is a generic term for change in length for a specific temperature

change, but there are precise terms that describe specific aspects of this material property. ASTM E338 Committee recommends the following nomenclature:¹⁵

Coefficient of linear thermal expansion (CTE or thermal expansivity):

$$\alpha \equiv \frac{1}{L} \frac{\Delta L}{\Delta T} \quad (17)$$

Instantaneous coefficient of linear thermal expansion:

$$\alpha' \equiv \lim_{\Delta T \rightarrow 0} \left(\frac{1}{L} \frac{\Delta L}{\Delta T} \right) \quad (18)$$

Mean coefficient of linear thermal expansion:

$$\bar{\alpha} \equiv \frac{1}{T_2 - T_1} \int_{T_1}^{T_2} \alpha' dT \quad (19)$$

In general, lower thermal expansion is better for optical system performance, as it minimizes the effect of thermal gradients on component dimensional changes. CTE is the prime parameter in materials selection for cooled mirrors.

Thermal conductivity is the quantity of heat transmitted per unit of time through a unit of area per unit of temperature gradient with units of W/m K. Higher thermal conductivity is desirable to minimize temperature gradients when there is a heat source to the optical system.

Specific heat, also called heat capacity per unit mass, is the quantity of heat required to change the temperature of a unit mass of material one degree under conditions of constant pressure. A material with high specific heat requires more heat to cause a temperature change that might cause a distortion. High specific heat also means that more energy is required to force a temperature change (e.g., in cooling an infrared telescope assembly to cryogenic temperatures).

Maximum usable temperature is not a hard number. It is more loosely defined as the temperature at which there is a significant change in the material due to one or more of a number of things, such as significant softening or change in strength, melting, recrystallization, and crystallographic phase change.

Mechanical Properties

Mechanical properties are divided into elastic/plastic properties and strength, and fracture properties. The elastic properties of a metal can be described by a 6×6 matrix of constants called the elastic stiffness constants.¹⁶⁻¹⁸ Because of symmetry considerations, there are a maximum of 21 independent constants that are further reduced for more symmetrical crystal types. For cubic materials there are three constants, C_{11} , C_{12} , and C_{44} , and for hexagonal five constants, C_{11} , C_{12} , C_{13} , C_{33} , and C_{44} . From these, the elastic properties of the material, Young's modulus E (the elastic modulus in tension), bulk modulus K , modulus of rigidity G (also called shear modulus), and Poisson's ratio ν can be calculated. The constants, and consequently the properties, vary as functions of temperature. The properties vary with crystallographic direction in single crystals,¹⁴ but in randomly oriented polycrystalline materials the macroproperties are usually isotropic.

Young's modulus of elasticity E is the measure of stiffness or rigidity of a metal—the ratio of stress, in the completely elastic region, to the corresponding strain. Bulk modulus K is the measure of resistance to change in volume—the ratio of hydrostatic stress to the corresponding change in volume. Shear modulus, or modulus of rigidity, G is the ratio of shear stress to the corresponding shear strain under completely elastic conditions.

Poisson's ratio ν is the ratio of the absolute value of the rate of transverse (lateral) strain to the corresponding axial strain resulting from uniformly distributed axial stress in the elastic deformation region.

For isotropic materials the properties are interrelated by the following equations:¹⁸

$$G = \frac{E}{2(1 + \nu)} \quad (20)$$

$$K = \frac{E}{3(1 - 2\nu)} \quad (21)$$

The mechanical strength and fracture properties are important for the structural aspect of the optical system. The components in the system must be able to support loads with no permanent deformation within limits set by the error budget and certainly with no fracture. For ductile materials such as copper, the yield and/or microyield strength may be the important parameters. On the other hand, for brittle or near-brittle metals such as beryllium, fracture toughness may be more important. For ceramic materials such as silicon carbide, fracture toughness and modulus of rupture are the important fracture criteria. A listing of definitions for each of these terms¹⁹ follows:

creep strength: the stress that will cause a given time-dependent plastic strain in a creep test for a given time.

ductility: the ability of a material to deform plastically before fracture.

fatigue strength: the maximum stress that can be sustained for a specific number of cycles without failure.

fracture toughness: a generic term for measures of resistance to extension of a crack.

hardness: a measure of the resistance of a material to surface indentation.

microcreep strength: the stress that will cause 1 ppm of permanent strain in a given time; usually less than the microyield strength.

microstrain: a deformation of 10^{-6} m/m (1 ppm)

microyield strength: the stress that will cause 1 ppm of permanent strain in a short time; also called precision elastic limit (PEL).

ultimate strength: the maximum stress a material can withstand without fracture.

yield strength: the stress at which a material exhibits a specified deviation from elastic behavior (proportionality of stress and strain), usually 2×10^{-3} m/m (0.2 percent).

Properties Important in Mirror Design

There are many factors that enter into the design of a mirror or mirror system, but the most important requirement is optical performance. Dimensional stability, weight, durability, and cost are some of the factors to be traded off before an effective design can be established.²⁰⁻²³ The loading conditions during fabrication, transportation, and use and the thermal environment play a substantial role in materials selection. To satisfy the end-use requirements, the optical, structural, and thermal performance must be predictable. Each of these factors has a set of parameters and associated material properties that can be used to design an optic to meet performance goals.

For optical performance, the shape or optical figure is the key performance factor followed by the optical properties of reflectance, absorptance, and complex refractive index. The optical properties of a mirror substrate material are only important when the mirror is to be used bare (i.e., with no optical coating).

To design for structural performance goals, deflections due to static (or inertial) and dynamic loads are usually calculated as a first estimate.²⁴ For this purpose, the well-known plate equations²⁵ are invoked. For the static case,

$$\delta = \beta q a^4 / D \quad (22)$$

where δ = deflection

β = deflection coefficient (depends on support condition)

q = normal loading (uniform load example)

a = plate radius (semidiameter)

D = flexural rigidity, defined as:

$$D = EI_0 / (1 - \nu^2) \quad (23)$$

where, in turn: E = Young's modulus of elasticity

I_0 = moment of inertia of the section

ν = Poisson's ratio.

But

$$q = \rho V_0 G \quad (24)$$

where ρ = material density

V_0 = volume of material per unit area of plate surface

G = load factor (g's)

After substitution and regrouping the terms:

$$\delta = \beta \frac{\rho(1 - \nu^2)}{E} \frac{V_0}{I_0} a^4 G \quad (25)$$

or:

$$\delta \times B = M \times S \times P \times G \quad (26)$$

where B = support condition

M = materials parameters

S = structural efficiency

P = plate size

G = load factor

This shows five terms, each representing a parameter to be optimized for mirror performance. B , P , and G will be determined from system requirements; S is related to the geometric design of the part; and M is the materials term showing that ρ , ν , and E are the important material properties for optimizing structural performance.

For the dynamic case of deflection due to a local angular acceleration $\ddot{\theta}$ about a diameter (scanning applications), the equation becomes:

$$\delta_{\text{DYN}} = \beta_D \frac{\rho(1 - \nu^2)}{E} \frac{V_0}{I_0} a^5 \frac{\ddot{\theta}}{g} \quad (27)$$

The same structural optimization parameters prevail as in the static case. Note that in both cases maximizing the term E/ρ (specific stiffness) minimizes deflection.

The determination of thermal performance²⁶⁻²⁷ is dependent on the thermal environment and thermal properties of the mirror material. For most applications, the most significant properties are the coefficient of thermal expansion CTE or α , and thermal conductivity k . Also important are the specific heat C_p , and thermal diffusivity D , a property related to dissipation of thermal gradients that is a combination of properties and

TABLE 1 Properties of Selected Mirror Materials

	ρ Density 10^3 kg/m^3	E Young's modulus GN/m^2	E/ρ Specific stiffness arb. units	CTE Thermal expansion $10^{-6}/\text{K}$	k Thermal conductivity W/m K	C_p Specific heat J/kg K	D Thermal diffusivity $10^{-6} \text{ m}^2/\text{s}$	Distortion coefficient	
								CTE/ k steady state $\mu\text{m/W}$	CTE/ D transient $\text{s/m}^2 \text{ K}$
Preferred	small	large	large	small	large	large	large	small	small
Fused silica	2.19	72	33	0.50	1.4	750	0.85	0.36	0.59
Beryllium: I-70	1.85	287	155	11.3	216	1925	57.2	0.05	0.20
Aluminum: 6061	2.70	68	25	22.5	167	896	69	0.13	0.33
Copper	8.94	117	13	16.5	391	385	115.5	0.53	0.14
304 stainless steel	8.00	193	24	14.7	16.2	500	4.0	0.91	3.68
Invar 36	8.05	141	18	1.0	10.4	515	2.6	0.10	0.38
Silicon	2.33	131	56	2.6	156	710	89.2	0.02	0.03
SiC: RB-30% Si	2.89	330	114	2.6	155	670	81.0	0.02	0.03
SiC: CVD	3.21	465	145	2.4	198	733	82.0	0.01	0.03

equal to $k/\rho C_p$. There are two important thermal figures of merit, the coefficients of thermal distortion α/k and α/D . The former expresses steady-state distortion per unit of input power, while the latter is related to transient distortions.

Typical room-temperature values for many of the important properties mentioned here are listed for a number of mirror materials in Table 1. It should be clear from the wide range of properties and figures of merit that no one material can satisfy all applications. A selection process is required and a tradeoff study has to be made for each individual application.²⁰

Metal optical components can be designed and fabricated to meet system requirements. However, unless they remain within specifications throughout their intended lifetime, they have failed. The most often noted changes that occur to degrade performance are dimensional instability and/or environment-related optical property degradation. Dimensional instabilities can take many forms with many causes, and there are any number of ways to minimize them. Dimensional instabilities can only be discussed briefly here; for a more complete discussion, consult Refs. 28 to 31. The instabilities most often observed are:

- *temporal instability*: a change in dimensions with time in a uniform environment (e.g., a mirror stored in a laboratory environment with no applied loads changes figure over a period of time)
- *thermal/mechanical cycling or hysteresis instability*: a change in dimensions when the environment is changed and then restored, where the measurements are made under the same conditions before and after the exposure (e.g., a mirror with a measured figure is cycled between high and low temperatures and, when remeasured under the original conditions, the figure has changed)
- *thermal instability*: a change in dimensions when the environment is changed, but completely reversible when the original environment is restored (e.g., a mirror is measured at room temperature, again at low temperature where the figure is different, and finally at the original conditions with the original figure restored)

There are other types of instabilities, but they are less common, particularly in metals. The sources of the dimensional changes cited here can be attributed to one or more of

the following:

- externally applied stress
- changes in internal stress
- microstructural changes
- inhomogeneity/anisotropy of properties

In general, temporal and cycling/hysteresis instabilities are primarily caused by changes in internal stress (i.e., stress relaxation). If the temperature is high enough, microstructural changes can take place as in annealing, recrystallization, or second-phase precipitation. Thermal instability is a result of inhomogeneity and/or anisotropy of thermal expansion within the component, is completely reversible, and cannot be eliminated by nondestructive methods.

To eliminate potential instabilities, care must be taken in the selection of materials and fabrication methods to avoid anisotropy and inhomogeneity. Further care is necessary to avoid any undue applied loads that could cause part deformation and subsequent residual stress. The fabrication methods should include stress-relief steps such as thermal annealing, chemical removal of damaged surfaces, and thermal or mechanical cycling. These steps become more critical for larger and more complex component geometries.

Instabilities can also be induced by attachments and amounts. Careful design to minimize induced stresses and selection of dissimilar materials with close thermal expansion matching is essential.³²

35.3 SUMMARY DATA

The properties presented here are representative for the materials and are not a complete presentation. For more complete compilations, the references should be consulted.

Optical Properties

Thin films and their properties are discussed in Vol. I, Chap. 42, and therefore are not presented here except in the case where bulk (surface) optical properties are not available.

Index of Refraction and Extinction Coefficient. The data for the optical constants of metals are substantial, with the most complete listing available in the two volumes of *Optical Constants of Metals*,^{33,34} from which most of the data presented here have been taken. Earlier compilations^{35,36} are also available. While most of the data are for deposited films, the references discuss properties of polished polycrystalline surfaces where available. Table 2 lists room temperature values for n and k of Al,³⁷ Be,³⁸ Cu,³⁹ Cr,⁴⁰ Au,³⁹ Fe,⁴⁰ Mo,³⁹ Ni,³⁹ Pt,³⁹ Ag,³⁹ W,³⁹ and α -SiC.⁴¹ Figures 2 to 14 graphically show these constants with the absorption edges shown in most cases.

Extensive reviews of the properties of aluminum³⁷ and beryllium³⁸ also discuss the effects of oxide layers on optical constants and reflectance. Oxide layers on aluminum typically reduce the optical constant values by 25 percent in the infrared, 10 to 15 percent in the visible, and very little in the ultraviolet.³⁷ As a result of the high values of n and k for aluminum in the visible and infrared, there are relatively large variations of optical constants with temperature, but they result in only small changes in reflectance.³⁷ The beryllium review³⁸ does not mention any variation of properties with temperature. The optical properties of beryllium and all hexagonal metals vary substantially with crystallographic direction. This variation with crystallography is shown for the dielectric constants

TABLE 2 n and k of Selected Metals at Room Temperature

Metal	eV	Wavelength Å	μm	n	k
Aluminum ³⁷	300.0	41.3		1.00	0.00
	180.0	68.9		0.99	0.01
	130.0	95.4		0.99	0.02
	110.0	113.0		0.99	0.03
	100.0	124.0		0.99	0.03
	95.0	131.0		1.00	0.04
	80.0	155.0		1.01	0.02
	75.0	165.0		1.01	0.02
	72.0	172.0		1.02	0.00
	50.0	248.0		0.97	0.01
	25.0	496.0		0.81	0.02
	17.0	729.0		0.47	0.04
	12.0	1,033.0	0.10	0.03	0.79
	6.00	2,066.0	0.21	0.13	2.39
	4.00	3,100.0	0.31	0.29	3.74
	3.10	4,000.0	0.40	0.49	4.86
	2.48	5,000.0	0.50	0.77	6.08
	2.07	6,000.0	0.60	1.02	7.26
	1.91	6,500.0	0.65	1.47	7.79
	1.77	7,000.0	0.70	1.83	8.31
	1.55	8,000.0	0.80	2.80	8.45
	1.10		1.13	1.20	11.2
	0.827		1.50	1.38	15.4
	0.620		2.00	2.15	20.7
	0.310		4.00	6.43	39.8
	0.177		7.00	14.0	66.2
	0.124		10.0	25.3	89.8
	0.062		20.0	60.7	147.0
	0.039		32.0	103.0	208.0
Beryllium ³⁸	300.0	41.3		1.00	0.00
	200.0	62.0		0.99	0.00
	150.0	82.7		0.99	0.01
	119.0	104.0		1.00	0.02
	100.0	124.0		0.99	0.00
	50.0	248.0		0.93	0.01
	25.0	496.0		0.71	0.10
	17.0	729.0		0.34	0.42
	12.0	1,033.0	0.10	0.30	1.07
	6.00	2,066.0	0.21	0.85	2.64
	4.00	3,100.0	0.31	2.47	3.08
		4,133.0	0.41	2.95	3.14
		5,166.0	0.52	3.03	3.18
		6,888.0	0.69	3.47	3.23
			1.03	3.26	3.96
			3.10	2.07	12.6
			6.20	3.66	26.7
			12.0	11.3	50.1
			21.0	19.9	77.1
			31.0	37.4	110.0
Copper ³⁹			62.0	86.1	157.0
	9,000.0	1.38		1.00	0.00
	4,000.0	3.10		1.00	0.00

TABLE 2 n and k of Selected Metals at Room Temperature (*Continued*)

Metal	eV	Wavelength Å	μm	n	k
Copper ³⁹	1,500.0	8.27		1.00	0.00
	1,000.0	12.4		1.00	0.00
	900.0	13.8		1.00	0.00
	500.0	24.8		1.00	0.00
	300.0	41.3		0.99	0.01
	200.0	62.0		0.98	0.02
	150.0	82.7		0.97	0.03
	120.0	103.0		0.97	0.05
	100.0	124.0		0.97	0.07
	50.0	248.0		0.95	0.13
	29.0	428.0		0.85	0.30
	26.0	477.0		0.92	0.40
	24.0	517.0		0.96	0.37
	23.0	539.0		0.94	0.37
	20.0	620.0		0.88	0.46
	15.0	827.0		1.01	0.71
	12.0	1,033.0	0.10	1.09	0.73
	6.50	1,907.0	0.19	0.96	1.37
	5.20	2,384.0	0.24	1.38	1.80
	4.80	2,583.0	0.26	1.53	1.71
	4.30	2,885.0	0.29	1.46	1.64
	2.60	4,768.0	0.48	1.15	2.5
	2.30	5,390.0	0.54	1.04	2.59
	2.10	5,904.0	0.59	0.47	2.81
	1.80	6,888.0	0.69	0.21	4.05
	1.50	8,265.0	0.83	0.26	5.26
	0.950		1.30	0.51	6.92
	0.620		2.00	0.85	10.6
	0.400		3.10	1.59	16.5
	0.200		6.20	5.23	33.0
	0.130		9.54	10.8	47.5
Chromium ⁴⁰	10,000.0	1.24		1.00	0.00
	6,015.0	2.06		1.00	0.00
	5,878.0	2.11		1.00	0.00
	3,008.0	4.12		1.00	0.00
	1,504.0	8.24		1.00	0.00
	992.0	12.5		1.00	0.00
	735.0	16.9		1.00	0.00
	702.0	17.7		1.00	0.00
	686.0	18.1		1.00	0.00
	403.0	30.8		1.00	0.00
	202.0	61.5		0.98	0.00
	100.0	124.0		0.94	0.03
	62.0	200.0		0.88	0.12
	52.0	238.0		0.92	0.18
	29.5	420.0		0.78	0.21
	24.3	510.0		0.67	0.39
	18.0	689.0		0.87	0.70
	14.3	867.0		1.06	0.82
	12.8	969.0		1.15	0.75
	11.4	1,088.0	0.109	1.08	0.69
	7.61	1,629.0	0.163	0.66	1.23

TABLE 2 n and k of Selected Metals at Room Temperature (*Continued*)

Metal	eV	Wavelength Å	μm	n	k
Chromium ⁴⁰	5.75	2,156.0	0.216	0.97	1.74
	4.80	2,583.0	0.258	0.86	2.13
	3.03	4,092.0	0.409	1.54	3.71
	2.42	5,123.0	0.512	2.75	4.46
	1.77	7,005.0	0.700	3.84	4.37
	1.26	9,843.0	0.984	4.50	4.28
	1.12		1.11	4.53	4.30
	0.66		1.88	3.96	5.95
	0.60		2.07	4.01	6.48
	0.34		3.65	2.89	12.0
	0.18		6.89	8.73	25.4
	0.09		13.8	11.8	33.9
	0.06		20.7	21.2	42.0
	0.04		31.0	14.9	65.2
Gold ³⁹	8,266.0	1.50		1.00	0.00
	2,480.0	5.00		1.00	0.00
	2,066.0	6.00		1.00	0.00
	1,012.0	12.25		1.00	0.00
	573.0	21.6		1.00	0.00
	220.0	56.4		0.99	0.01
	150.0	82.7		0.96	0.01
	86.0	144.0		0.89	0.06
	84.5	147.0		0.89	0.07
	84.0	148.0		0.89	0.06
	68.0	182.0		0.86	0.12
	60.0	207.0		0.86	0.16
	34.0	365.0		0.78	0.47
	30.0	413.0		0.89	0.60
	29.0	428.0		0.91	0.60
	27.0	459.0		0.90	0.64
	26.0	480.0		0.85	0.56
	21.8	570.0		1.02	0.85
	19.4	640.0		1.16	0.73
	17.7	700.0		1.08	0.68
	15.8	785.0		1.03	0.74
	12.4	1,000.0	0.10	1.20	0.84
	8.27	1,550.0	0.15	1.45	1.11
	7.29	1,700.0	0.17	1.52	1.07
	6.36	1,950.0	0.20	1.42	1.12
	4.10	3,024.0	0.30	1.81	1.92
	3.90	3,179.0	0.32	1.84	1.90
	3.60	3,444.0	0.34	1.77	1.85
	3.00	4,133.0	0.41	1.64	1.96
	2.60	4,769.0	0.48	1.24	1.80
	2.20	5,636.0	0.56	0.31	2.88
	1.80	6,888.0	0.69	0.16	3.80
	1.40	8,856.0	0.89	0.21	5.88
	1.20		1.03	0.27	7.07
	0.82		1.51	0.54	9.58
	0.40		3.10	1.73	19.2
	0.20		6.20	5.42	37.5
	0.125		9.92	12.2	54.7

TABLE 2 n and k of Selected Metals at Room Temperature (*Continued*)

Metal	eV	Wavelength Å	μm	n	k
Iron ^{36,40}	10,000.0	1.24		1.00	0.00
	7,071.0	1.75		1.00	0.00
	3,619.0	3.43		1.00	0.00
	1,575.0	7.87		1.00	0.00
	884.0	14.0		1.00	0.00
	825.0	15.0		1.00	0.00
	320.0	38.8		0.99	0.00
	211.0	58.7		0.98	0.01
	153.0	81.2		0.97	0.02
	94.0	132.0		0.94	0.05
	65.0	191.0		0.90	0.12
	56.6	219.0		0.98	0.19
	54.0	230.0		1.11	0.18
	51.6	240.0		0.97	0.05
	30.0	413.0		0.82	0.13
	22.2	559.0		0.71	0.35
	20.5	606.0		0.74	0.42
	18.0	689.0		0.78	0.51
	15.8	785.0		0.77	0.61
	11.5	1,078.0	0.11	0.93	0.84
	11.0	1,127.0	0.11	0.91	0.83
	10.3	1,200.0	0.12	0.87	0.91
	8.00	1,550.0	0.15	0.94	1.18
	5.00	2,480.0	0.25	1.14	1.87
	3.00	4,133.0	0.41	1.88	3.12
	2.30	5,390.0	0.54	2.65	3.34
	2.10	5,903.0	0.59	2.80	3.34
	1.50	8,265.0	0.83	3.05	3.77
	1.24		1.00	3.23	4.35
	0.496		2.50	4.13	8.59
	0.248		5.00	4.59	15.4
	0.124		10.0	5.81	30.4
	0.062		20.0	9.87	60.1
	0.037		33.3	22.5	100.0
	0.025		50.0	45.7	141.0
	0.015		80.0	75.2	158.0
	0.010		125.0	120.0	207.0
	0.006		200.0	183.0	260.0
	0.004		287.0	238.0	306.0
Molybdenum ³⁹	2,000.0	6.19		1.00	0.00
	1,041.0	11.6		1.00	0.00
	396.0	31.3		1.00	0.01
	303.0	40.9		1.00	0.01
	211.0	58.8		0.99	0.00
	100.0	124.0		0.93	0.01
	60.0	207.0		0.90	0.11
	37.5	331.0		0.81	0.29
	35.0	354.0		0.87	0.38
	33.8	367.0		0.91	0.33
	33.0	376.0		0.90	0.33
	31.4	394.0		0.92	0.31

TABLE 2 n and k of Selected Metals at Room Temperature (*Continued*)

Metal	eV	Wavelength Å	μm	n	k
Molybdenum ³⁹	29.2	424.0		0.84	0.26
	23.4	530.0		0.58	0.55
	17.6	704.0		0.94	1.14
	15.6	795.0		1.15	1.01
	15.0	827.0		1.14	0.99
	14.4	861.0		1.13	1.00
	13.2	939.0		1.20	1.03
	12.0	1,033.0	0.10	1.26	0.92
	11.0	1,127.0	0.11	1.05	0.77
	8.80	1,409.0	0.14	0.65	1.41
	6.20	2,000.0	0.20	0.81	2.50
	4.40	2,818.0	0.28	2.39	3.88
	3.30	3,757.0	0.38	3.06	3.18
	3.10	4,000.0	0.40	3.03	3.22
	2.40	5,166.0	0.52	3.59	3.78
	2.30	5,391.0	0.54	3.79	3.61
	2.20	5,636.0	0.56	3.76	3.41
	2.05	6,052.0	0.61	3.68	3.49
	1.90	6,526.0	0.65	3.74	3.58
	1.70	7,293.0	0.73	3.84	3.51
	1.50	8,266.0	0.83	3.53	3.30
	1.20		1.03	2.44	4.22
	0.58		2.14	1.34	11.3
	0.24		5.17	3.61	30.0
	0.12		10.3	13.4	58.4
	0.10		12.4	18.5	68.5
Nickel ³⁹	9,919.0	1.25		1.00	0.00
	4,133.0	3.00		1.00	0.00
	1,771.0	7.00		1.00	0.00
	929.0	13.3		1.00	0.00
	500.0	24.8		1.00	0.00
	300.0	41.3		0.99	0.01
	180.0	68.9		0.98	0.02
	120.0	103.0		0.96	0.05
	84.0	148.0		0.93	0.11
	68.0	182.0		0.98	0.17
	66.0	188.0		1.01	0.16
	64.0	194.0		0.98	0.11
	50.0	248.0		0.93	0.15
	45.0	276.0		0.88	0.13
	35.0	354.0		0.86	0.24
	23.0	539.0		0.92	0.44
	20.5	605.0		0.89	0.49
	13.0	954.0		1.08	0.71
	10.0	1,240.0	0.12	0.95	0.87
	7.20	1,722.0	0.17	1.03	1.27
	6.20	2,000.0	0.20	1.00	1.54
	4.80	2,583.0	0.26	1.53	2.11
	4.15	2,988.0	0.30	1.74	2.00
	3.95	3,140.0	0.31	1.72	1.98
	3.15	3,938.0	0.39	1.61	2.33
	2.40	5,166.0	0.52	1.71	3.06

TABLE 2 n and k of Selected Metals at Room Temperature (*Continued*)

Metal	eV	Wavelength Å	μm	n	k
Nickel ³⁹	1.80	6,888.0	0.69	2.14	4.00
	1.20		1.03	2.85	5.10
	0.45		2.76	4.20	10.2
	0.40		3.10	3.84	11.4
	0.28		4.43	4.30	16.0
	0.22		5.64	4.11	20.2
	0.12		10.3	7.11	38.3
	0.10		12.4	9.54	45.8
Platinum ³⁹	2,000.0	6.20		1.00	0.00
	1,016.0	12.2		1.00	0.00
	504.0	24.6		0.99	0.00
	244.0	50.8		0.99	0.01
	121.0	102.0		0.95	0.02
	83.7	150.0		0.88	0.08
	72.9	170.0		0.89	0.10
	53.9	230.0		0.86	0.20
	51.7	240.0		0.88	0.22
	45.6	250.0		0.87	0.16
	32.6	380.0		0.66	0.45
	30.2	410.0		0.70	0.58
	29.5	420.0		0.71	0.57
	28.8	430.0		0.72	0.65
	28.2	440.0		0.72	0.58
	24.8	500.0		0.71	0.72
	20.7	600.0		0.84	0.94
	16.8	740.0		1.05	0.82
	13.2	940.0		1.20	0.93
	12.7	980.0		1.17	0.96
	10.1	1,230.0	0.12	1.36	1.18
	9.05	1,370.0	0.14	1.43	1.14
	8.38	1,480.0	0.15	1.47	1.15
	7.87	1,575.0	0.16	1.46	1.19
	7.29	1,700.0	0.17	1.49	1.22
	6.05	2,050.0	0.20	1.19	1.40
	5.40	2,296.0	0.23	1.36	1.61
	3.00	4,133.0	0.41	1.75	2.92
	2.30	5,390.0	0.54	2.10	3.67
	1.80	6,888.0	0.69	2.51	4.43
	1.20		1.03	3.55	5.92
	0.78		1.55	5.38	7.04
	0.70		1.77	5.71	6.83
	0.65		1.91	5.52	6.66
	0.40		3.10	2.81	11.4
	0.20		6.20	5.90	24.0
	0.13		9.54	9.91	36.7
	0.10		12.4	13.2	44.7
Silver ³⁹	10,000.0	1.24		1.00	0.00
	6,000.0	2.07		1.00	0.00
	3,000.0	4.13		1.00	0.00
	1,500.0	8.26		1.00	0.00
	800.0	15.5		1.00	0.00
	370.0	33.5		1.01	0.01

TABLE 2 n and k of Selected Metals at Room Temperature (*Continued*)

Metal	eV	Wavelength Å	μm	n	k
Silver ³⁰	350.0	35.4		1.00	0.00
	170.0	72.9		0.97	0.00
	110.0	113.0		0.90	0.02
	95.0	131.0		0.86	0.06
	85.0	146.0		0.85	0.11
	64.0	194.0		0.89	0.21
	50.0	248.0		0.88	0.29
	44.0	282.0		0.90	0.33
	35.0	354.0		0.87	0.45
	31.0	400.0		0.93	0.53
	27.5	451.0		0.85	0.62
	22.5	551.0		1.03	0.62
	21.0	590.0		1.11	0.56
	20.0	620.0		1.10	0.55
	15.0	827.0		1.24	0.69
	13.0	954.0		1.32	0.60
	10.9	1,137.0	0.11	1.28	0.56
	10.0	1,240.0	0.12	1.24	0.57
	9.20	1,348.0	0.13	1.18	0.55
	7.60	1,631.0	0.16	0.94	0.83
	4.85	2,556.0	0.26	1.34	1.35
	4.15	2,988.0	0.30	1.52	0.99
	3.90	3,179.0	0.32	0.93	0.50
	3.10	4,000.0	0.40	0.17	1.95
	2.20	5,636.0	0.56	0.12	3.45
	1.80	6,888.0	0.69	0.14	4.44
	1.20		1.03	0.23	6.99
	0.62		2.00	0.65	12.2
	0.24		5.17	3.73	31.3
	0.125		9.92	13.1	53.7
Tungsten ³⁹	2,000.0	6.20		1.00	0.00
	1,016.0	12.2		1.00	0.00
	516.0	24.0		0.99	0.00
	244.0	50.8		0.99	0.02
	100.0	124.0		0.94	0.04
	43.0	288.0		0.74	0.27
	38.5	322.0		0.82	0.33
	35.0	354.0		0.85	0.31
	33.0	376.0		0.82	0.28
	32.0	388.0		0.79	0.30
	30.5	406.0		0.77	0.29
	23.8	521.0		0.48	0.60
	22.9	541.0		0.49	0.69
	22.1	561.0		0.49	0.76
	16.0	775.0		0.98	1.14
	15.5	800.0		0.96	1.12
	14.6	849.0		0.90	1.20
	11.8	1,051.0	0.11	1.18	1.48
	10.8	1,148.0	0.11	1.29	1.39
	10.3	1,204.0	0.12	1.22	1.33
	7.80	1,590.0	0.16	0.93	2.06
	5.60	2,214.0	0.22	2.43	3.70

TABLE 2 n and k of Selected Metals at Room Temperature (*Continued*)

Metal	eV	Wavelength Å	μm	n	k
Tungsten ³⁹	5.00	2,480.0	0.25	3.40	2.85
	4.30	2,883.0	0.29	3.07	2.31
	4.00	3,100.0	0.31	2.95	2.43
	3.45	3,594.0	0.36	3.32	2.70
	3.25	3,815.0	0.38	3.45	2.49
	3.10	4,000.0	0.40	3.39	2.41
	2.80	4,428.0	0.44	3.30	2.49
	1.85	6,702.0	0.67	3.76	2.95
	1.75	7,085.0	0.71	3.85	2.86
	1.60	7,749.0	0.77	3.67	2.68
	1.20		1.03	3.00	3.64
	0.96		1.29	3.15	4.41
	0.92		1.35	3.14	4.45
	0.85		1.46	2.80	4.33
	0.58		2.14	1.18	8.44
	0.40		3.10	1.94	13.2
	0.34		3.65	1.71	15.7
	0.18		6.89	4.72	31.5
	0.12		10.3	10.1	46.4
	0.07		17.7	26.5	73.8
	0.05		24.8	46.5	93.7
Silicon carbide ⁴¹	30.0	413.0		0.74	0.11
	20.5	605.0		0.35	0.53
	13.1	946.0		0.68	1.41
	9.50	1,305.0	0.13	1.46	2.21
	9.00	1,378.0	0.14	1.60	2.15
	7.60	1,631.0	0.16	2.59	2.87
	6.40	1,937.0	0.19	4.05	1.42
	5.00	2,480.0	0.25	3.16	0.26
	3.90	3,179.0	0.32	2.92	0.01
	3.00	4,133.0	0.41	2.75	0.00
	2.50	4,959.0	0.50	2.68	0.00
	1.79	6,911.0	0.69	2.62	—
	1.50	8,266.0	0.83	2.60	—
	0.62		2.00	2.57	0.00
	0.31		4.00	2.52	0.00
	0.12		6.67	2.33	0.02
	0.11		9.80	1.29	0.01
	0.10		10.40	0.09	0.63
	0.10		10.81	0.06	1.57
	0.10		11.9	0.16	4.51
	0.09		12.6	8.74	18.4
	0.08		12.7	17.7	6.03
	0.05		13.1	7.35	0.27
			15.4	4.09	0.02
			25.0	3.34	—

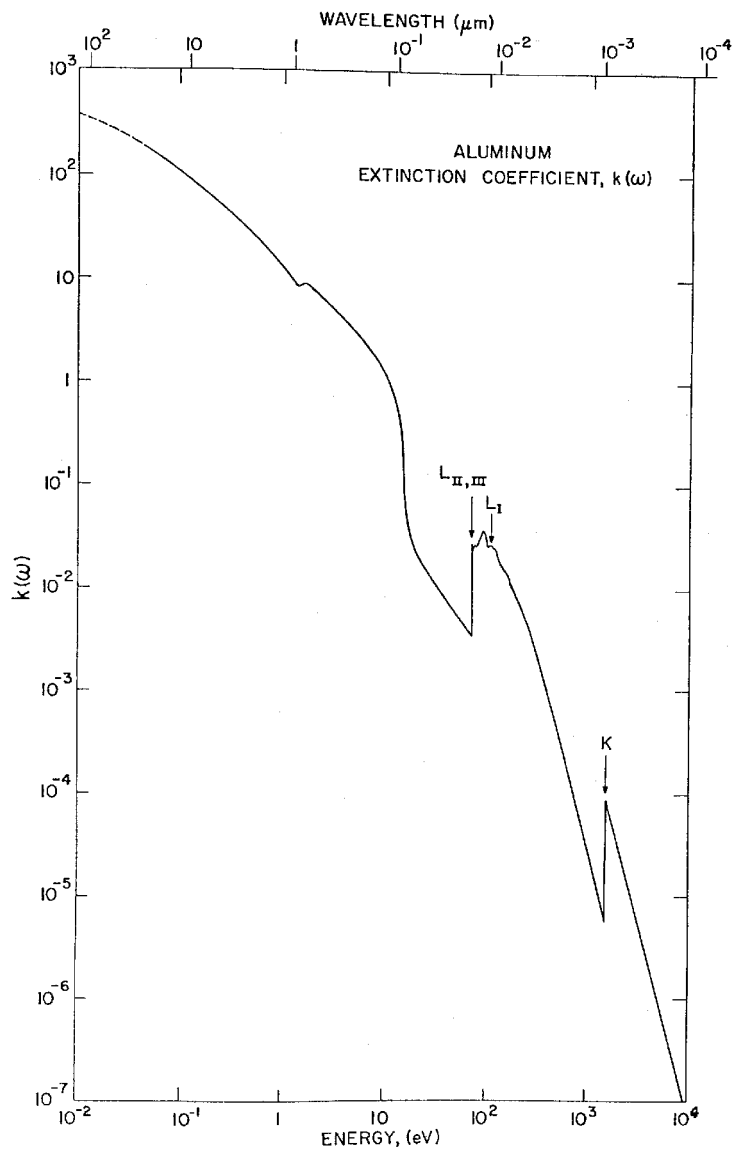


FIGURE 2 k for aluminum vs. photon energy.³⁷

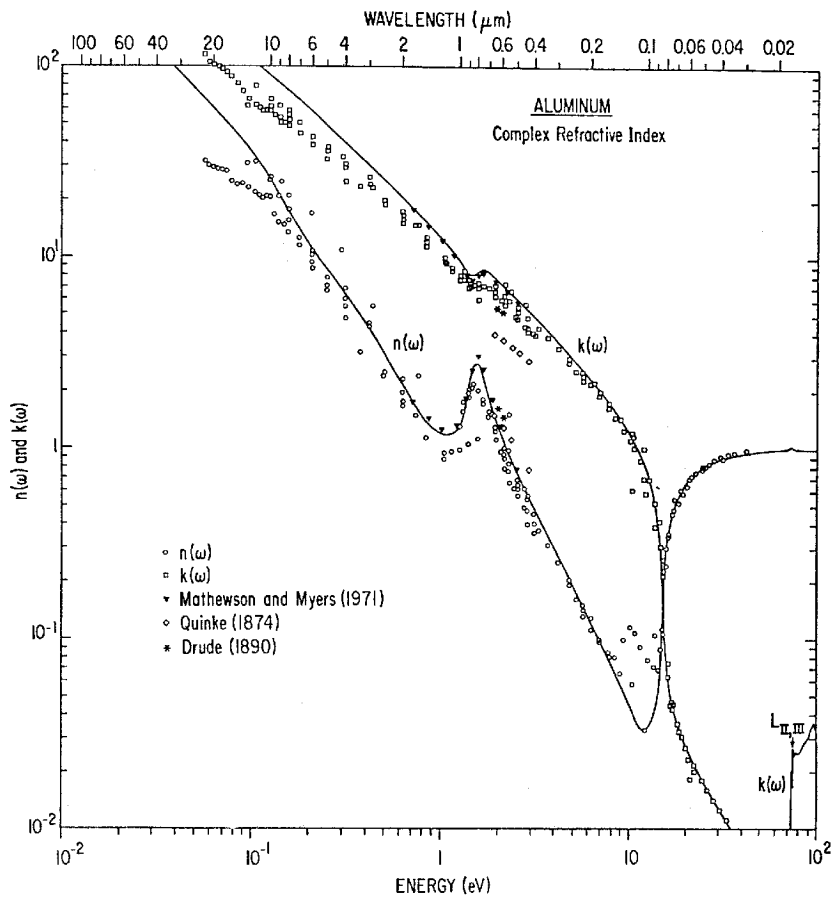


FIGURE 3 n and k for aluminum vs. photon energy.³⁷

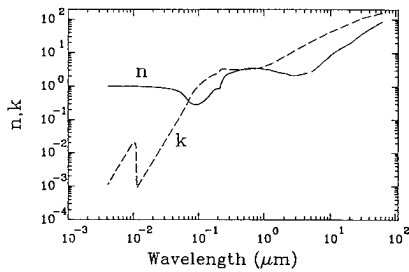


FIGURE 4 n and k for beryllium vs. wavelength.³⁸

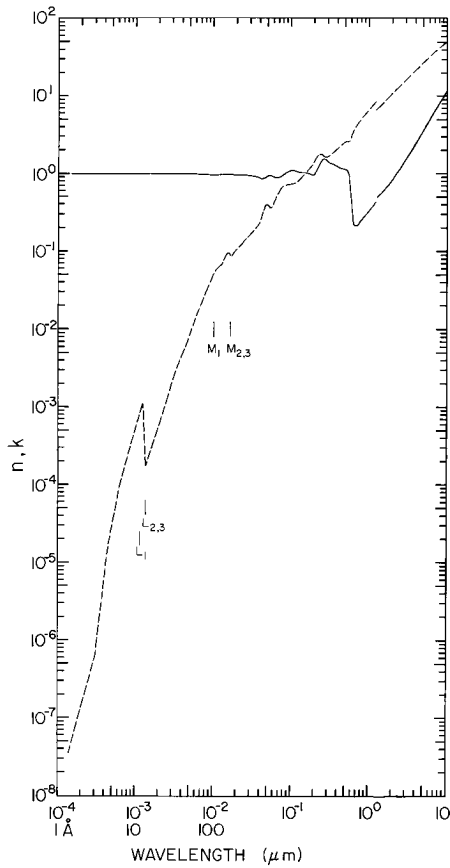


FIGURE 5 n and k for copper vs. wavelength.³⁹

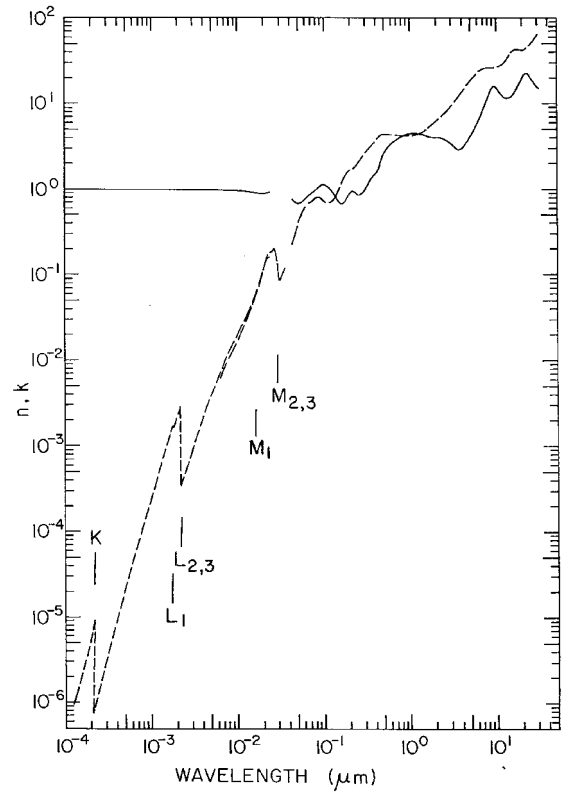


FIGURE 6 n and k for chromium vs. wavelength.⁴⁰

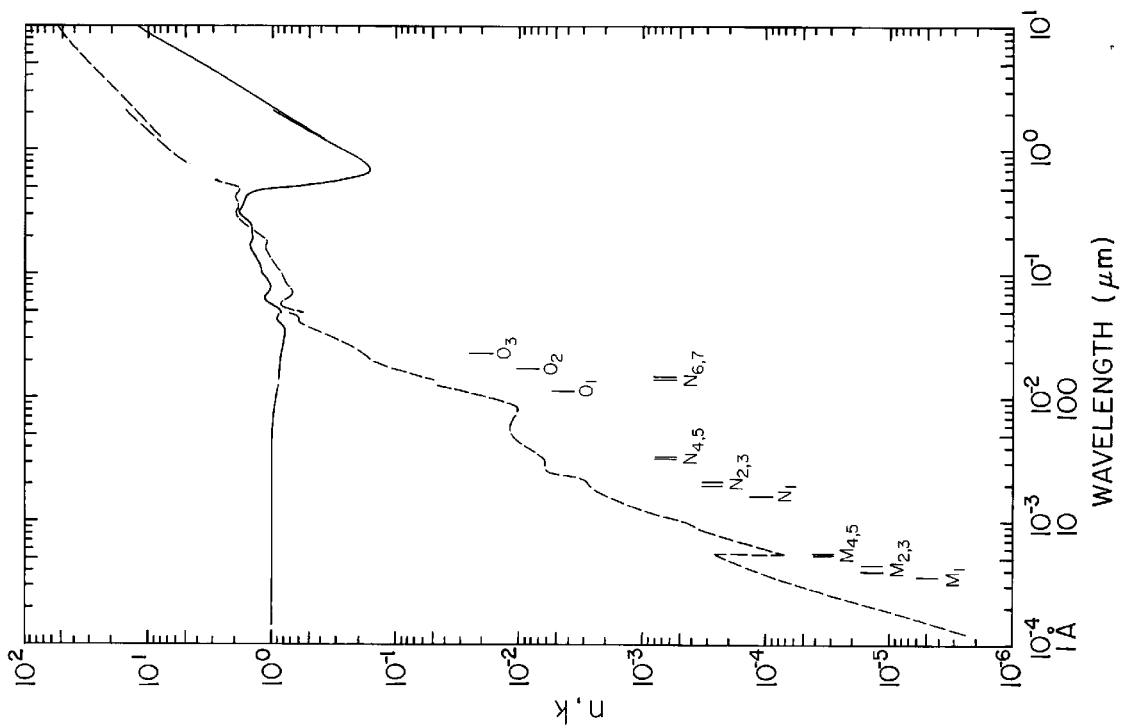


FIGURE 7 n and k for gold vs. wavelength.³⁹

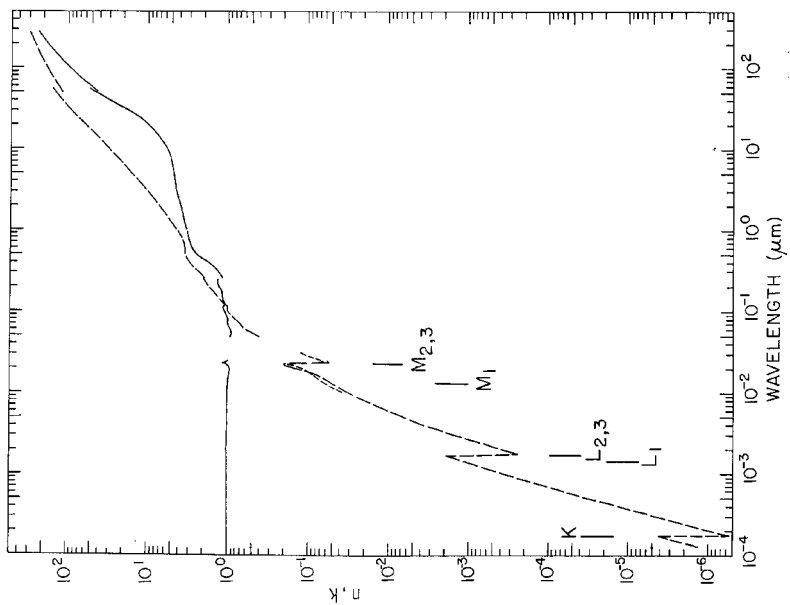


FIGURE 8 n and k for iron vs. wavelength.⁴⁰

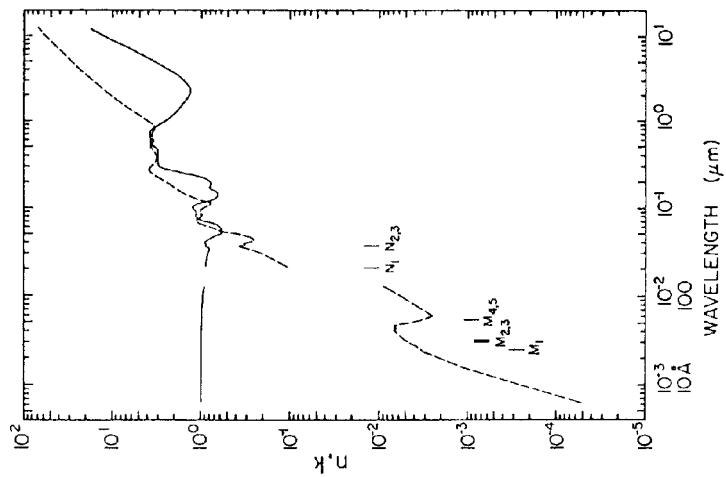


FIGURE 9 n and k for molybdenum vs. wavelength.³⁹

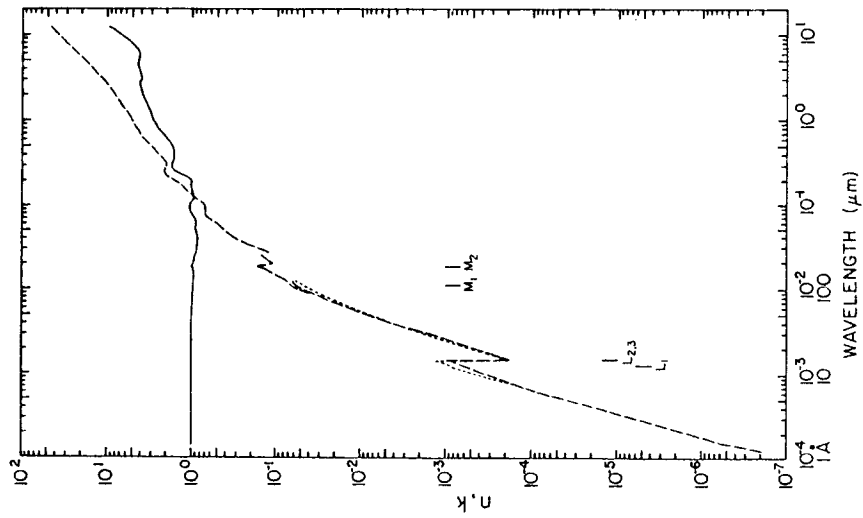


FIGURE 10 n and k for nickel vs. wavelength.³⁹

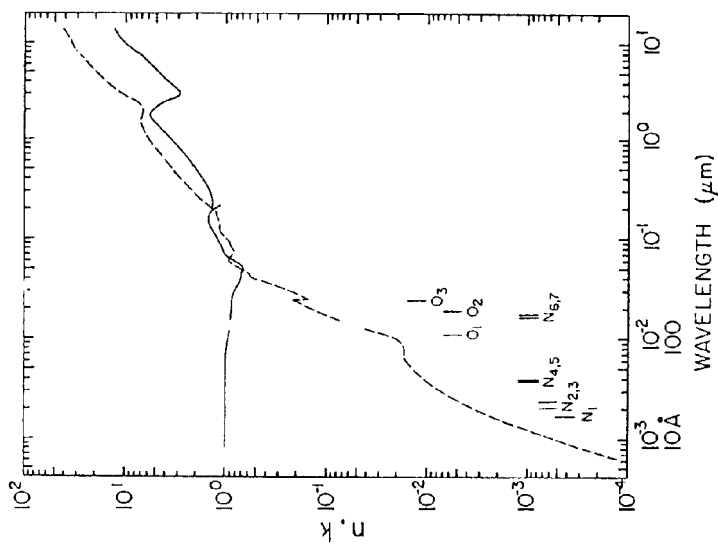


FIGURE 11 n and k for platinum vs. wavelength.³⁹

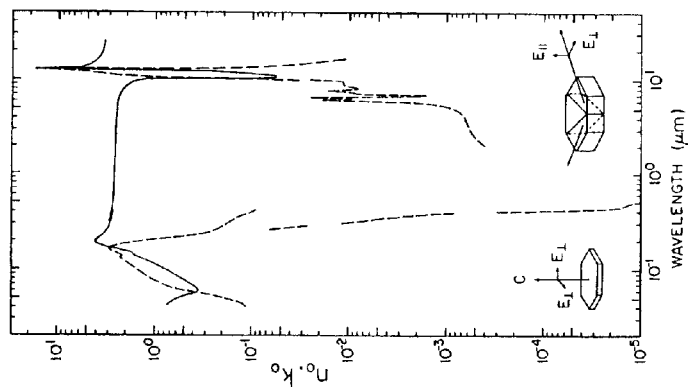


FIGURE 12 n and k for silicon carbide vs. wavelength.⁴¹

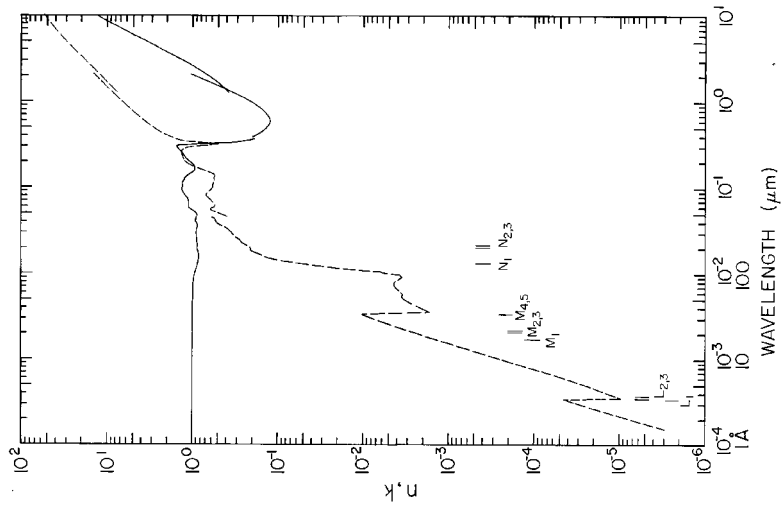


FIGURE 13 n and k for silver as a function of wavelength.³⁹

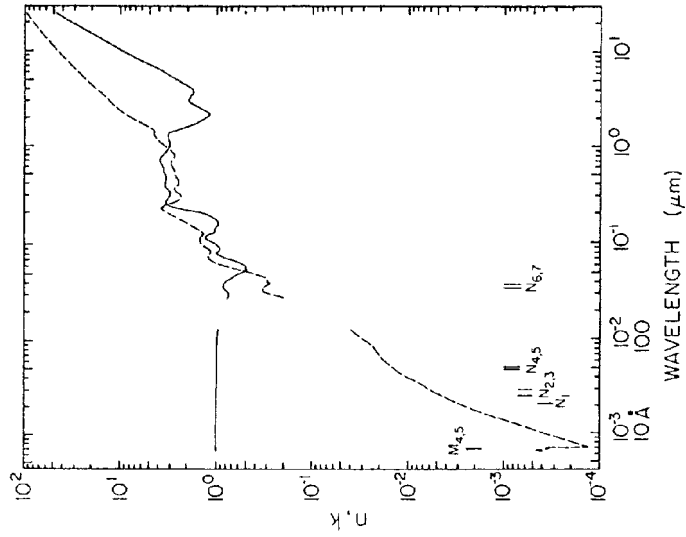


FIGURE 14 n and k for tungsten vs. wavelength.³⁹

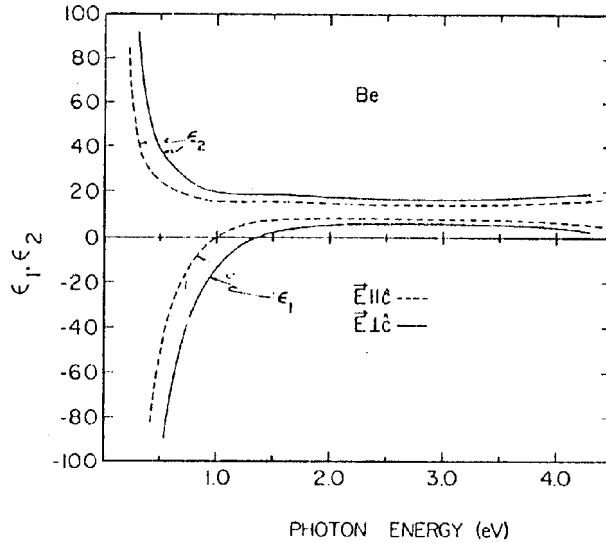


FIGURE 15 Dielectric function for beryllium vs. photon energy showing variation with crystallographic direction.⁴²

of beryllium in Fig. 15.⁴² The optical constants can be obtained from the dielectric constants using the following equations:⁹

$$n = \{[(\epsilon_1^2 + \epsilon_2^2)^{1/2} + \epsilon_1]/2\}^{1/2} \quad (28)$$

$$k = \{[(\epsilon_1^2 + \epsilon_2^2)^{1/2} - \epsilon_1]/2\}^{1/2} \quad (29)$$

This variation in optical properties results in related variations in reflectance and absorptance that may be the main contributors to a phenomenon called *anomalous scatter*, where the measured scatter from polished surfaces does not scale with wavelength when compared to the measured surface roughness.⁴³⁻⁴⁷

The optical constants reported for SiC are for single-crystal hexagonal material.

Reflectance and Absorbance

Reflectance data in the literature are extensive. Summaries have been published for most metals³⁵⁻³⁶ primarily at normal incidence, both as deposited films and polished bulk material. Reflectance as a function of angle is presented for a number of metals in Refs. 48 and 49. Selected data are also included in Ref. 50. Temperature dependence of reflectance is discussed in a number of articles, but little measured data are available. Absorption data summaries are not as readily available, with one summary³⁵ and many articles for specific materials, primarily at laser wavelengths and often as a function of temperature. Table 3 lists values of room-temperature normal-incidence reflectance as a function of wavelength, and Figs. 16 to 26 show r and a calculated from n and k in the range of 0.015 to 10 μm .³⁵ Figure 27³⁵ shows reflectance for polarized radiation as a function of incidence angle for three combinations of n and k , illustrating the tendency toward total external reflectance for angles greater than about 80°.

Figures 28 to 34 show reflectance for polished surfaces and thin films of Al, Be, SiC, and Ni, including effects of oxide films on the surface.⁵¹ One effect of absorption is to limit

TABLE 3 Reflectance of Selected Metals at Normal Incidence

Metal	eV	Wavelength Å	μm	R
Aluminum ³⁶	0.040		31.0	0.9923
	0.050		24.8	0.9915
	0.060		20.7	0.9906
	0.070		17.7	0.9899
	0.080		15.5	0.9895
	0.090		13.8	0.9892
	0.100		12.4	0.9889
	0.125		9.92	0.9884
	0.175		7.08	0.9879
	0.200		6.20	0.9873
	0.250		4.96	0.9858
	0.300		4.13	0.9844
	0.400		3.10	0.9826
	0.600		2.07	0.9806
	0.800		1.55	0.9778
	0.900		1.38	0.9749
	1.00		1.24	0.9697
	1.10		1.13	0.9630
	1.20		1.03	0.9521
	1.30	9537.0	0.95	0.9318
	1.40	8856.0	0.89	0.8852
	1.50	8265.0	0.83	0.8678
	1.60	7749.0	0.77	0.8794
	1.70	7293.0	0.73	0.8972
	1.80	6888.0	0.69	0.9069
	2.00	6199.0	0.62	0.9148
	2.40	5166.0	0.52	0.9228
	2.80	4428.0	0.44	0.9242
	3.20	3874.0	0.39	0.9243
	3.60	3444.0	0.34	0.9246
	4.00	3100.0	0.31	0.9248
	4.60	2695.0	0.27	0.9249
	5.00	2497.0	0.25	0.9244
	6.00	2066.0	0.21	0.9257
	8.00	1550.0	0.15	0.9269
	10.00	1240.0	0.12	0.9286
	11.00	1127.0	0.11	0.9298
	13.00	954.0		0.8960
	13.50	918.0		0.8789
	14.00	886.0		0.8486
	14.40	861.0		0.8102
	14.60	849.0		0.7802
	14.80	838.0		0.7202
	15.00	827.0		0.6119
	15.20	816.0		0.4903
	15.40	805.0		0.3881
	15.60	795.0		0.3182
	15.80	785.0		0.2694
	16.00	775.0		0.2326
	16.20	765.0		0.2031
	16.40	756.0		0.1789
	16.75	740.0		0.1460

TABLE 3 Reflectance of Selected Metals at Normal Incidence (*Continued*)

Metal	eV	Wavelength Å	μm	R
Aluminum ³⁶	17.00	729.0		0.1278
	17.50	708.0		0.1005
	18.00	689.0		0.0809
	19.00	653.0		0.0554
	20.0	620.0		0.0398
	21.0	590.0		0.0296
	22.0	564.0		0.0226
	23.0	539.0		0.0177
	24.0	517.0		0.0140
	25.0	496.0		0.0113
	26.0	477.0		0.0092
	27.0	459.0		0.0076
	28.0	443.0		0.0063
	30.0	413.0		0.0044
	35.0	354.0		0.0020
	40.0	310.0		0.0010
	45.0	276.0		0.0005
	50.0	248.0		0.0003
	55.0	225.0		0.0001
	60.0	206.0		0.0000
	70.0	177.0		0.0000
	72.5	171.0		0.0002
	75.0	165.0		0.0002
	80.0	155.0		0.0002
	85.0	146.0		0.0002
	95.0	131.0		0.0003
	100.0	124.0		0.0002
	120.0	103.0		0.0002
	130.0	95.4		0.0001
	150.0	82.7		0.0001
	170.0	72.9		0.0001
	180.0	68.9		0.0000
	200.0	62.0		0.0000
	300.0	41.3		0.0000
Beryllium ³⁸	0.020		61.99	0.989
	0.040		31.00	0.989
	0.060		20.66	0.988
	0.080		15.50	0.985
	0.100		12.40	0.983
	0.120		10.33	0.982
	0.160		7.75	0.981
	0.200		6.20	0.980
	0.240		5.17	0.978
	0.280		4.43	0.972
	0.320		3.87	0.966
	0.380		3.26	0.955
	0.440		2.82	0.940
	0.500		2.48	0.917
	0.560		2.21	0.887
	0.600		2.07	0.869
	0.660		1.88	0.841
	0.720		1.72	0.810

TABLE 3 Reflectance of Selected Metals at Normal Incidence (*Continued*)

Metal	eV	Wavelength Å	μm	R
Beryllium ³⁸	0.780		1.59	0.775
	0.860		1.44	0.736
	0.940		1.32	0.694
	1.00		1.24	0.667
	1.10		1.13	0.640
	1.20		1.03	0.615
	1.40	8856.0	0.89	0.575
	1.60	7749.0	0.77	0.555
	1.90	6525.0	0.65	0.540
	2.40	5166.0	0.52	0.538
	2.80	4428.0	0.44	0.537
	3.00	4133.0	0.41	0.537
	3.30	3757.0	0.38	0.536
	3.60	3444.0	0.34	0.536
	3.80	3263.0	0.33	0.538
	4.00	3100.0	0.31	0.541
	4.20	2952.0	0.30	0.547
	4.40	2818.0	0.28	0.558
	4.60	2695.0	0.27	0.575
Copper ³⁶	0.10		12.4	0.980
	0.50		2.48	0.979
	1.00		1.24	0.976
	1.50	8265.0	0.83	0.965
	1.70	7293.0	0.73	0.958
	1.80	6888.0	0.69	0.952
	1.90	6525.0	0.65	0.943
	2.00	6199.0	0.62	0.910
	2.10	5904.0	0.59	0.814
	2.20	5635.0	0.56	0.673
	2.30	5390.0	0.54	0.618
	2.40	5166.0	0.52	0.602
	2.60	4768.0	0.48	0.577
	2.80	4428.0	0.44	0.545
	3.00	4133.0	0.41	0.509
	3.20	3874.0	0.39	0.468
	3.40	3646.0	0.36	0.434
	3.60	3444.0	0.34	0.407
	3.80	3263.0	0.33	0.387
	4.00	3100.0	0.31	0.364
	4.20	2952.0	0.30	0.336
	4.40	2818.0	0.28	0.329
	4.60	2695.0	0.27	0.334
	4.80	2583.0	0.26	0.345
	5.00	2497.0	0.25	0.366
	5.20	2384.0	0.24	0.380
	5.40	2296.0	0.23	0.389
	5.60	2214.0	0.22	0.391
	5.80	2138.0	0.21	0.389
	6.00	2066.0	0.21	0.380
	6.50	1907.0	0.19	0.329
	7.00	1771.0	0.18	0.271
	7.50	1653.0	0.17	0.230

TABLE 3 Reflectance of Selected Metals at Normal Incidence (*Continued*)

Metal	eV	Wavelength Å	μm	R
Copper ³⁶	8.00	1550.0	0.15	0.206
	8.50	1459.0	0.15	0.189
	9.00	1378.0	0.14	0.171
	9.50	1305.0	0.13	0.154
	10.00	1240.0	0.12	0.139
	11.00	1127.0	0.11	0.118
	12.00	1033.0	0.10	0.111
	13.00	954.0		0.109
	14.00	886.0		0.111
	15.00	827.0		0.111
	16.00	775.0		0.106
	17.00	729.0		0.097
	18.00	689.0		0.084
	19.00	653.0		0.071
	20.00	620.0		0.059
	21.00	590.0		0.048
	22.00	564.0		0.040
	23.00	539.0		0.035
	24.00	517.0		0.035
	25.00	496.0		0.040
	26.00	477.0		0.044
	27.00	459.0		0.043
	28.00	443.0		0.039
	29.00	428.0		0.032
	30.00	413.0		0.025
	32.00	387.0		0.017
	34.00	365.0		0.014
	36.00	344.0		0.012
	38.00	326.0		0.010
	40.00	310.0		0.009
	45.00	276.0		0.006
	50.00	248.0		0.005
	55.00	225.0		0.004
	60.00	206.0		0.003
	70.00	177.0		0.002
	90.00	138.0		0.002
Chromium ³⁶	0.06		20.70	0.962
	0.10		12.40	0.955
	0.14		8.86	0.936
	0.18		6.89	0.953
	0.22		5.64	0.954
	0.26		4.77	0.951
	0.30		4.13	0.943
	0.42		2.95	0.862
	0.54		2.30	0.788
	0.66		1.88	0.736
	0.78		1.59	0.680
	0.90		1.38	0.650
	1.00		1.24	0.639
	1.12		1.11	0.631
	1.24	9998.0	1.00	0.629
	1.36	9116.0	0.91	0.631

TABLE 3 Reflectance of Selected Metals at Normal Incidence (*Continued*)

Metal	eV	Wavelength Å	μm	R
Chromium ³⁶	1.46	8492.0	0.85	0.632
	1.77	7005.0	0.70	0.639
	2.00	6199.0	0.62	0.644
	2.20	5635.0	0.56	0.656
	2.40	5166.0	0.52	0.677
	2.60	4768.0	0.48	0.698
	2.80	4428.0	0.44	0.703
	3.00	4133.0	0.41	0.695
	4.00	3100.0	0.31	0.651
	4.40	2818.0	0.28	0.620
	4.80	2583.0	0.26	0.572
	5.20	2384.0	0.24	0.503
	5.60	2214.0	0.22	0.443
	6.00	2066.0	0.21	0.444
	7.00	1771.0	0.18	0.425
	7.60	1631.0	0.16	0.378
	8.00	1550.0	0.15	0.315
	8.50	1459.0	0.15	0.235
	9.00	1378.0	0.14	0.170
	10.00	1240.0	0.12	0.120
	11.00	1127.0	0.11	0.103
	11.50	1078.0	0.11	0.100
	12.00	1033.0	0.10	0.101
	13.00	954.0		0.119
	14.00	886.0		0.135
	15.00	827.0		0.143
	16.00	775.0		0.139
	18.00	689.0		0.129
	19.00	653.0		0.131
	20.00	620.0		0.130
	22.00	563.0		0.112
	24.00	517.0		0.096
	26.00	477.0		0.063
	28.00	443.0		0.037
	30.00	413.0		0.030
Gold (electropolished) ³⁶	0.10		12.40	0.995
	0.20		6.20	0.995
	0.40		3.10	0.995
	0.60		2.07	0.994
	0.80		1.55	0.993
	1.00		1.24	0.992
	1.20		1.03	0.991
	1.40	8856.0	0.89	0.989
	1.60	7749.0	0.77	0.986
	1.80	6888.0	0.69	0.979
	2.00	6199.0	0.62	0.953
	2.10	5904.0	0.59	0.925
	2.20	5635.0	0.56	0.880
	2.30	5390.0	0.54	0.807
	2.40	5166.0	0.52	0.647
	2.50	4959.0	0.50	0.438
	2.60	4768.0	0.48	0.331

TABLE 3 Reflectance of Selected Metals at Normal Incidence (*Continued*)

Metal	eV	Wavelength Å	μm	R
Gold (electropolished) ³⁶	2.70	4592.0	0.46	0.356
	2.80	4428.0	0.44	0.368
	2.90	4275.0	0.43	0.368
	3.00	4133.0	0.41	0.369
	3.10	3999.0	0.40	0.371
	3.20	3874.0	0.39	0.368
	3.40	3646.0	0.36	0.356
	3.60	3444.0	0.34	0.346
	3.80	3263.0	0.33	0.360
	4.00	3100.0	0.31	0.369
	4.20	2952.0	0.30	0.367
	4.40	2818.0	0.28	0.370
	4.60	2695.0	0.27	0.364
	4.80	2583.0	0.26	0.344
	5.00	2497.0	0.25	0.319
	5.40	2296.0	0.23	0.275
	5.80	2138.0	0.21	0.236
	6.20	2000.0	0.20	0.203
	6.60	1878.0	0.19	0.177
	7.00	1771.0	0.18	0.162
	7.40	1675.0	0.17	0.164
	7.80	1589.0	0.16	0.171
	8.20	1512.0	0.15	0.155
	8.60	1442.0	0.14	0.144
	9.00	1378.0	0.14	0.133
	9.40	1319.0	0.13	0.122
	9.80	1265.0	0.13	0.124
	10.20	1215.0	0.12	0.127
	11.00	1127.0	0.11	0.116
	12.00	1033.0	0.10	0.109
	14.00	886.0		0.140
	16.00	775.0		0.123
	18.00	689.0		0.109
	20.00	620.0		0.133
	22.00	563.0		0.164
	24.00	517.0		0.125
	26.00	477.0		0.079
	28.00	443.0		0.063
	30.00	413.0		0.064
Iron ³⁶	0.10		12.40	0.978
	0.15		8.27	0.956
	0.20		6.20	0.958
	0.26		4.77	0.911
	0.30		4.13	0.892
	0.36		3.44	0.867
	0.40		3.10	0.858
	0.50		2.48	0.817
	0.60		2.07	0.783
	0.70		1.77	0.752
	0.80		1.55	0.725
	0.90		1.38	0.700
	1.00		1.24	0.678
	1.10		1.13	0.660

TABLE 3 Reflectance of Selected Metals at Normal Incidence (*Continued*)

Metal	eV	Wavelength Å	μm	R
Iron ³⁶	1.20		1.03	0.641
	1.30	9537.0	0.95	0.626
	1.40	8856.0	0.89	0.609
	1.50	8265.0	0.83	0.601
	1.60	7749.0	0.77	0.585
	1.70	7293.0	0.73	0.577
	1.80	6888.0	0.69	0.573
	1.90	6525.0	0.65	0.563
	2.00	6199.0	0.62	0.563
	2.20	5635.0	0.56	0.563
	2.40	5166.0	0.52	0.567
	2.60	4768.0	0.48	0.576
	2.80	4428.0	0.44	0.580
	3.00	4133.0	0.41	0.583
	3.20	3874.0	0.39	0.576
	3.40	3646.0	0.36	0.565
	3.60	3444.0	0.34	0.548
	4.00	3100.0	0.31	0.527
	4.33	2863.0	0.29	0.494
	4.67	2655.0	0.27	0.470
	5.00	2497.0	0.25	0.435
	5.50	2254.0	0.23	0.401
	6.00	2066.0	0.21	0.366
	6.50	1907.0	0.19	0.358
	7.00	1771.0	0.18	0.333
	7.50	1653.0	0.17	0.298
	8.00	1550.0	0.15	0.272
	8.50	1459.0	0.15	0.251
	9.00	1378.0	0.14	0.236
	9.50	1305.0	0.13	0.226
	10.00	1240.0	0.12	0.213
	11.00	1127.0	0.11	0.162
	11.17	1110.0	0.11	0.159
	11.33	1094.0	0.11	0.159
	11.50	1078.0	0.11	0.160
	12.00	1033.0	0.10	0.163
	12.50	992.0		0.165
	13.00	954.0		0.162
	13.50	918.0		0.159
	14.00	886.0		0.151
	15.00	827.0		0.135
	16.00	775.0		0.116
	17.00	729.0		0.102
	18.00	689.0		0.091
	20.00	620.0		0.083
	22.00	563.0		0.068
	24.00	517.0		0.045
	26.00	477.0		0.031
	28.00	443.0		0.021
	30.00	413.0		0.014
Molybdenum ³⁶	0.10		12.40	0.985
	0.20		6.20	0.985
	0.30		4.13	0.983

TABLE 3 Reflectance of Selected Metals at Normal Incidence (*Continued*)

Metal	eV	Wavelength Å	μm	R
Molybdenum ³⁶	0.50		2.70	0.971
	0.70		1.77	0.932
	0.90		1.38	0.859
	1.00		1.24	0.805
	1.10		1.13	0.743
	1.20		1.03	0.671
	1.30	9537.0	0.95	0.608
	1.40	8856.0	0.89	0.562
	1.50	8265.0	0.83	0.550
	1.60	7749.0	0.77	0.562
	1.70	7293.0	0.73	0.570
	1.80	6888.0	0.69	0.576
	2.00	6199.0	0.62	0.571
	2.20	5635.0	0.56	0.562
	2.40	5166.0	0.52	0.594
	2.60	4768.0	0.48	0.582
	2.80	4428.0	0.44	0.565
	3.00	4133.0	0.41	0.550
	3.20	3874.0	0.39	0.540
	3.40	3646.0	0.36	0.541
	3.60	3444.0	0.34	0.546
	3.80	3263.0	0.33	0.554
	4.00	3100.0	0.31	0.576
	4.20	2952.0	0.30	0.610
	4.40	2818.0	0.28	0.640
	4.60	2695.0	0.27	0.658
	4.80	2583.0	0.26	0.678
	5.00	2497.0	0.25	0.695
	5.20	2384.0	0.24	0.706
	5.40	2296.0	0.23	0.706
	5.60	2214.0	0.22	0.700
	6.00	2066.0	0.21	0.674
	6.40	1937.0	0.19	0.641
	6.80	1823.0	0.18	0.592
	7.20	1722.0	0.17	0.548
	7.40	1675.0	0.17	0.542
	7.60	1631.0	0.16	0.552
	7.80	1589.0	0.16	0.542
	8.00	1550.0	0.15	0.530
	8.40	1476.0	0.15	0.495
	8.80	1409.0	0.14	0.450
	9.20	1348.0	0.13	0.385
	9.60	1291.0	0.13	0.320
	10.00	1240.0	0.12	0.250
	10.40	1192.0	0.12	0.188
	10.60	1170.0	0.12	0.138
	11.20	1107.0	0.11	0.123
	11.60	1069.0	0.11	0.135
	12.00	1033.0	0.10	0.154
	12.80	969.0		0.178
	13.60	912.0		0.187
	14.40	861.0		0.182

TABLE 3 Reflectance of Selected Metals at Normal Incidence (*Continued*)

Metal	eV	Wavelength Å	μm	R
Molybdenum ³⁶	14.80	838.0		0.179
	15.00	827.0		0.179
	16.00	775.0		0.194
	17.00	729.0		0.233
	18.00	689.0		0.270
	19.00	653.0		0.284
	20.00	620.0		0.264
	22.00	563.0		0.207
	24.00	517.0		0.151
	26.00	477.0		0.071
	28.00	443.0		0.036
	30.00	413.0		0.023
	32.00	387.0		0.030
	34.00	365.0		0.034
	36.00	344.0		0.043
	38.00	326.0		0.033
	40.00	310.0		0.025
Nickel ³⁶	0.10		12.40	0.983
	0.15		8.27	0.978
	0.20		6.20	0.969
	0.30		4.13	0.934
	0.40		3.10	0.900
	0.60		2.07	0.835
	0.80		1.55	0.794
	1.00		1.24	0.753
	1.20		1.03	0.721
	1.40	8856.0	0.89	0.695
	1.60	7749.0	0.77	0.679
	1.80	6888.0	0.69	0.670
	2.00	6199.0	0.62	0.649
	2.40	5166.0	0.52	0.590
	2.80	4428.0	0.44	0.525
	3.20	3874.0	0.39	0.467
	3.60	3444.0	0.34	0.416
	3.80	3263.0	0.33	0.397
	4.00	3100.0	0.31	0.392
	4.20	2952.0	0.30	0.396
	4.60	2695.0	0.27	0.421
	5.00	2497.0	0.25	0.449
	5.20	2384.0	0.24	0.454
	5.40	2296.0	0.23	0.449
	5.80	2138.0	0.21	0.417
	6.20	2000.0	0.20	0.371
	6.60	1878.0	0.19	0.325
	7.00	1771.0	0.18	0.291
	8.00	1550.0	0.15	0.248
	9.00	1378.0	0.14	0.211
	10.00	1240.0	0.12	0.166
	11.00	1127.0	0.11	0.115
	12.00	1033.0	0.10	0.108
	13.00	954.0		0.105
	14.00	886.0		0.106

TABLE 3 Reflectance of Selected Metals at Normal Incidence (*Continued*)

Metal	eV	Wavelength Å	μm	R
Nickel ³⁶	15.00	827.0		0.107
	16.00	775.0		0.103
	18.00	689.0		0.092
	20.00	620.0		0.071
	22.00	564.0		0.055
	24.00	517.0		0.051
	27.00	459.0		0.042
	30.00	413.0		0.034
	35.00	354.0		0.022
	40.00	310.0		0.014
	50.00	248.0		0.004
	60.00	206.0		0.002
	65.00	191.0		0.002
	70.00	177.0		0.004
	90.00	138.0		0.002
Platinum ³⁶	0.10		12.40	0.976
	0.15		8.27	0.969
	0.20		6.20	0.962
	0.30		4.13	0.945
	0.40		3.10	0.922
	0.45		2.76	0.882
	0.50		2.50	0.813
	0.55		2.25	0.777
	0.60		2.07	0.753
	0.65		1.91	0.746
	0.70		1.77	0.751
	0.80		1.55	0.762
	0.90		1.38	0.765
	1.00		1.24	0.762
	1.20		1.03	0.746
	1.40	8856.0	0.89	0.725
	1.60	7749.0	0.77	0.706
	1.80	6888.0	0.69	0.686
	2.00	6199.0	0.62	0.664
	2.50	4959.0	0.50	0.616
	3.00	4133.0	0.41	0.565
	4.00	3100.0	0.31	0.472
	5.00	2497.0	0.25	0.372
	6.00	2066.0	0.21	0.276
	7.00	1771.0	0.18	0.230
	8.00	1550.0	0.15	0.216
	9.00	1378.0	0.14	0.200
	9.20	1348.0	0.13	0.198
	9.40	1319.0	0.13	0.200
	10.20	1215.0	0.12	0.211
	11.00	1127.0	0.11	0.199
	12.00	1033.0	0.10	0.173
	12.80	969.0		0.158
	13.60	912.0		0.155
	14.80	838.0		0.157
	15.20	816.0		0.155
	16.00	775.0		0.146

TABLE 3 Reflectance of Selected Metals at Normal Incidence (*Continued*)

Metal	eV	Wavelength Å	μm	R
Platinum ³⁶	17.50	708.0		0.135
	18.00	689.0		0.142
	20.00	620.0		0.197
	21.00	590.0		0.226
	22.00	564.0		0.240
	23.00	539.0		0.226
	24.00	517.0		0.201
	26.00	477.0		0.150
	28.00	443.0		0.125
	29.00	428.0		0.118
	30.00	413.0		0.124
Silver ³⁶	0.10		12.40	0.995
	0.20		6.20	0.995
	0.30		4.13	0.994
	0.40		3.10	0.993
	0.50		2.48	0.992
	1.00		1.24	0.987
	1.50	8265.0	0.83	0.960
	2.00	6199.0	0.62	0.944
	2.50	4959.0	0.50	0.914
	3.00	4133.0	0.41	0.864
	3.25	3815.0	0.38	0.816
	3.50	3542.0	0.35	0.756
	3.60	3444.0	0.34	0.671
	3.70	3351.0	0.34	0.475
	3.77	3289.0	0.33	0.154
	3.80	3263.0	0.33	0.053
	3.90	3179.0	0.32	0.040
	4.00	3100.0	0.31	0.103
	4.10	3024.0	0.30	0.153
	4.20	2952.0	0.30	0.194
	4.30	2883.0	0.29	0.208
	4.50	2755.0	0.28	0.238
	4.75	2610.0	0.26	0.252
	5.00	2497.0	0.25	0.257
	5.50	2254.0	0.23	0.257
	6.00	2066.0	0.21	0.246
	6.50	1907.0	0.19	0.225
	7.00	1771.0	0.18	0.196
	7.50	1653.0	0.17	0.157
	8.00	1550.0	0.15	0.114
	9.00	1378.0	0.14	0.074
	10.00	1240.0	0.12	0.082
	11.00	1127.0	0.11	0.088
	12.00	1033.0	0.10	0.100
	13.00	954.0		0.112
	14.00	886.0		0.141
	15.00	827.0		0.156
	16.00	775.0		0.151
	17.00	729.0		0.139
	18.00	689.0		0.124
	19.00	653.0		0.111

TABLE 3 Reflectance of Selected Metals at Normal Incidence (*Continued*)

Metal	eV	Wavelength Å	μm	R
Silver ³⁶	20.00	620.0		0.103
	21.00	590.0		0.112
	21.50	577.0		0.124
	22.00	564.0		0.141
	22.50	551.0		0.157
	23.00	539.0		0.163
	24.00	517.0		0.165
	25.00	496.0		0.154
	26.00	477.0		0.133
	28.00	443.0		0.090
	30.00	413.0		0.074
	34.00	365.0		0.067
	38.00	326.0		0.043
	42.00	295.0		0.036
	46.00	270.0		0.031
	50.00	248.0		0.027
	56.00	221.0		0.024
	62.00	200.0		0.016
	66.00	188.0		0.016
	70.00	177.0		0.021
	76.00	163.0		0.013
	80.00	155.0		0.012
	90.00	138.0		0.009
	100.00	124.0		0.005
Tungsten ³⁶	0.10		12.40	0.983
	0.20		6.20	0.981
	0.30		4.13	0.979
	0.38		3.26	0.963
	0.46		2.70	0.952
	0.54		2.30	0.948
	0.62		2.00	0.917
	0.70		1.77	0.856
	0.74		1.68	0.810
	0.78		1.59	0.759
	0.82		1.51	0.710
	0.86		1.44	0.661
	0.98		1.27	0.653
	1.10		1.13	0.627
	1.20		1.03	0.590
	1.30	9537.0	0.95	0.545
	1.40	8856.0	0.89	0.515
	1.50	8265.0	0.83	0.500
	1.60	7749.0	0.77	0.494
	1.70	7293.0	0.73	0.507
	1.80	6888.0	0.69	0.518
	1.90	6525.0	0.65	0.518
	2.10	5904.0	0.59	0.506
	2.50	4959.0	0.50	0.487
	3.00	4133.0	0.41	0.459
	3.50	3542.0	0.35	0.488
	4.00	3100.0	0.31	0.451
	4.20	2952.0	0.30	0.440

TABLE 3 Reflectance of Selected Metals at Normal Incidence (*Continued*)

Metal	eV	Wavelength Å	μm	R
Tungsten ³⁶	4.60	2695.0	0.27	0.455
	5.00	2497.0	0.25	0.505
	5.40	2296.0	0.23	0.586
	5.80	2138.0	0.21	0.637
	6.20	2000.0	0.20	0.646
	6.60	1878.0	0.19	0.631
	7.00	1771.0	0.18	0.607
	7.60	1631.0	0.16	0.556
	8.00	1550.0	0.15	0.505
	8.40	1476.0	0.15	0.449
	9.00	1378.0	0.14	0.388
	10.00	1240.0	0.12	0.287
	10.40	1192.0	0.12	0.270
	11.00	1127.0	0.11	0.290
	11.80	1051.0	0.11	0.318
	12.80	969.0		0.333
	13.60	912.0		0.325
	14.80	838.0		0.276
	15.60	795.0		0.246
	16.00	775.0		0.249
	16.80	738.0		0.273
	17.60	704.0		0.304
	18.80	659.0		0.340
	20.00	620.0		0.354
	21.20	585.0		0.331
	22.40	553.0		0.287
	23.60	525.0		0.252
	24.00	517.0		0.234
	24.80	500.0		0.191
	25.60	484.0		0.150
	26.80	463.0		0.105
	28.00	443.0		0.073
	30.00	413.0		0.047
	34.00	365.0		0.032
	36.00	344.0		0.036
	40.00	310.0		0.045

the penetration depth of incident radiation. Penetration depth is shown in Fig. 35 as a function of wavelength for Al, Be, and Ni.⁵¹

Absorption is a critical parameter for high-energy laser components, and is discussed in hundreds of papers as a function of surface morphology, angle of incidence, polarization state, and temperature. Only a few representative examples of this body of work can be cited here. When absorptance measurements were made of metal mirrors as a function of angle of incidence, polarization state, and wavelength,⁵² it was found that measured values agreed with theory except at high angles of incidence where surface condition plays an undefined role. With the advent of diamond-turning as a mirror-finishing method, many papers have addressed absorptance characteristics of these unique surfaces as a function of surface morphology and angle of incidence, particularly on Ag and Cu mirrors.^{53,54} It has been observed that mirrors have the lowest absorptance when the light is s-polarized and the grooves are oriented parallel to the plane of incidence.⁵⁴ The temperature dependence

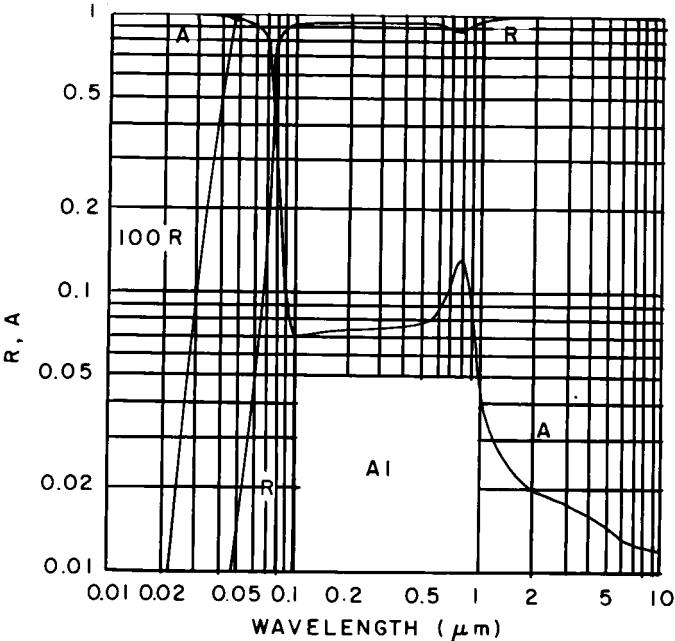


FIGURE 16 Reflectance and absorptance for aluminum vs. wavelength calculated for normal incidence.³⁵ (With permission.)

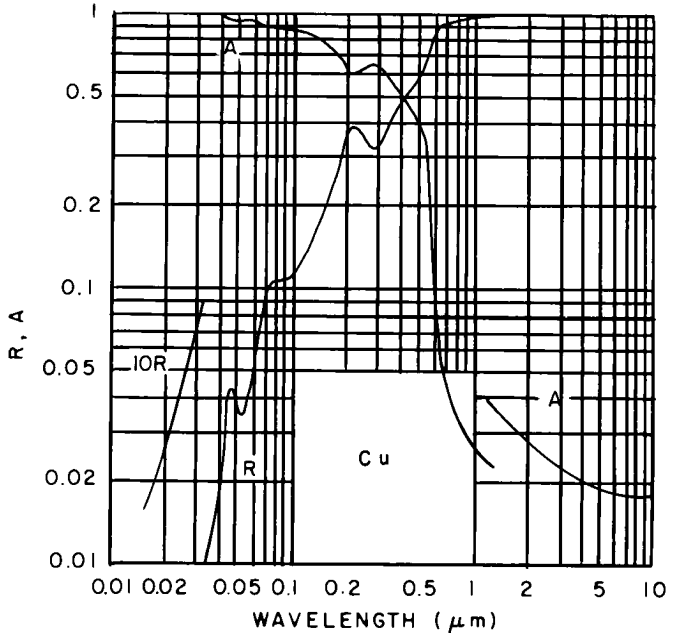


FIGURE 17 Reflectance and absorptance for copper vs. wavelength calculated for normal incidence.³⁵ (With permission.)

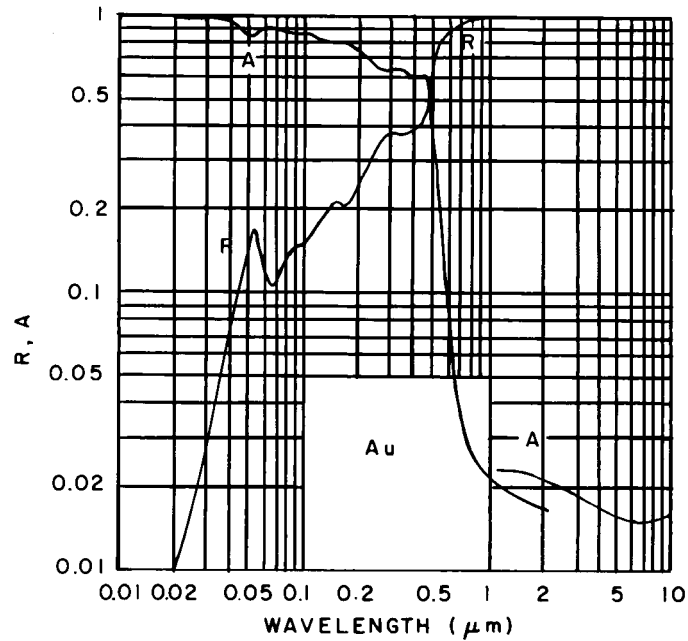


FIGURE 18 Reflectance and absorptance for gold vs. wavelength calculated for normal incidence.³⁵ (With permission.)

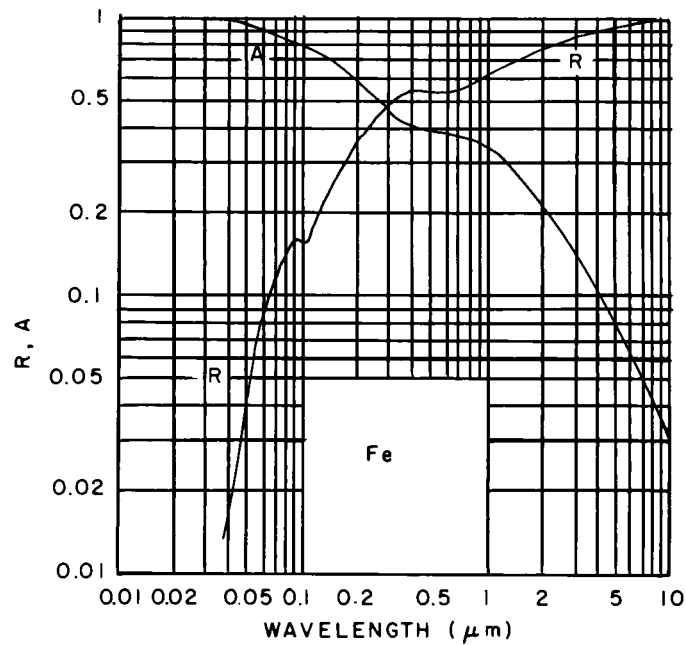


FIGURE 19 Reflectance and absorptance for iron vs. wavelength calculated for normal incidence.³⁵ (With permission.)

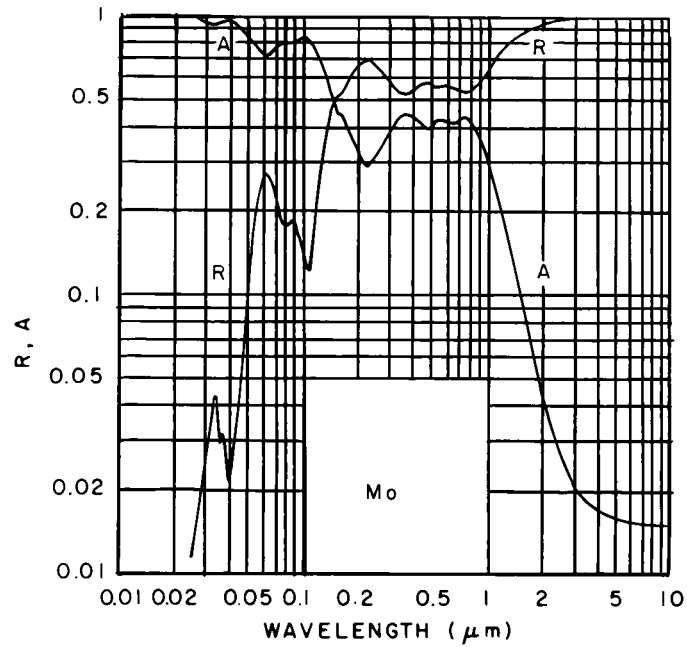


FIGURE 20 Reflectance and absorptance for molybdenum vs. wavelength calculated for normal incidence.³⁵ (With permission.)

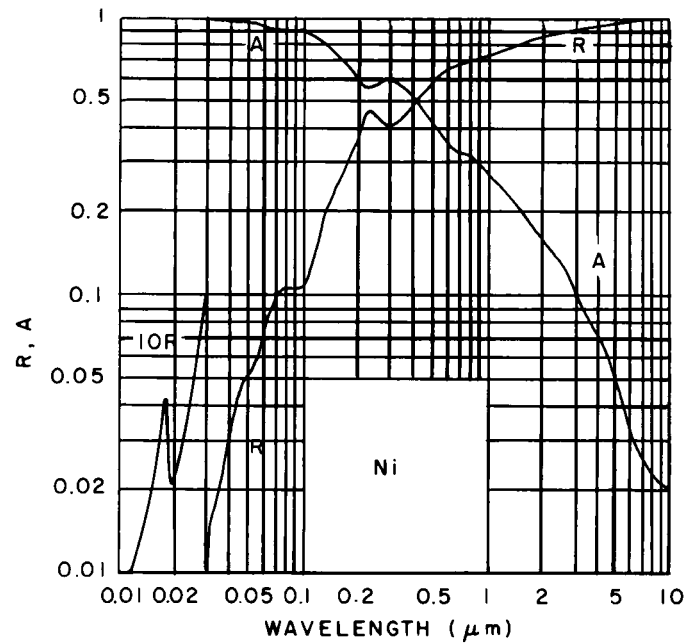


FIGURE 21 Reflectance and absorptance for nickel vs. wavelength calculated for normal incidence.³⁵ (With permission.)

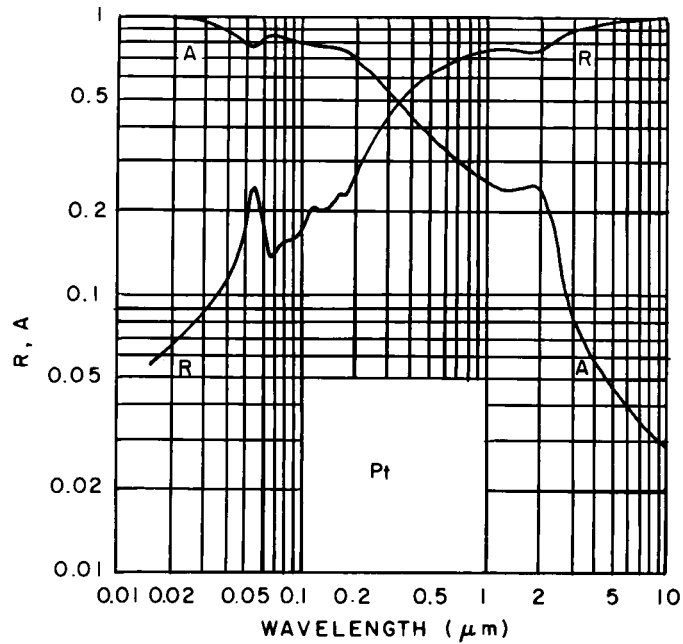


FIGURE 22 Reflectance and absorptance for platinum vs. wavelength calculated for normal incidence.³⁵ (With permission.)

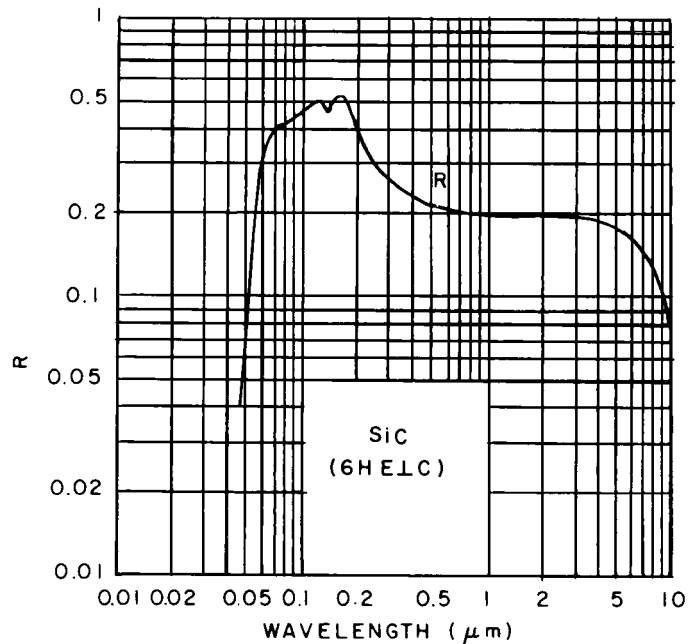


FIGURE 23 Reflectance for the basal plane of hexagonal silicon carbide vs. wavelength calculated for normal incidence.³⁵ (With permission.)

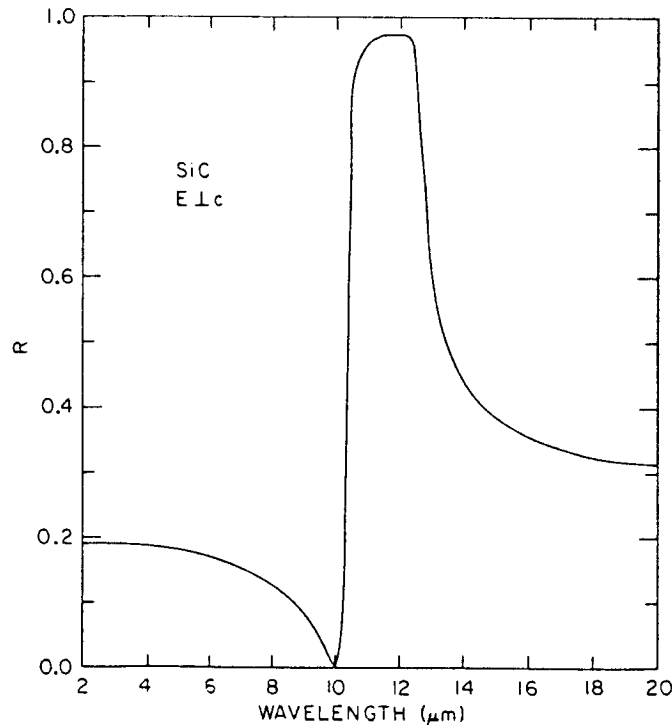


FIGURE 24 Infrared reflectance for the basal plane of hexagonal silicon carbide vs. wavelength calculated for normal incidence.⁵⁵ (With permission.)

of optical absorption has long been known,⁵⁵ but measurements and theory do not always agree, particularly at shorter wavelengths. Figure 36 shows absorptance of Mo as a function of temperature at a wavelength of 10.6 μm .⁵⁵

Mass absorption of energetic photons⁵⁶ follows the same relationship as described in Eq. (4), but with the product mass attenuation coefficient μ and mass density ρ substituted for absorption coefficient α . Table 4 lists mass attenuation coefficients for selected elements at energies between 1 keV (soft x rays) and 1 GeV (hard gamma rays). Units for the coefficient are m^2/kg , so that when multiplied by mass density in kg/m^3 , and depth x in m, the exponent in the equation is dimensionless. To a high approximation, mass attenuation is additive for elements present in a body, independent of the way in which they are bound in chemical compounds. Table 4 is highly abridged; the original⁵⁶ shows all elements and absorption edges.

Emittance. Where the transmittance of a material is essentially zero, the absorptance equals the emittance as described above and expressed in Eqs. (15) and (16). Spectral emittance ϵ_s is the emittance as a function of wavelength at constant temperature. These data have been presented as absorptance curves in Figs. 16 to 22, 25, and 26. For SiC, ϵ_s is given in Fig. 37.⁵⁷ Spectral emittance of unoxidized surfaces at a wavelength of 0.65 μm is given for selected materials in Table 5.⁵⁸

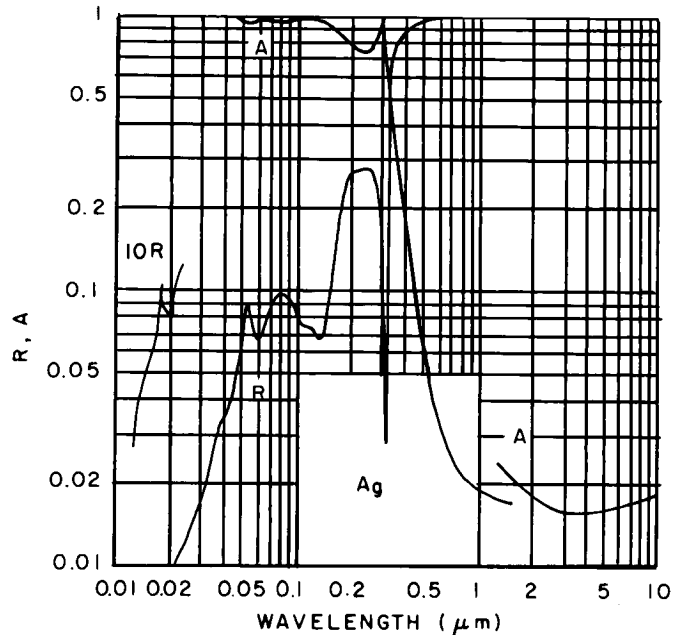


FIGURE 25 Reflectance and absorptance for silver vs. wavelength calculated for normal incidence.³⁵ (With permission.)

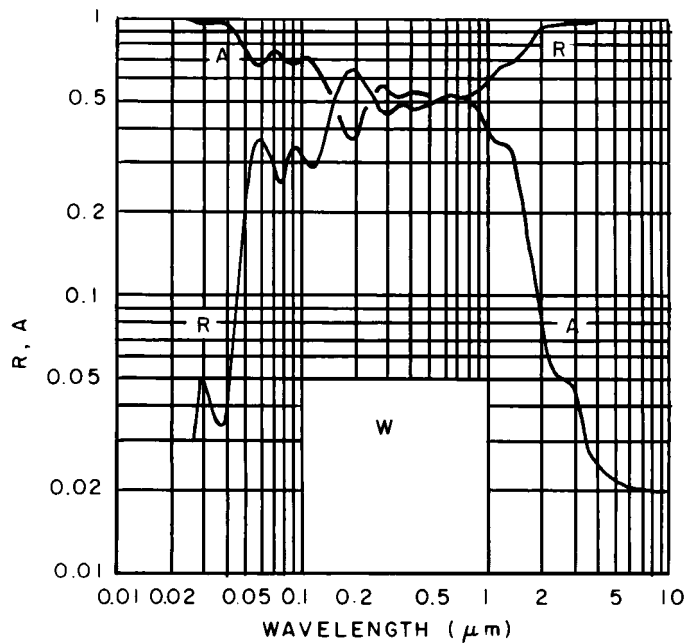


FIGURE 26 Reflectance and absorptance for tungsten vs. wavelength calculated for normal incidence.³⁵ (With permission.)

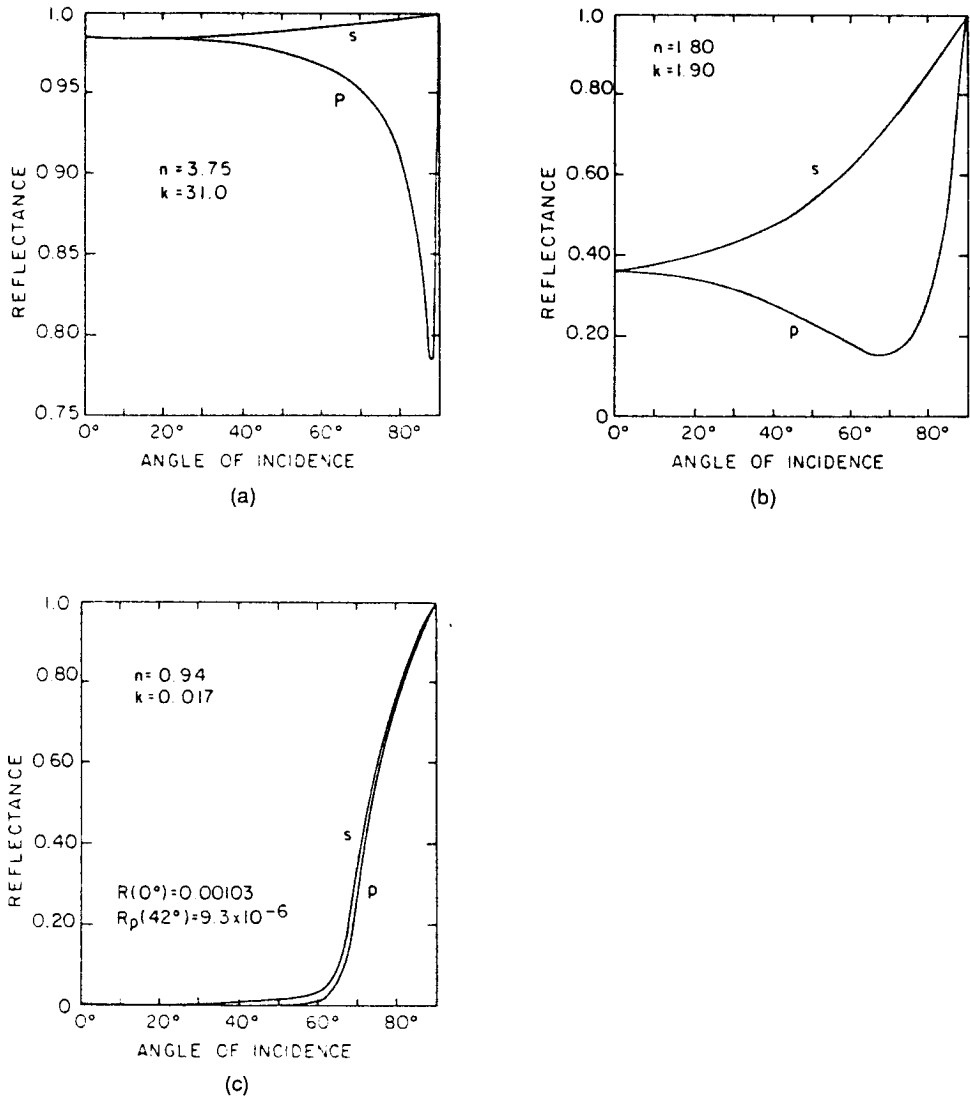


FIGURE 27 Reflectance for polarized radiation vs. angle of incidence for a vacuum-metal interface.³⁵ (With permission.) (a) $n = 3.75$, $k = 31.0$, approximate values for gold at $\lambda = 5 \mu\text{m}$; (b) $n = 1.80$, $k = 1.90$, $\lambda = 0.3 \mu\text{m}$; (c) $n = 0.94$, $k = 0.017$, approximate values for gold at $\lambda = 0.01 \mu\text{m}$. Note the tendency toward total external reflectance for angle $\geq 80^\circ$.

Total emittance ϵ_t is the emittance integrated over all wavelengths and usually given as a function of temperature. The total emittance of SiC is given in Fig. 38,⁵⁹ and for selected materials in Table 6.⁶⁰ Numerous papers by groups at the University of New Orleans (Ramanathan et al.^{61–65}) and at Cornell University (Sievers et al.^{66,67}) give high- and low-temperature data for the total hemispherical emittance of a number of metals including Ag, Al, Cu, Mo, W, and AISI 304 stainless steel.

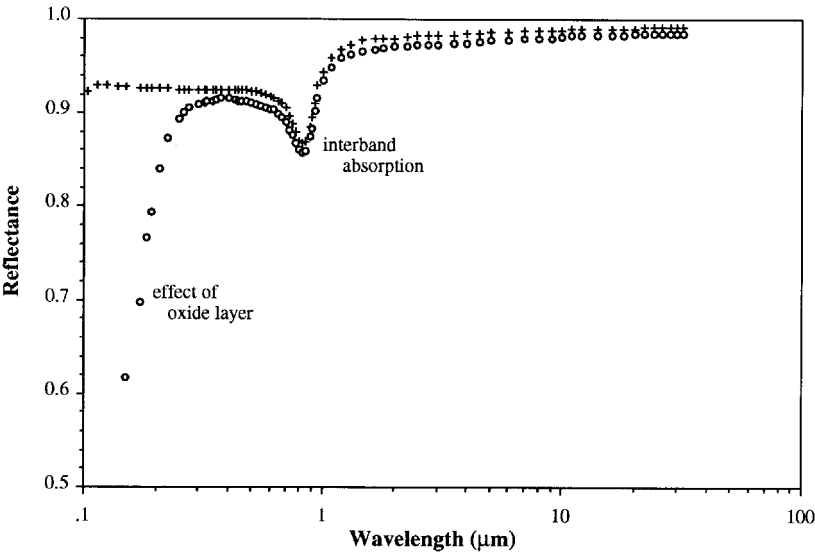


FIGURE 28 Effect of oxide layer on the reflectivity of aluminum vs. wavelength⁵¹ calculated from n and k .³⁷

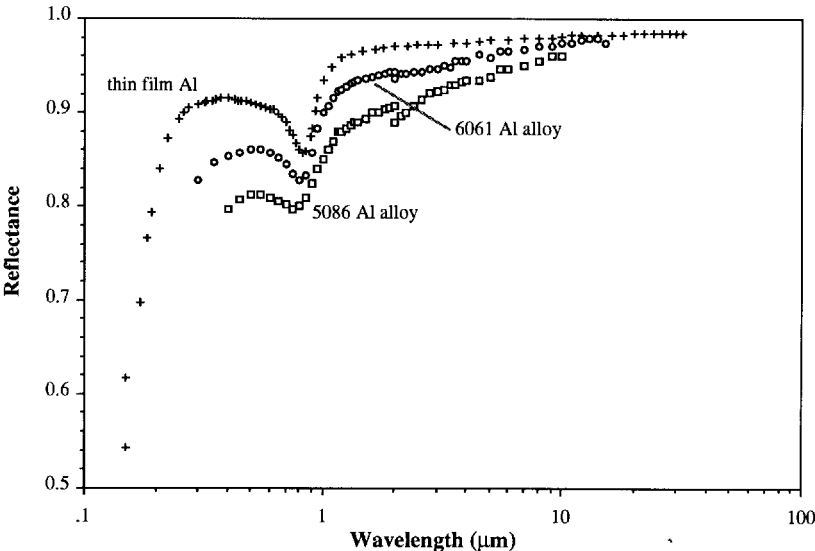


FIGURE 29 Reflectance of optical-grade aluminum alloys vs. wavelength.⁵¹

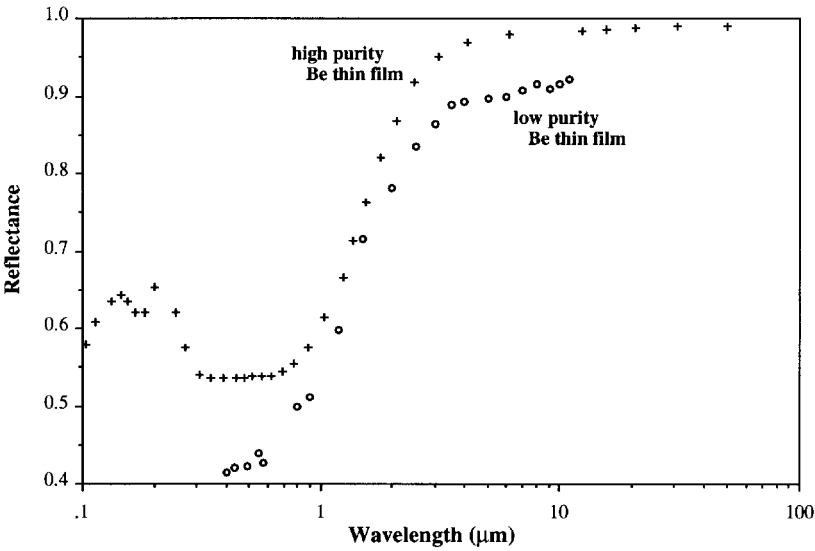


FIGURE 30 Effect of impurities on the reflectance of beryllium thin films vs. wavelength.⁵¹

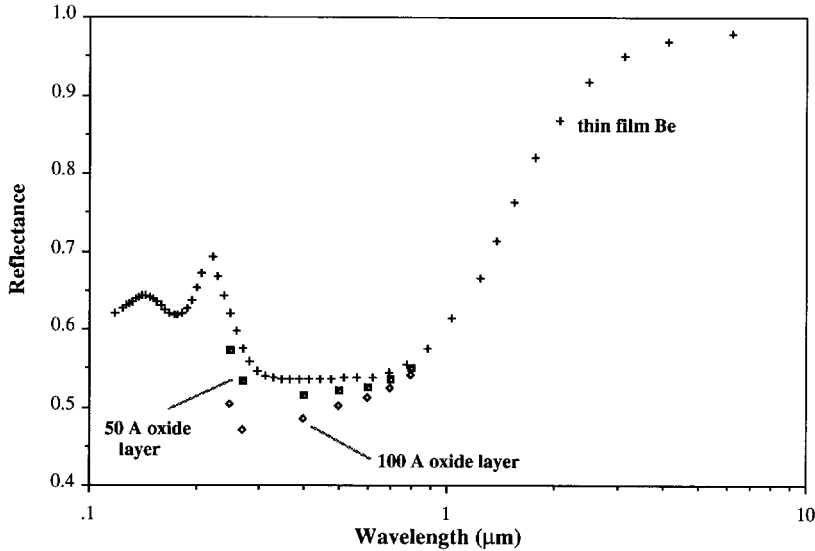


FIGURE 31 Effect of oxide layer thickness on the reflectance of beryllium vs. wavelength⁵¹ calculated from n and k .³⁸

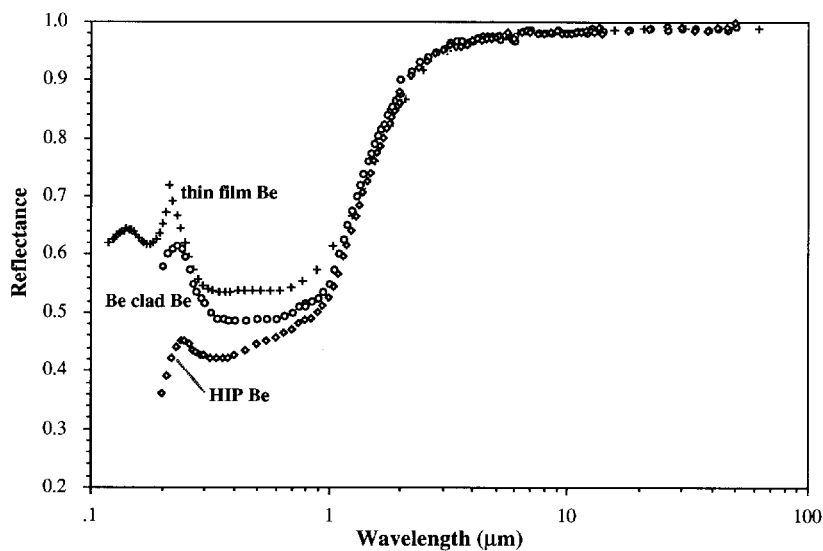


FIGURE 32 Reflectance of polished and evaporated beryllium vs. wavelength;⁵¹ comparison of evaporated high-purity thin film,³⁸ polished high-purity thick film, and polished bulk beryllium (2 percent BeO).

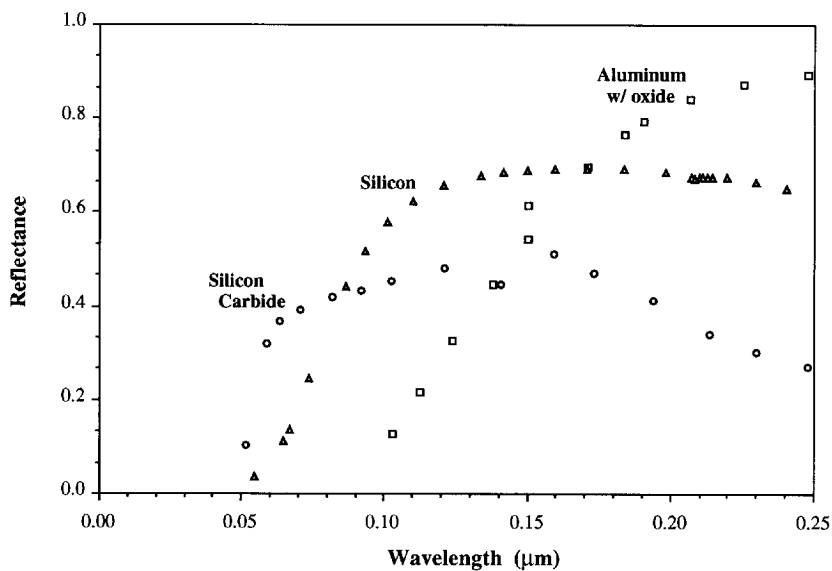


FIGURE 33 Ultraviolet reflectance of aluminum, silicon, and silicon carbide vs. wavelength.⁵¹

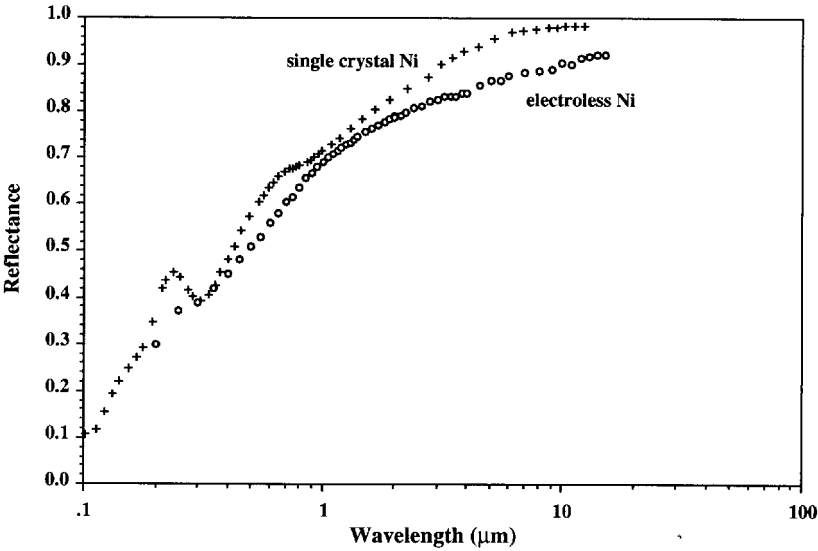


FIGURE 34 Reflectance of pure nickel³⁹ and electroless nickel (Ni-P alloy)⁵¹ vs. wavelength calculated from n and k .

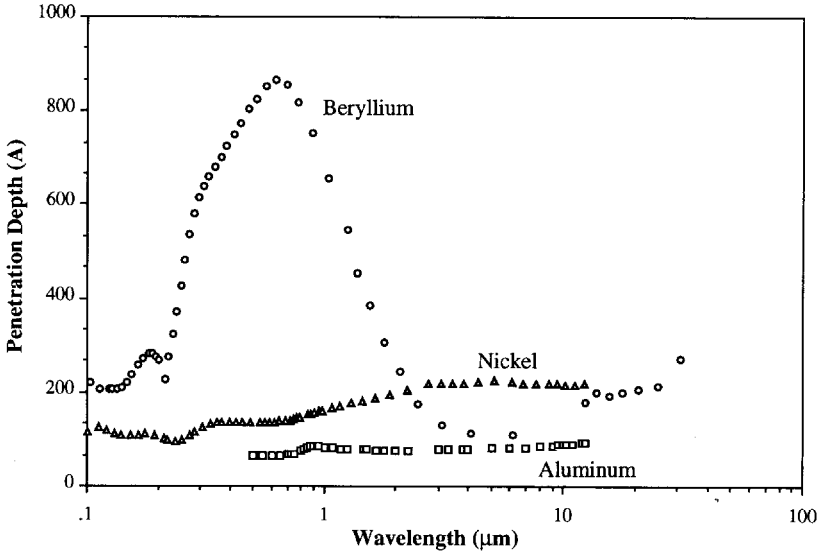


FIGURE 35 Penetration depth in Ångströms vs. wavelength for aluminum, beryllium, and nickel.⁵¹

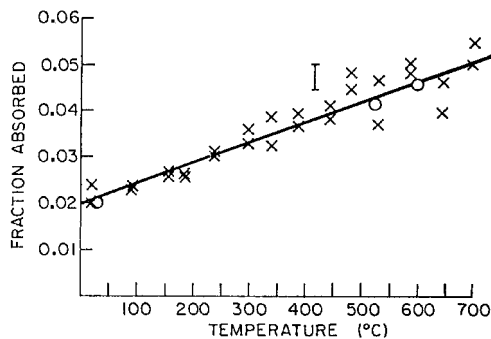


FIGURE 36 The 10.6-μm absorptance of Mo vs. temperature.⁵³ x is heating and o is cooling. The straight line is a least-squares fit to the data.

Physical Properties

The physical properties at room temperature of a number of metals are listed in Table 7. the crystal form does not appreciably affect the physical properties, but is a factor in the isotropy of thermal and mechanical properties. For most metals, resistivity is directly proportional to temperature and pure metals generally have increased resistivity with increasing amounts of alloying elements. This is shown graphically for copper in Fig. 39.⁶⁸ Resistivity for a number of pure, polycrystalline metals is listed as a function of temperature in Table 8.⁶⁹

TABLE 4 Mass Attenuation Coefficients for Photons⁵⁶
Mass attenuation coefficient, m²/kg

Atomic no.		Photon energy, MeV						
		0.001	0.01	0.1	1.0	10.0	100.0	1000.0
Be	4	6.04 × 10 ¹	6.47 × 10 ⁻²	1.33 × 10 ⁻²	5.65 × 10 ⁻³	1.63 × 10 ⁻³	9.94 × 10 ⁻⁴	1.12 × 10 ⁻³
C	6	2.21 × 10 ⁻²	2.37 × 10 ⁻¹	1.51 × 10 ⁻²	6.36 × 10 ⁻³	1.96 × 10 ⁻³	1.46 × 10 ⁻³	1.70 × 10 ⁻³
O	8	4.59 × 10 ²	5.95 × 10 ⁻¹	1.55 × 10 ⁻²	6.37 × 10 ⁻³	2.09 × 10 ⁻³	1.79 × 10 ⁻³	2.13 × 10 ⁻³
Mg	12	9.22 × 10 ¹	2.11	1.69 × 10 ⁻²	6.30 × 10 ⁻³	2.31 × 10 ⁻³	2.42 × 10 ⁻³	2.90 × 10 ⁻³
Al	13	1.19 × 10 ²	2.62	1.70 × 10 ⁻²	6.15 × 10 ⁻³	2.32 × 10 ⁻³	2.52 × 10 ⁻³	3.03 × 10 ⁻³
Si	14	1.57 × 10 ²	3.39	1.84 × 10 ⁻²	6.36 × 10 ⁻³	2.46 × 10 ⁻³	2.76 × 10 ⁻³	3.34 × 10 ⁻³
P	15	1.91 × 10 ²	4.04	1.87 × 10 ⁻²	6.18 × 10 ⁻³	2.45 × 10 ⁻³	2.84 × 10 ⁻³	3.45 × 10 ⁻³
Ti	22	5.87 × 10 ²	1.11 × 10 ¹	2.72 × 10 ⁻²	5.89 × 10 ⁻³	2.73 × 10 ⁻³	3.71 × 10 ⁻³	4.56 × 10 ⁻³
Cr	24	7.40 × 10 ²	1.39 × 10 ¹	3.17 × 10 ⁻²	5.93 × 10 ⁻³	2.86 × 10 ⁻³	4.01 × 10 ⁻³	4.93 × 10 ⁻³
Fe	26	9.09 × 10 ²	1.71 × 10 ¹	3.72 × 10 ⁻²	5.99 × 10 ⁻³	2.99 × 10 ⁻³	4.33 × 10 ⁻³	5.33 × 10 ⁻³
Ni	28	9.86 × 10 ²	2.09 × 10 ¹	4.44 × 10 ⁻²	6.16 × 10 ⁻³	3.18 × 10 ⁻³	4.73 × 10 ⁻³	5.81 × 10 ⁻³
Cu	29	1.06 × 10 ³	2.16 × 10 ¹	4.58 × 10 ⁻²	5.90 × 10 ⁻³	3.10 × 10 ⁻³	4.66 × 10 ⁻³	5.72 × 10 ⁻³
Zn	30	1.55 × 10 ²	2.33 × 10 ¹	4.97 × 10 ⁻²	5.94 × 10 ⁻³	3.18 × 10 ⁻³	4.82 × 10 ⁻³	5.91 × 10 ⁻³
Ge	32	1.89 × 10 ²	3.74	5.55 × 10 ⁻²	5.73 × 10 ⁻³	3.16 × 10 ⁻³	4.89 × 10 ⁻³	6.00 × 10 ⁻³
Mo	42	4.94 × 10 ²	8.58	1.10 × 10 ⁻¹	5.84 × 10 ⁻³	3.65 × 10 ⁻³	6.10 × 10 ⁻³	7.51 × 10 ⁻³
Ag	47	7.04 × 10 ²	1.19 × 10 ¹	1.47 × 10 ⁻¹	5.92 × 10 ⁻³	3.88 × 10 ⁻³	6.67 × 10 ⁻³	8.20 × 10 ⁻³
W	74	3.68 × 10 ²	9.69	4.44 × 10 ⁻¹	6.62 × 10 ⁻³	4.75 × 10 ⁻³	8.80 × 10 ⁻³	1.08 × 10 ⁻²
Pt	78	4.43 × 10 ²	1.13 × 10 ¹	4.99 × 10 ⁻¹	6.86 × 10 ⁻³	4.87 × 10 ⁻³	9.08 × 10 ⁻³	1.12 × 10 ⁻²
Au	79	4.65 × 10 ²	1.18 × 10 ¹	5.16 × 10 ⁻¹	6.95 × 10 ⁻³	4.93 × 10 ⁻³	9.19 × 10 ⁻³	1.13 × 10 ⁻²

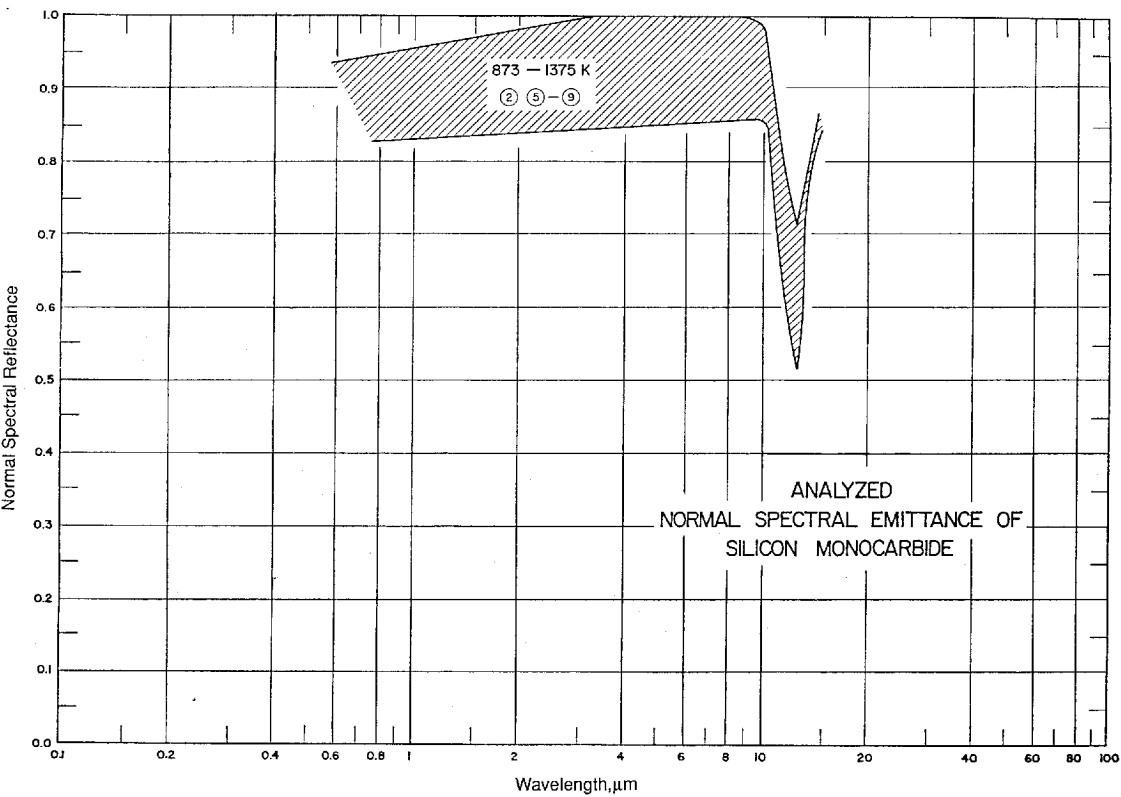


FIGURE 37 Analyzed normal spectral emittance of silicon carbide vs. wavelength.⁵⁷

TABLE 5 Normal Spectral Emittance of Selected Metals ($\lambda = 0.65 \mu\text{m}$)⁵⁸

Metal	Emissivity
Beryllium	0.61
Chromium	0.34
Copper	0.10
Gold	0.14
Iron	0.35
Cast iron	0.37
Molybdenum	0.37
Nickel	0.36
80Ni-20Cr	0.35
Palladium	0.33
Platinum	0.30
Silver	0.07
Steel	0.35
Tantalum	0.49
Titanium	0.63
Tungsten	0.43

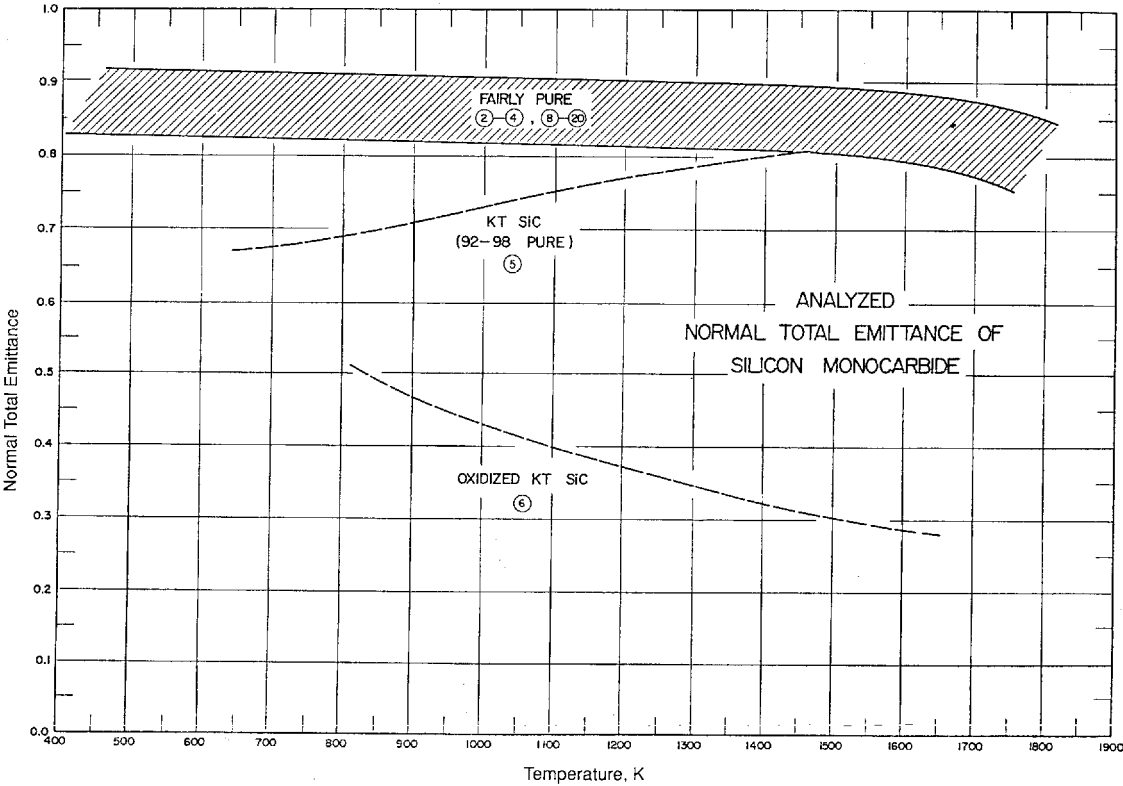


FIGURE 38 Analyzed normal total emittance of silicon carbide vs. temperature.⁵⁹

TABLE 6 Total Emittance of Selected Materials⁶⁰

Metal	Temperature (°C)	Emissivity
80 Ni-20Cr	100	0.87
	600	0.87
	1300	0.89
Aluminum		
Polished	50–500	0.04–0.06
Oxidized	200	0.11
	600	0.19
Chromium		
Polished	50	0.1
	500–1000	0.28–0.38
Copper		
Oxidized	50	0.6–0.7
	500	0.88
	50–100	0.02
Unoxidized	100	0.02

TABLE 6 Total Emittance of Selected Materials (*Continued*)

Metal	Temperature (°C)	Emissivity
Glass	20–100	0.94–0.91
	250–1000	0.87–0.72
	1100–1500	0.7–0.67
Gold		
Carefully polished	200–600	0.02–0.03
Unoxidized	100	0.02
Iron, cast		
Oxidized	200	0.64
	600	0.78
Unoxidized	100	0.21
Molybdenum	600–1000	0.08–0.13
	1500–2200	0.19–0.26
Nickel		
Polished	200–400	0.07–0.09
Unoxidized	25	0.045
	100	0.06
	500	0.12
	1000	0.19
Platinum		
Polished	200–600	0.05–0.1
Unoxidized	25	0.017
	100	0.047
	500	0.096
	1000	0.152
Silver		
Polished	200–600	0.02–0.03
Unoxidized	100	0.02
	500	0.035
Steel		
304 SS	500	0.35
Unoxidized	100	0.08
Tantalum, unoxidized	1500	0.21
	2000	0.26
Tungsten, unoxidized	25	0.024
	100	0.032
	500	0.071
	1000	0.15

Thermal Properties

The thermal properties of materials were documented in 1970 through 1977 in the 13-volume series edited by Touloukian et al.⁷⁰ of the Thermophysical Properties Research Center at Purdue University. The properties database continues to be updated by the Center for Information and Numerical Data Analysis and Synthesis (CINDAS).¹

Selected properties of coefficient of thermal expansion, CTE, thermal conductivity k , and specific heat C_p at room temperature, are listed in Table 9. Maximum usable temperatures are also listed in the table.

TABLE 7 Composition and Physical Properties of Metals

Metal	Mass density 10 ³ kg/m ³	Electrical conductivity % IACS ^a	Electrical resistivity ρ , n ohm m	Crystal form ^c	Chemical composition weight %, typical	Reference
Aluminum: 5086-O	2.66	31	56	fcc	4.0 Mg, 0.4 Mn, 0.15 Cr, bal. Al	84
Aluminum: 6061-T6	2.70	43	40	fcc	1.0 Mg, 0.6 Si, 0.3 Cu, 0.2 Cr, bal. Al	84
Beryllium: 1-70-H	1.85	43	40	cph	99.0 Be min., 0.6 BeO, 0.08 Fe, 0.05 C, 0.03 Al, 0.02 Mg	85
Copper: OFC	8.94	101	17	fcc	99.95 Cu min.	84
Gold	19.3	73	24	fcc	99.99 Au min.	84
Invar 36	8.1	^d	820	bcc	36.0 Ni, 0.35 Mn, 0.2 Si, 0.02 C, bal. Fe	86
Molybdenum	10.22	34 ^e	52 ^e	bcc	99.9 Mo min., 0.015 C max.	84
Nickel: 200	8.9	18	95	fcc	99.0 Ni min.	84
Nickel: electroless plate	7.75	^d	900	fcc	10.5 P, bal. Ni	87
Silicon	2.33	^f	^f	dia. cubic	99.99 Si	84
Silicon carbide (SiC): CVD	3.21	^f	^f	cubic	99.99 SiC (beta)	88
SiC: reaction sintered	2.91	^f	^f	cph + dia. cubic	74.0 SiC (alpha), 26.0 Si	88
Silver	10.49	103	15 ^e	fcc	99.9 Ag min.	84
Stainless steel: 304	8.00	^d	720	fcc	19.0 Cr, 9.0 Ni, 1.0 Mn, 0.5 Si, bal. Fe	89
Stainless steel: 416	7.80	^d	570	distorted bcc	13.0 Cr, 0.6 Mn, 0.6 Mo, 0.5 Si, bal. Fe	89
Stainless steel: 430	7.80	^d	600	bcc	17.0 Cr, 0.5 Mn, 0.5 Si, bal. Fe	89
Titanium: 6A14V	4.43	^d	1710	bcc + cph	6.0 Al, 4.0 V, bal. Ti	90

^a For equal volume at 293 K

^b At 293 K

^c fcc = face centered cubic; cph = close-packed hexagonal; bcc = body centered cubic

^d Not available

^e At 273 K

^f Depends on impurity content

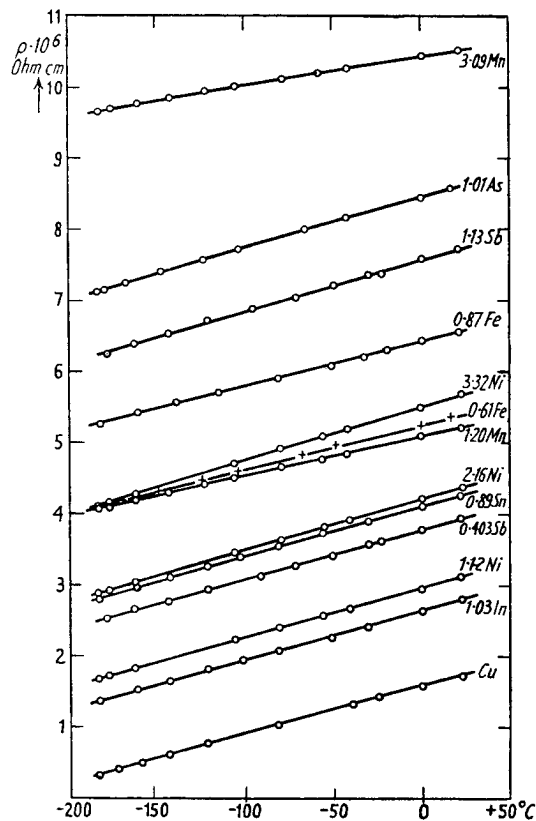


FIGURE 39 Electrical resistance of Cu and Cu alloys vs. temperature;⁶⁸ composition is in atomic percent.

The CTE of a material is a measure of length change at a specific temperature, useful for determining dimensional sensitivity to local temperature gradients. The total expansion (contraction) per unit length $\Delta L/L$ for a temperature change ΔT is the area under the CTE vs. T curve between the temperature extremes. Table 10 and Figs. 40 through 42 show recommended^{71,72} CTE vs. T relationships for a number of materials. More recent expansion data have been published for many materials that are too numerous to list here, but those for beryllium⁷³ and beta silicon carbide⁷⁴ are included in Table 10.

Thermal conductivities of many pure polycrystalline materials have been published by the National Bureau of Standards^{75,76} (now National Institute for Science and Technology) as part of the National Standard Reference Data System. Selected portions of these data, along with data from Touloukian et al.,^{77,78} and specific data for beryllium⁷⁹ and beta silicon carbide,⁸⁰ are listed in Table 11 and shown in Figs. 43 through 46.

The specific heat of metals is very well documented.^{73,81-83} Table 12 and Figs. 47 through 49 show the temperature dependence of this property. Table values are cited in J/kg K, numerically equal to W s/kg K.

Mechanical Properties

Mechanical properties are arbitrarily divided between the elastic properties of moduli, Poisson's ratio, and elastic stiffness, and the strength and fracture properties. All of these

TABLE 8 Electrical Resistivity (nohm m) of Pure, Polycrystalline Metals⁶⁹

Temp. (K)	Aluminum	Beryllium	Chromium	Copper	Gold	Iron	Molybdenum	Nickel	Platinum	Silver	Tungsten
1	0.0010	0.332		0.020	0.220	0.225	0.0070	0.032	0.02	0.010	0.0002
10	0.0019	0.332		0.020	0.226	0.238	0.0089	0.057	0.154	0.012	0.0014
20	0.0076	0.336		0.028	0.350	0.287	0.0261	0.140	0.484	0.042	0.012
40	0.181	0.367		0.239	1.41	0.758	0.457	0.68	4.09	0.539	0.544
60	0.959	0.67		0.971	3.08	2.71	2.06	2.42	11.07	1.62	2.66
80	2.45	0.75		2.15	4.81	6.93	4.82	5.45	19.22	2.89	6.06
100	4.42	1.33	16.0	3.48	6.50	12.8	8.58	9.6	27.55	4.18	10.2
150	10.06	5.10	45.0	6.99	10.61	31.5	19.9	22.1	47.6	7.26	20.9
200	15.87	12.9	77.0	10.46	14.62	52.0	31.3	36.7	67.7	10.29	31.8
273	24.17	30.2	118.0	15.43	20.51	85.7	48.5	61.6	96.0	14.67	48.2
293	26.50	35.6	125.0	16.78	22.14	96.1	53.4	69.3	105.0	15.87	52.8
298	27.09	37.0	126.0	17.12	22.55	98.7	54.7	71.2	107.0	16.17	53.9
300	27.33	37.6	127.0	17.25	22.71	99.8	55.2	72.0	108.0	16.29	54.4
400	38.7	67.6	158.0	24.02	31.07	161.0	80.2	118.0	146.0	22.41	78.3
500	49.9	99.0	201.0	30.90	39.70	237.0	106.0	177.0	183.0	28.7	103.0
600	61.3	132.0	247.0	37.92	48.70	329.0	131.0	255.0	219.0	35.3	130.0
700	73.5	165.0	295.0	45.14	58.20	440.0	158.0	321.0	254.0	42.1	157.0
800	87.0	200.0	346.0	52.62	68.10	571.0	184.0	355.0	287.0	49.1	186.0
900	101.8	237.0	399.0	60.41	78.60		212.0	386.0	320.0	56.4	215.0

properties can be anisotropic as described by the elastic stiffness constants, but that level of detail is not included here. In general, cubic materials are isotropic in thermal properties and anisotropic in elastic properties. Materials of any of the other crystalline forms will be anisotropic in both thermal and elastic properties. For an in-depth treatment of this subject see, for example, Ref. 4.

TABLE 9 Thermal Properties of Metals at Room Temperature

Metal	Coeff. of thermal expansion ppm/K	Thermal conductivity W/m K	Specific Heat J/kg K	Maximum temperature K	References
Aluminum: 5086-O	22.6	127	900	475	84
Aluminum: 6061-T6	22.5	167	896	425	84
Beryllium: I-70-H	11.3	216	1925	800	85
Copper: OFC	16.5	391	385	400	84
Gold	14.2	300	130	400	84
Iron	11.8	81	450	900	84
Invar 36	1.0	10	515	475	86
Molybdenum	4.8	142	276	1100	84
Nickel: 200	13.4	70	456	650	84
Nickel: Electroless plate (11% P)	11.0	7	460	425	87
(8% P)	12.8			450	91
Silicon	2.6	156	710	725	84
Silicon Carbide (SiC): CVD	2.2	198	733	1200	88
	2.4	250	700		92
SiC: Reaction sintered	2.6	155	670	1100	92
Silver	19.0	428	235	400	84
Stainless steel: 304	14.7	16	500	700	89
Stainless steel: 416	9.5	25	460	500	89
Stainless steel: 430	10.4	26	460	870	89
Titanium: 6A14V	8.6	7	520	650	84

TABLE 10 Temperature Dependence of the Coefficient of Linear Thermal Expansion (ppm/K) of Selected Materials

Temp K	6061 Al	Be	Cu	Au	Fe	304 SS	416 SS	Mo	Ni	Ag	Si	alpha SiC	beta SiC
5		0.0003	0.005	0.03	0.01				0.02	0.015		0.01	
10		0.001										0.02	
20		0.005				9.8	4.3	0.3			0		
25		0.009	0.63	2.8	0.2			0.4	0.25	1.9	0	0.03	
50		0.096	3.87	7.7	1.3	10.5	4.9	1	1.5	8.2	−0.2	0.06	
75		0.47							4.3		−0.5	0.09	
100	12.2	1.32	10.3	11.8	5.6	11.4	6	2.8	6.6	14.2	−0.4	0.14	
125	18.7	2.55											
150	19.3	4.01				12.4	7				0.5	0.4	
175	20.3	5.54											
200	20.9	7.00	15.2	13.7	10.1	13.2	7.9	4.6	11.3	17.8	1.5	1.5	
225	21.5	8.32											
250	21.5	9.50				14.1	8.8				2.2	2.8	
293	22.5	11.3	16.5	14.2	11.8	14.7	9.5	4.8	13.4	18.9	2.6	3.3	3.26
300		11.5										3.4	3.29
350	23.8												3.46
400	25.0	13.6	17.6	14.8	13.4	16.3	10.9	4.9	14.5	19.7	3.2	4	3.62
450	26.3												3.77
500	27.5	15.1	18.3	15.4	14.4	17.5	12.1	5.1	15.3	20.6	3.5	4.2	3.92
600	30.1	16.6	18.9	15.9	15.1	18.6	12.9	5.3	15.9	21.5	3.7	4.5	4.19
700		17.8	19.5	16.4	15.7	19.5	13.5	5.5	16.4	22.6	3.9	4.7	4.42
800		19.1	20.3	17	16.2	20.2	13.8	5.7	16.8	23.7	4.1	4.9	4.62
900		20.0	21.3	17.7	16.4		13.9	6	17.1	24.8	4.3	5.1	4.79
1000		20.9	22.4	18.6	16.6	21.1	13.9	6.2	17.4	25.9	4.4	5.3	4.92
Reference	71	73	71	71	71	71	71	71	71	71	72	72	74

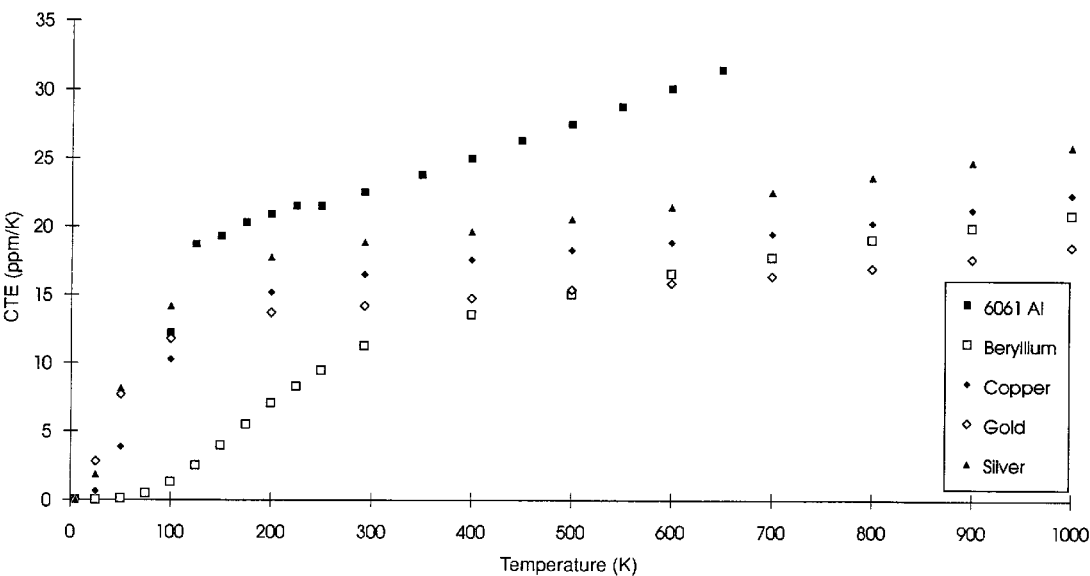


FIGURE 40 Coefficient of linear thermal expansion of 6061 aluminum alloy,⁷¹ beryllium,⁷³ copper,⁷¹ gold,⁷¹ and silver⁷¹ vs. temperature.

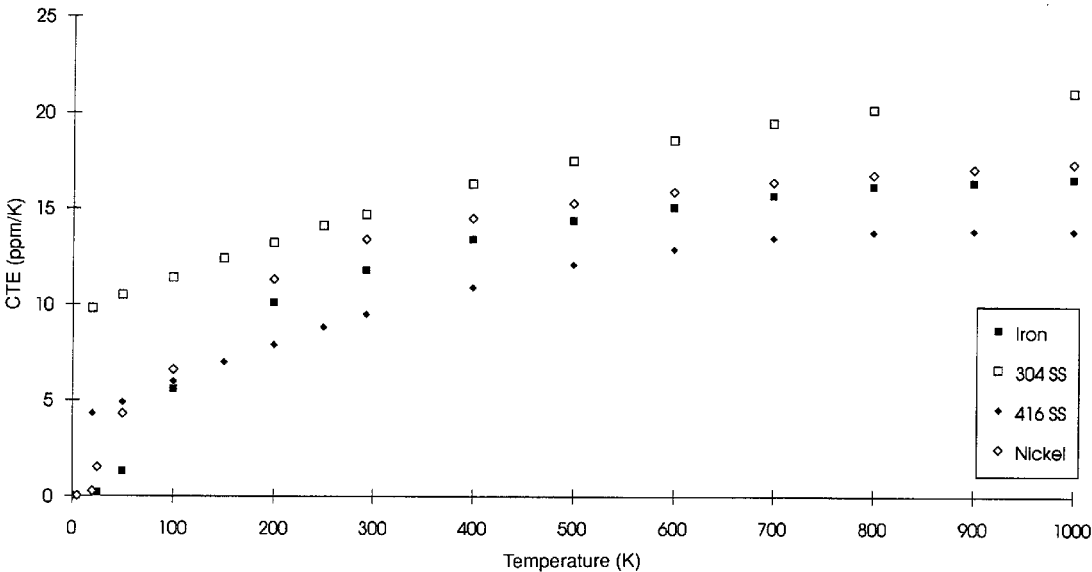


FIGURE 41 Coefficient of linear thermal expansion of iron,⁷¹ stainless steel types 304⁷¹ and 416,⁷¹ and nickel⁷¹ vs. temperature.

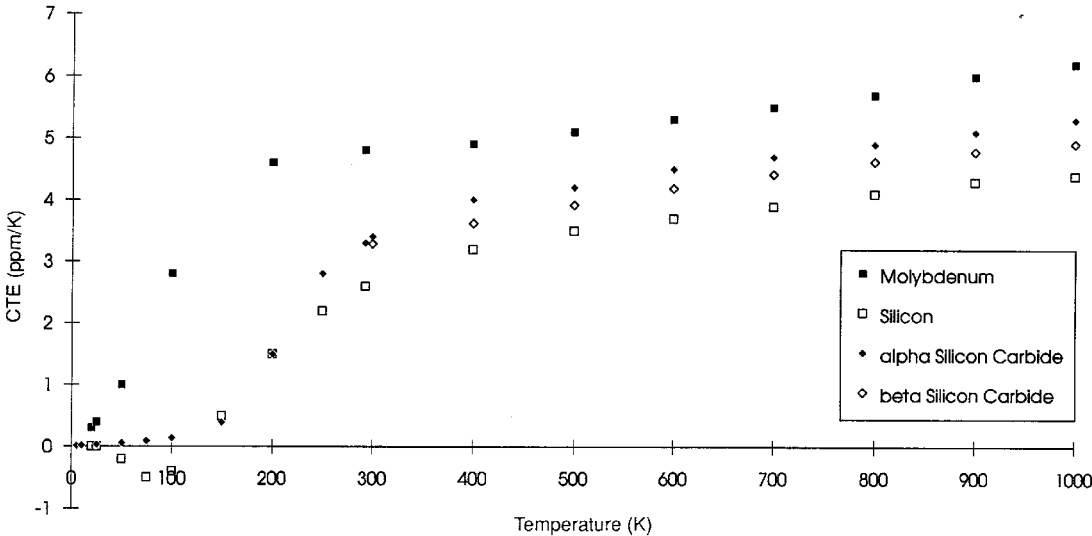


FIGURE 42 Coefficient of linear thermal expansion of molybdenum,⁷¹ silicon,⁷² and alpha⁷² and beta⁷⁴ silicon carbide vs. temperature.

TABLE 11 Temperature Dependence of the Thermal Conductivity (W/m K) of Selected Materials

Temp K	Pure Al	6061 Al	5086 Al	Be	Cu	Au	Fe	304 SS	Mo	Ni	Ag	Si	alpha SiC	beta SiC
5	3,810				13,800	2,070	371		73	316	17,200	424		
10	6,610	87	8		19,600	2,820	705	1	145	600	16,800	2,110		
20	5,650	170	17	60	10,500	1,500	997		277	856	5,100	4,940	950	
50	1,000	278	40	140	1,220	420	936	6	300	336	700	2,680	2,872	
75	450			197			186		220	207	484	1,510	2,797	
100	300	213	64	268	463	345	132	10	179	158	450	884	2,048	
123														179
150		200	79	301	428	335	104	12	149	121	432	409		
167													970	
173														223
200	237	203	93	282	413	327	94	13	143	106	430	264		
250		209	103	232	404	320								
273	236		109		401	318	84	15	139	94	428	168		202
293		212												
298			115											193
300	237			200	398	315	80	15	138	90	427	148	420	
400	240			160	392	312	69	17	134	80	420	99		
500	237			139	388	309	61	18	130	72	413	76		
600	232			126	383	304	55	20	126	66	405	62		
700	226			115	377	298	49	21	122	65	397	51		
800	220			107	371	292	43	22	118	67	389	42		
900	213			98	364	285	38	24	115	70	382	36		
1000				89	357	278	33	25	112	72	374	31		
Reference	75, 76	77	77	79	77	77	77	77	77	77	77	77	78	80

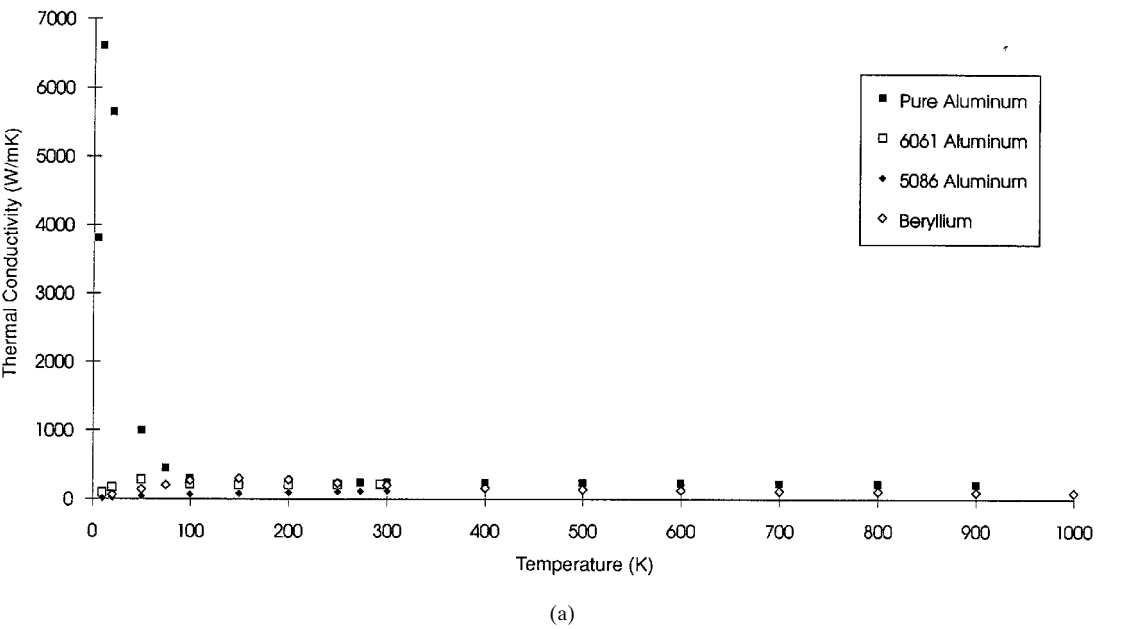
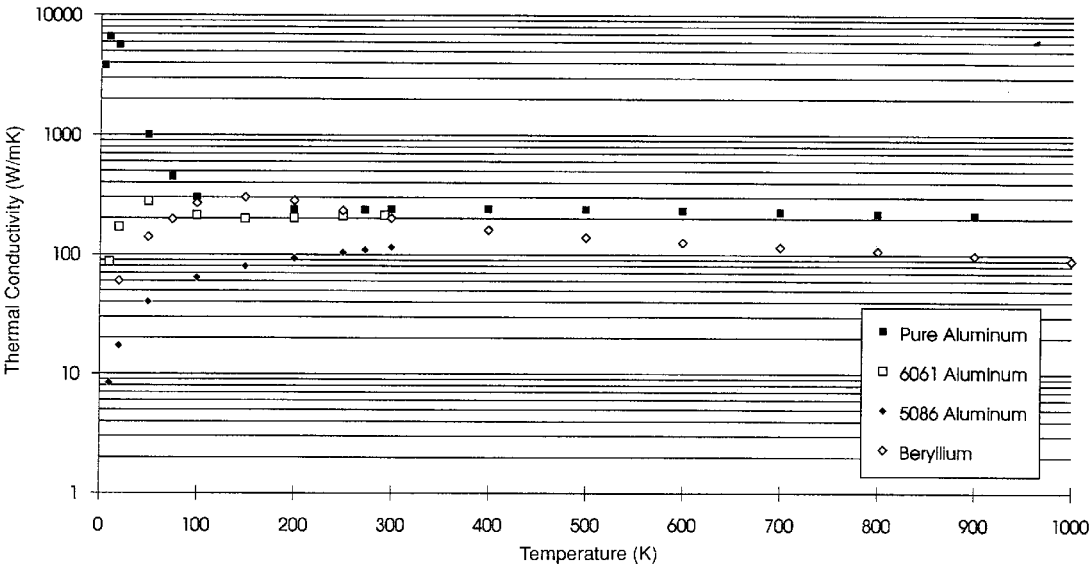
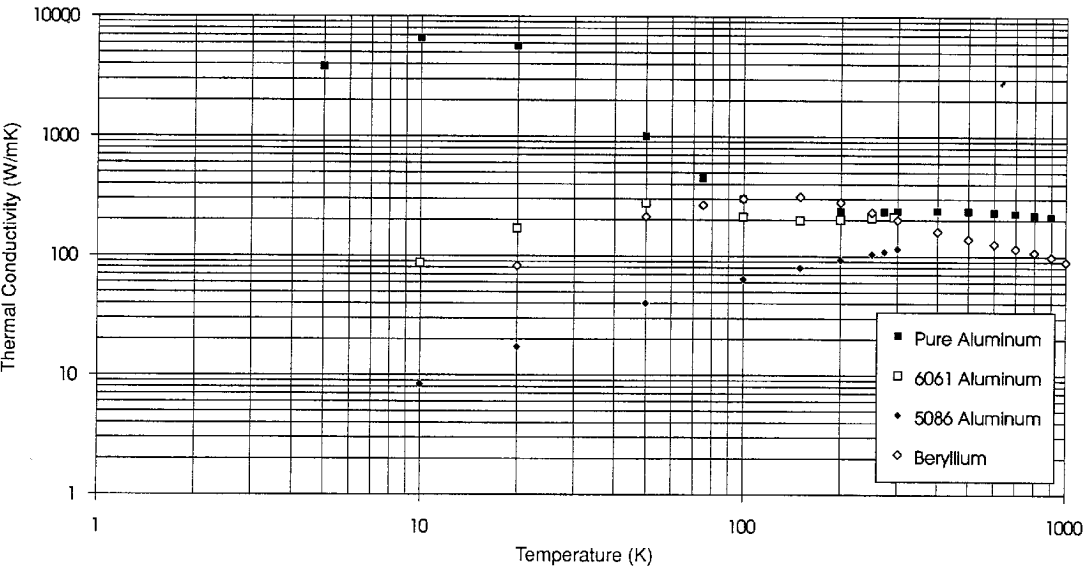


FIGURE 43 Thermal conductivity of three aluminum alloys⁷⁵⁻⁷⁷ and beryllium⁷⁹ vs. temperature.

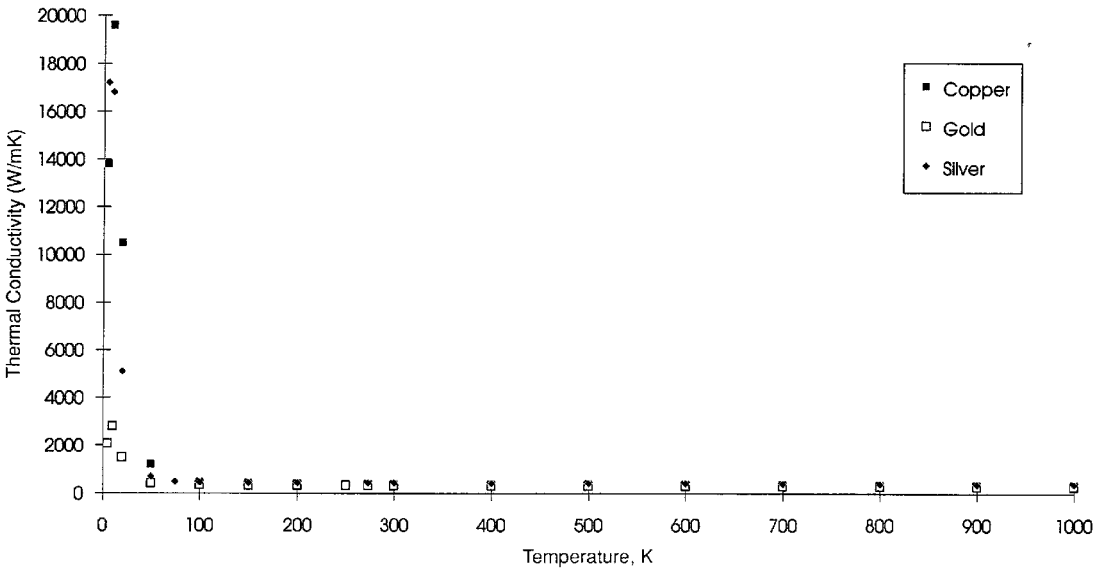


(b)

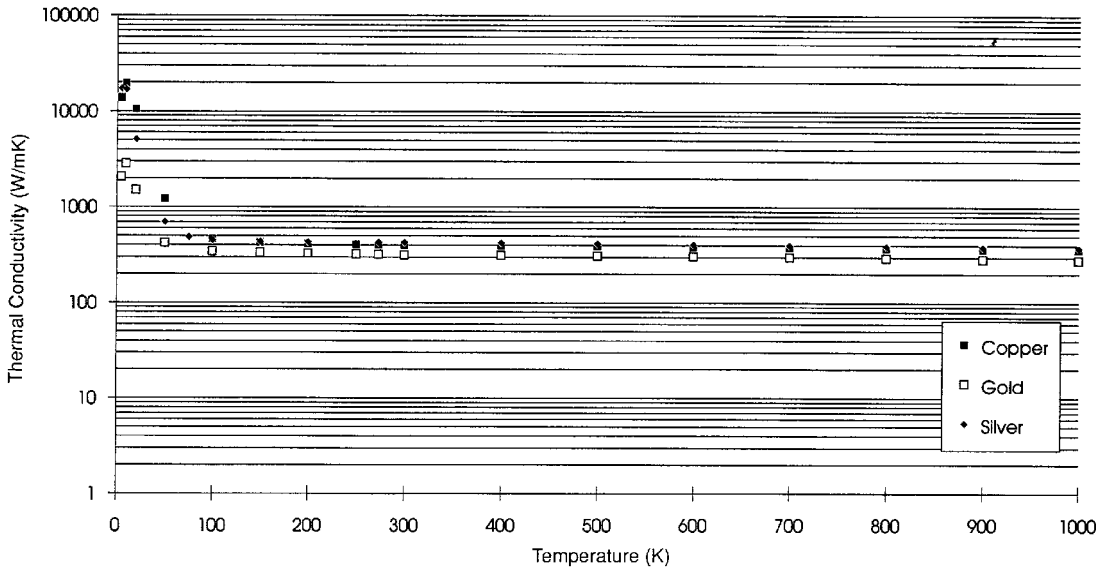


(c)

FIGURE 43 (Continued)

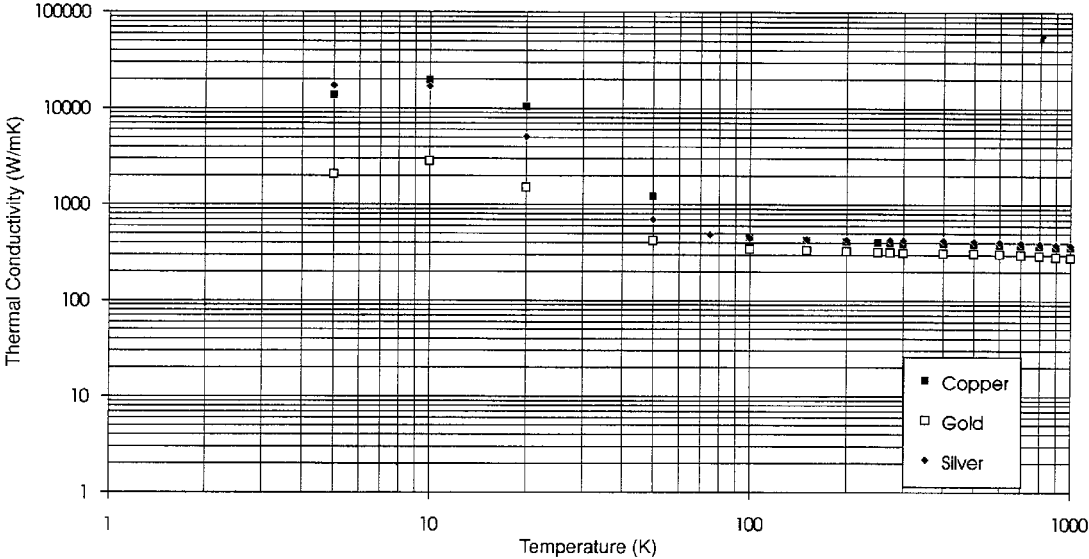


(a)



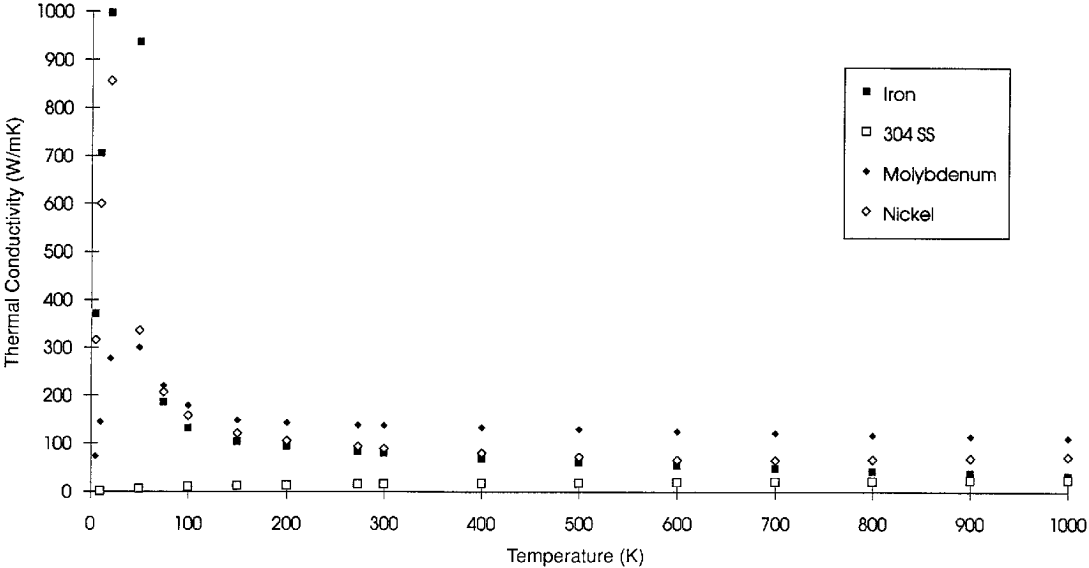
(b)

FIGURE 44 Thermal conductivity of copper,⁷⁷ gold,⁷⁷ and silver⁷⁷ vs. temperature.



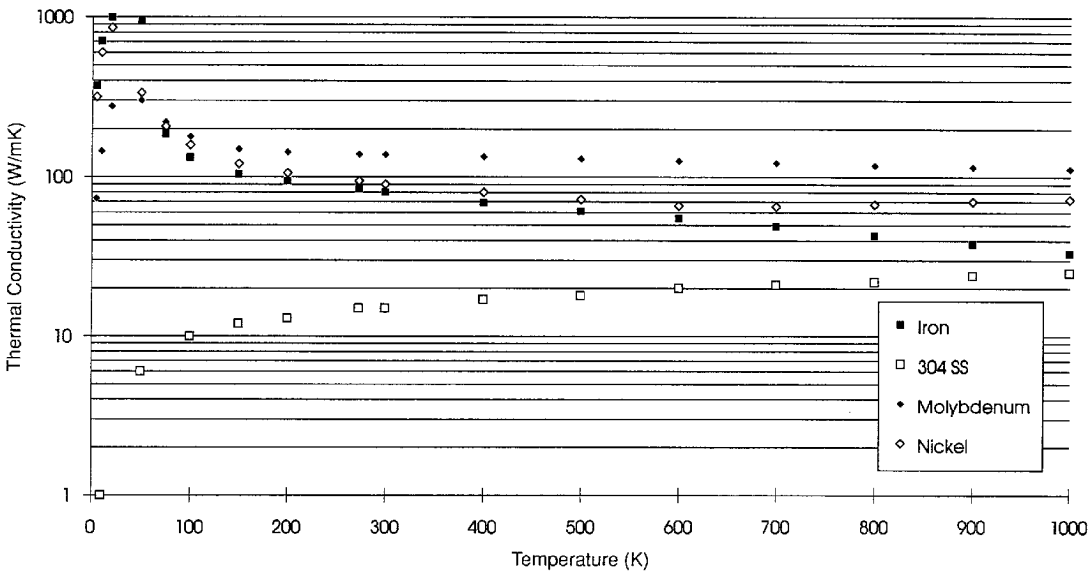
(c)

FIGURE 44 (Continued)

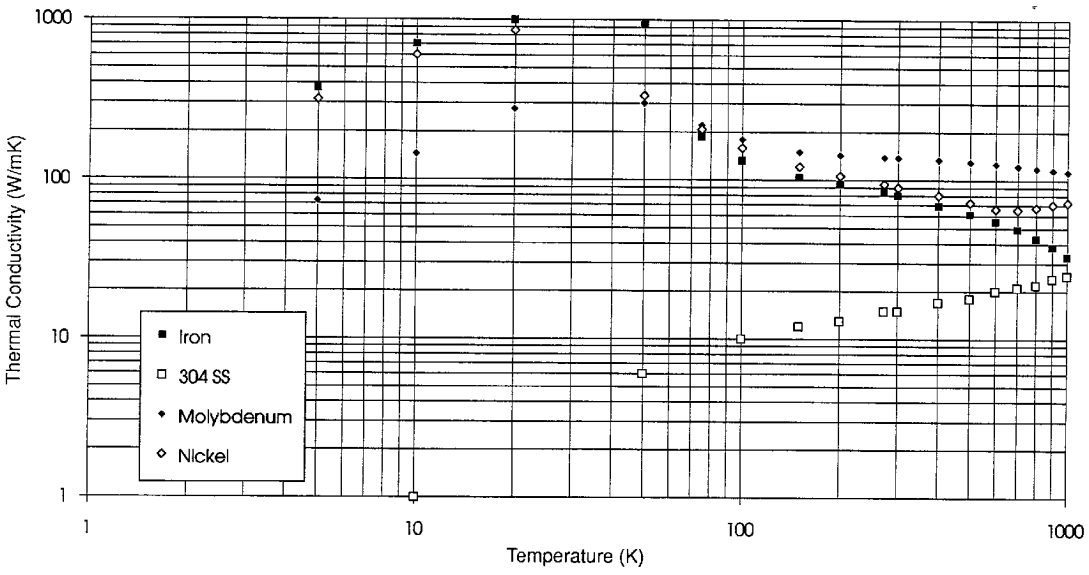


(a)

FIGURE 45 Thermal conductivity of iron,⁷⁷ type 304 stainless steel,⁷⁷ molybdenum,⁷⁷ and nickel⁷⁷ vs. temperature.

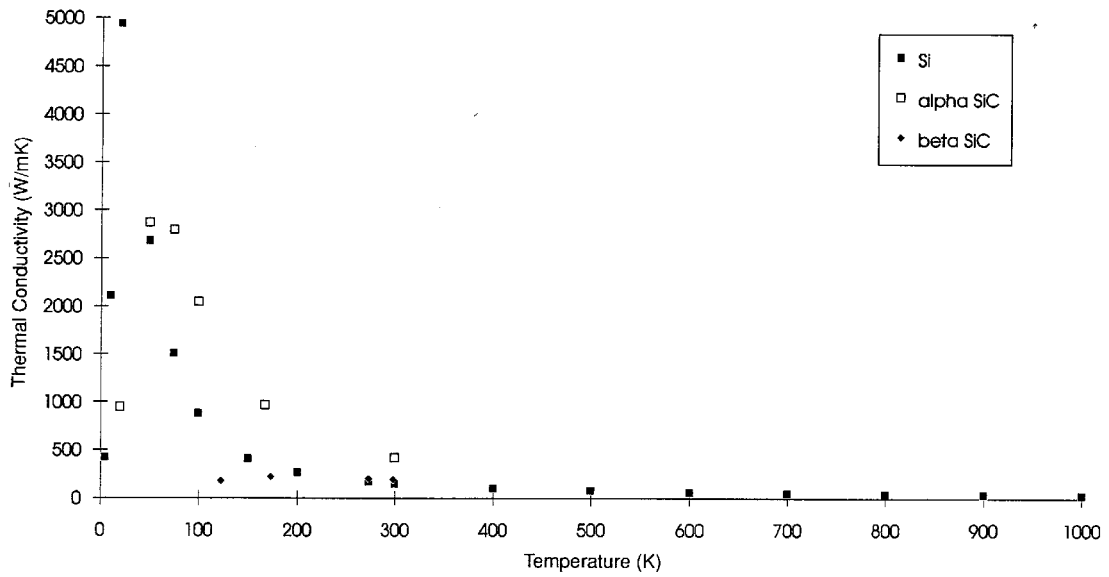


(b)

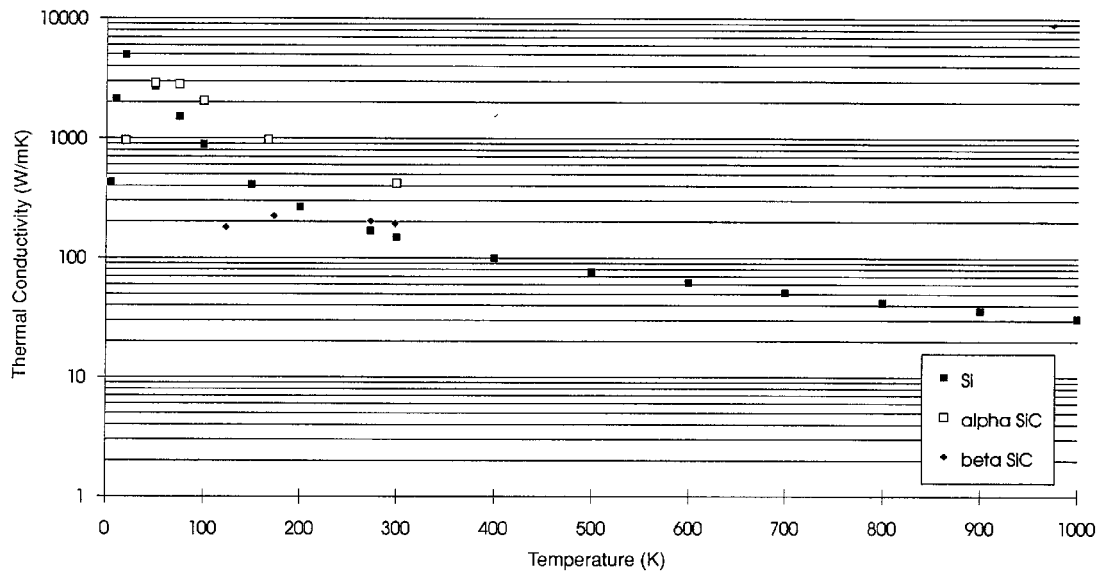


(c)

FIGURE 45 (Continued)

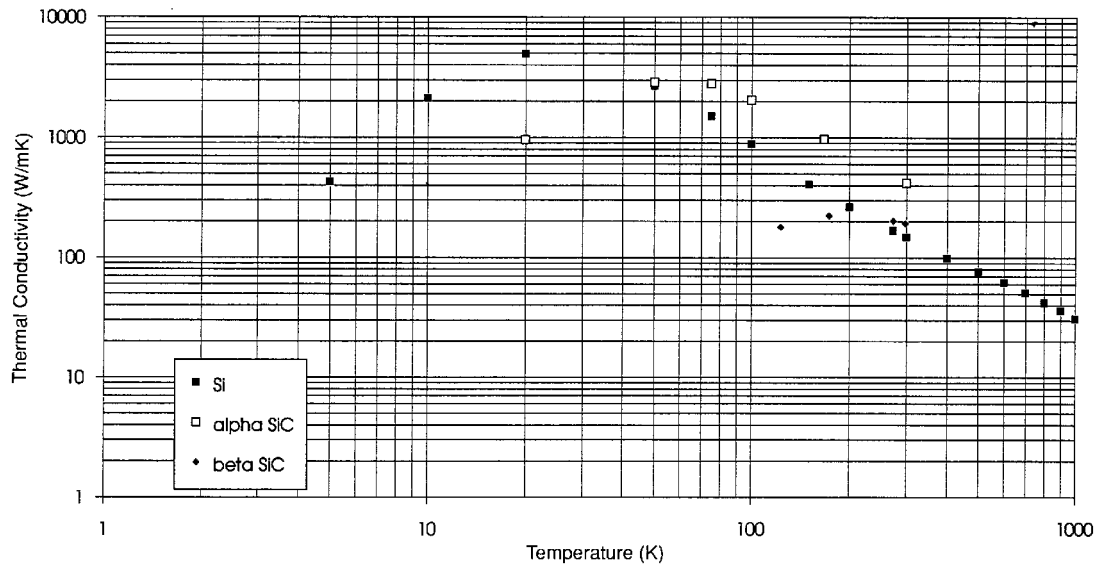


(a)



(b)

FIGURE 46 Thermal conductivity of silicon⁷⁷ and alpha⁷⁸ and beta⁸⁰ silicon carbide vs. temperature.



(c)

FIGURE 46 (Continued)

TABLE 12 Temperature Dependence of the Specific Heat (J/kg K) of Selected Materials

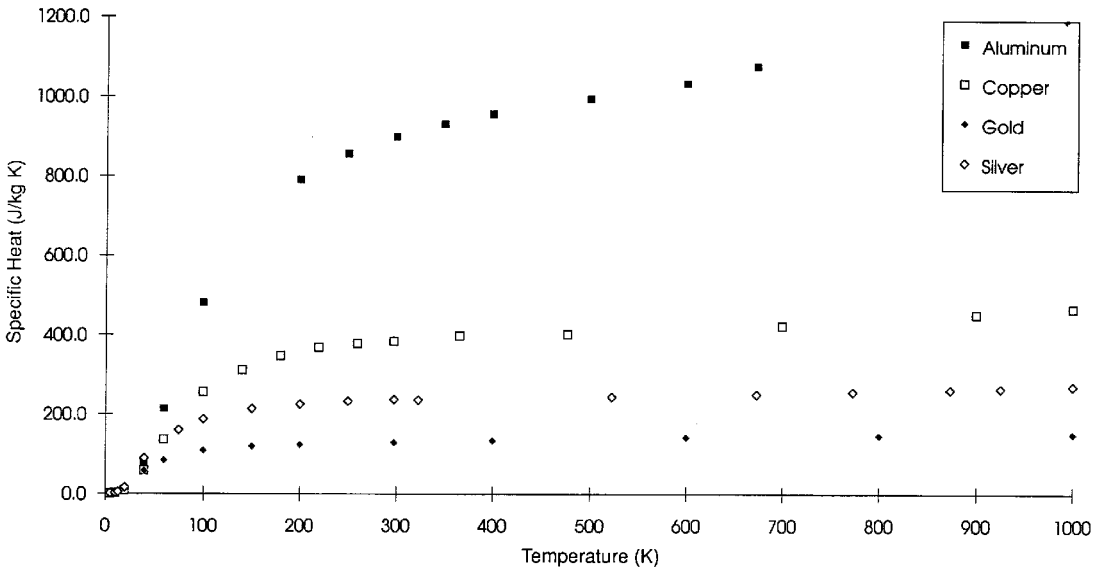
[illegible]

TABLE 12 Temperature Dependence of the Specific Heat (J/kg K) of Selected Materials (*Continued*)

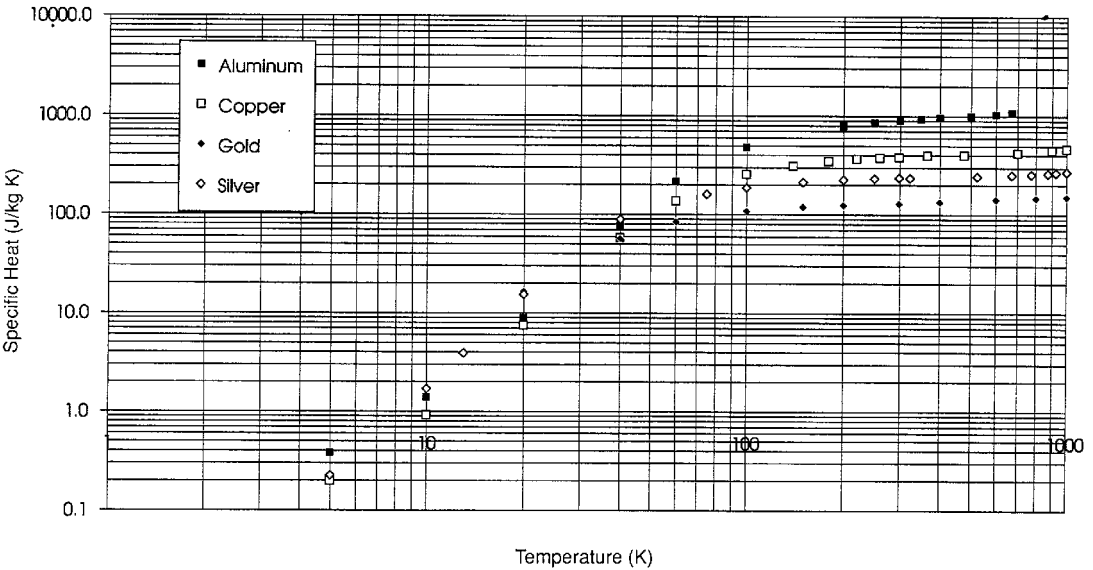
Temp K	Al	Be	Cu	Au	Fe	430 SS	Mo	Ni	Ag	Si	beta SiC
366			398								
373		2051					261	471		770	880
400	956			134	487						
473							266	514		825	1020
477			402								
500	995				526						
523								541	244		
573							271	573		848	1050
600	1034			142	568						
623		2574						626			
629								656			
630								669			
631								652			
673	1076	2658					277	530	251	864	1150
700			423		617	649					
733								526			
773								527	257	881	1200
800		2817		147	687	753					
873							288	542	262	898	
900		2918	452		786	862					
973							294	556		913	
1000		3022	467	151	1016	971			272		
Reference	81, 82	73, 83	83	83	83	83	83	83	83	83	80

Elastic Properties. The principal elastic stiffnesses C_{ij} of single crystals of some materials are given in Table 13. The three moduli and Poisson's ratio for polycrystalline materials are given in Table 14. These properties vary little with temperature, increasing temperature causing a gradual decrease in the moduli.

Strength and Fracture Properties The properties of tensile yield (at 0.2 percent offset), microyield strength, ductility (expressed as percent elongation in 50 mm), fracture toughness, flexural strength, and mechanical hardness are listed in Table 15. Most of these properties vary with temperature: strength and hardness decreasing, and fracture toughness and ductility increasing with temperature.

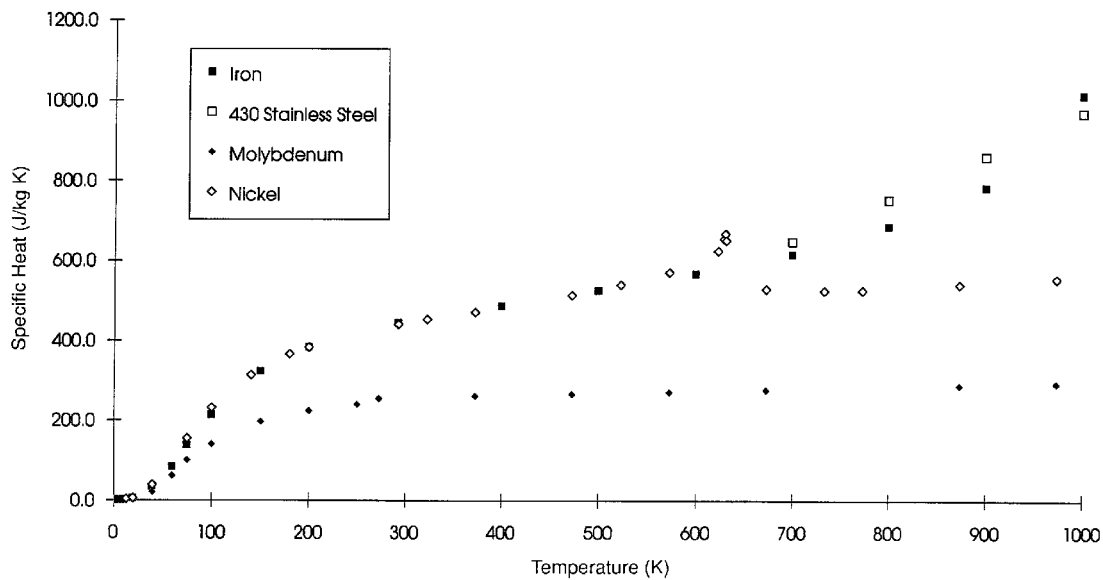


(a)

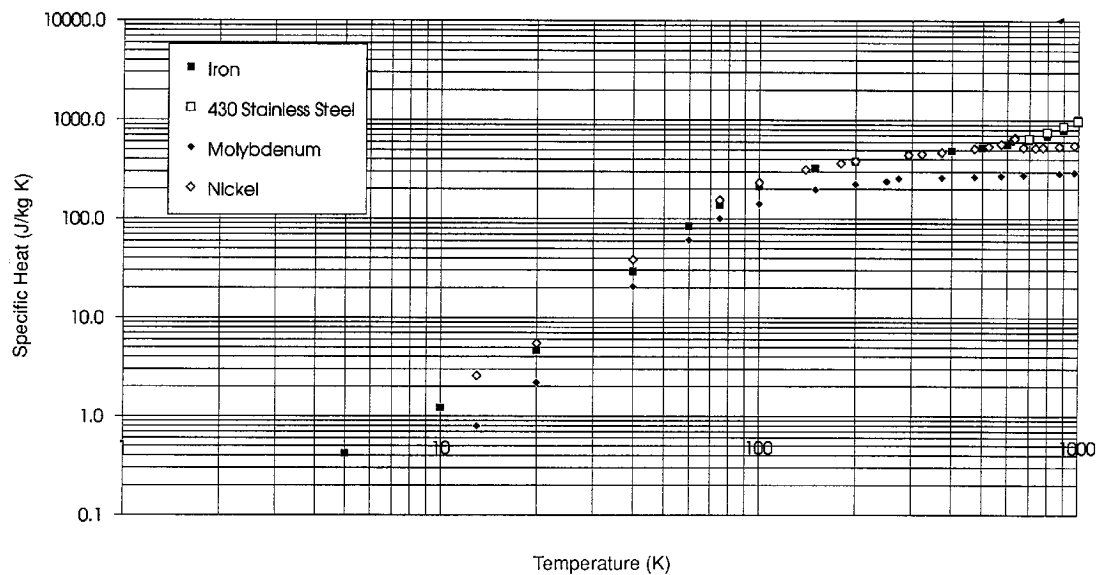


(b)

FIGURE 47 Specific heat of aluminum,^{81,82} copper,⁸³ gold,⁸³ and silver⁸³ vs. temperature.

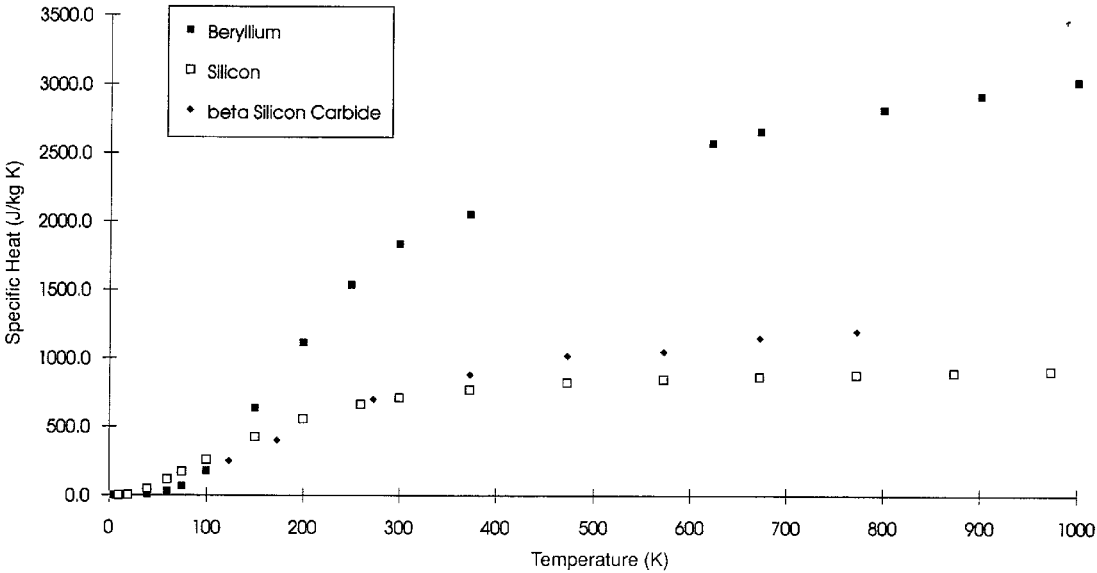


(a)

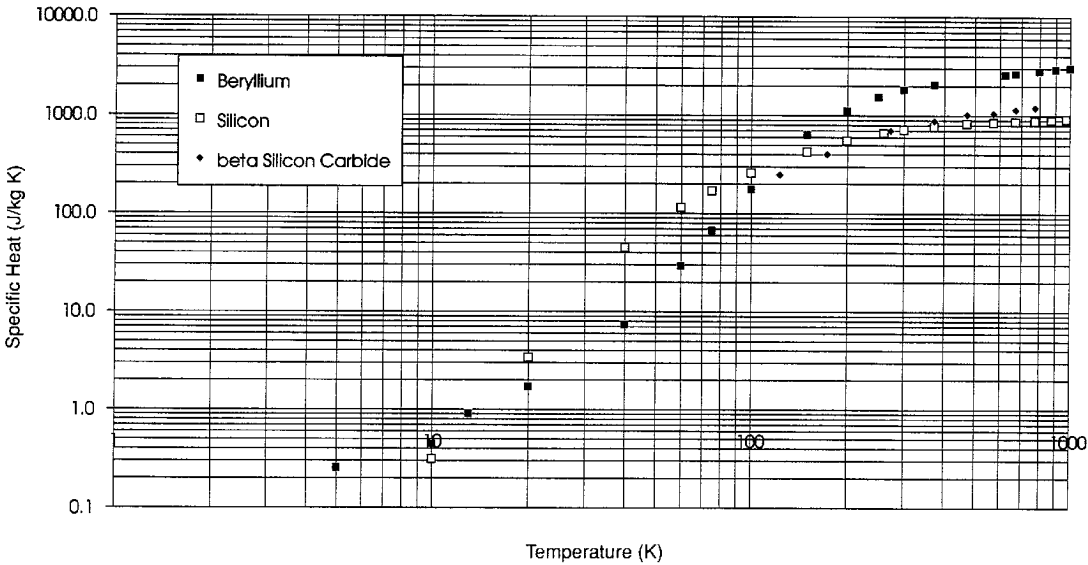


(b)

FIGURE 48 Specific heat of iron,⁸³ type 430 stainless steel,⁸³ molybdenum,⁸³ and nickel⁸³ vs. temperature.



(a)



(b)

FIGURE 49 Specific heat of beryllium,^{73,83} silicon,⁸³ and beta silicon carbide⁸⁰ vs. temperature.

TABLE 13 Elastic Stiffness Constants for Selected Single Crystal Metals

	Elastic stiffness (GN/m ²)				
Cubic metals ⁹³	C_{11}	C_{44}	C_{12}		
Aluminum	108.0	28.3	62.0		
Chromium	346.0	100.0	66.0		
Copper	169.0	75.3	122.0		
Germanium	129.0	67.1	48.0		
Gold	190.0	42.3	161.0		
Iron	230.0	117.0	135.0		
Molybdenum	459.0	111.0	168.0		
Nickel	247.0	122.0	153.0		
Silicon	165.0	79.2	64.0		
Silicon carbide ⁹⁴	352.0	233.0	140.0		
Silver	123.0	45.3	92.0		
Tantalum	262.0	82.6	156.0		
Tungsten	517.0	157.0	203.0		
Hexagonal metals	C_{11}	C_{33}	C_{44}	C_{12}	C_{13}
Beryllium ⁹⁵	288.8	354.2	154.9	21.1	4.7
Magnesium ⁹³	22.0	19.7	60.9	-7.8	-5.0
Silicon carbide ⁹⁴	500.0	521.0	168.0	98.0	

TABLE 14 Elastic Moduli and Poisson's Ratio for Selected Polycrystalline Materials

Material	Young's modulus GN/m ²	Shear modulus GN/m ²	Bulk modulus GN/m ²	Poisson's ratio	Reference
Aluminum: 5086-O	71.0	26.4		0.33	84
Aluminum: 6061-T6	68.9	25.9		0.33	84
Beryllium: I-701-H	315.4	148.4	115.0	0.043	96
Copper	129.8	48.3	137.8	0.343	97
Germanium	79.9	29.6		0.32	97
Gold	78.5	26.0	171.0	0.42	97
Invar 36	144.0	57.2	99.4	0.259	97
Iron	211.4	81.6	169.8	0.293	97
Molybdenum	324.8	125.6	261.2	0.293	97
Nickel	199.5	76.0	177.3	0.312	97
Platinum	170.0	60.9	276.0	0.39	97
Silicon	113.0	39.7		0.42	97
Silicon carbide: CVD	461.0			0.21	80
Silicon carbide: reaction sintered	413.0			0.24	88
Silver	82.7	30.3	103.6	0.367	97
Stainless steel: 304	193.0	77.0		0.27	97
Stainless steel: 416	215.0	83.9	166.0	0.283	97
Stainless steel: 430	200.0	80.0		0.27	97
Tantalum	185.7	62.2	196.3	0.342	97
Tungsten	411.0	160.6	311.0	0.28	97

TABLE 15 Strength and Fracture Properties for Selected Materials

Material	Yield strength MN/m ²	Microyield strength MN/m ²	Elongation (in 50 mm) %	Fracture toughness MN m ^{-3/2}	Flexural strength MN/m ²	Hardness*	Reference
Aluminum: 5086-O	115.0	40.0	22.0	>25.0	—	55 HRB	84
Aluminum: 6061-T6	276.0	160.0	15.0	<25.0	—	95 HRB	84
Beryllium: I-70-H	276.0	30.0	4.0	12.0	—	80 HRB	84, 85
Copper	195.0	12.0	42.0	—	—	10 HRB	84
Germanium	—	—	—	1.0	110.0	800 HK	84
Gold	125.0	—	30.0	—	—	30 HK	84
Invar 36	276.0	37.0	35.0	—	—	70 HRB	86
Molybdenum	600.0	—	40.0	—	—	150 HK	84
Nickel	148.0	—	47.0	—	—	109 HRB	84
Platinum	150.0	—	35.0	—	—	40 HK	84
Silicon	—	—	—	1.0	207.0	1150 HK	84
Silicon carbide: CVD	—	—	—	3.0	595.0	2500 HK	80
Silicon carbide: reaction sintered	—	—	—	2.0	290.0	2326 HK	88
Silver	130.0	—	47.0	—	—	32 HK	84
Stainless steel: 304	241.0	—	60.0	—	—	80 HRB	89
Stainless steel: 416	950.0	—	12.0	—	—	41 HRC	89
Stainless steel: 430	380.0	—	25.0	—	—	86 HRB	89
Tantalum	220.0	—	30.0	—	—	120 HK	84
Tungsten	780.0	—	2.0	—	—	350 HK	84

* HK = Knoop (kg/mm²); HRB = Rockwell B; HRC = Rockwell C.

35.4 REFERENCES

1. Center for Information and Numerical Data Analysis and Synthesis (CINDAS), Purdue Univ., 2595 Yeager Rd., W. Lafayette, IN 47906, (800) 428-7675.
2. Optical Properties of Solids and Liquids (OPTROP), Sandia National Laboratory, Div. 1824, P.O. Box 5800, Albuquerque, NM 87185, (505) 844-2109.
3. H. Wawrousek, J. H. Westbrook, and W. Grattideg (eds.), "Data Sources of Mechanical and Physical Properties of Engineering Materials," *Physik Daten/Physics Data*, No. 30-1, Fachinformationszentrum Karlsruhe, 1989.
4. M. E. Lines, "Physical Properties of Materials: Theoretical Overview," in Paul Klocck (ed.), *Handbook of Infrared Optical Materials*, Marcel Dekker, New York, 1991, pp. 1-69.
5. N. F. Mott and H. Jones, *The Theory of The Properties of Metals and Alloys*, Dover, New York, 1958, pp. 105-125.
6. A. V. Sokolov, *Optical Properties of Metals*, American Elsevier, New York, 1967.
7. F. Wooten, *Optical Properties of Solids*, Academic Press, New York, 1972.
8. M. Born and E. Wolf, *Principles of Optics*, 5th ed., Pergamon Press, London, 1975, pp. 611-627.
9. This discussion is adapted with permission from M. Bass, "Laser-Materials Interactions," in *Encyclopedia of Physical Science and Technology* 8, Academic Press, New York, 1992, pp. 415-418.
10. F. Stern in F. Seitz and D. Turnbull (eds.), *Solid State Physics*, vol. 15, Academic Press, New York, 1963, pp. 300-324.
11. L. D. Landau and E. M. Lifshitz, *Electrodynamics of Continuous Media*, Addison-Wesley, Reading, Mass., 1965, pp. 257-284.

12. H. A. Lorentz, *The Theory of Electrons*, Dover, New York, 1952.
13. P. K. L. Drude, *Theory of Optics*, Dover, New York, 1959.
14. C. S. Barrett, *Structure of Metals*, 2d ed., McGraw-Hill, New York, 1952, pp. 521–537.
15. As reported by S. F. Jacobs in “Variable Invariables—Dimensional Instability with Time and Temperature,” P. R. Yoder, Jr. (ed.), *Optomechanical Design*, Critical Reviews of Optical Science and Technology, **CR43**, SPIE Optical Engineering Press, Bellingham, Wash., 1992, p. 201.
16. C. Kittel, *Introduction to Solid State Physics*, 3d ed., Wiley, New York, 1966, pp. 111–129.
17. H. Reisman and P. S. Pawlik, *Elasticity*, Wiley, New York, 1980, pp. 128–135.
18. A. Kelly and N. H. Macmillan, *Strong Solids*, 3d ed., Clarendon Press, Oxford, 1986, pp. 382–393.
19. For more complete descriptions see, for example, *Metals Handbook*, 9th ed., **8**, Mechanical Testing, American Society for Metals, Metals Park, OH, 1985, pp. 1–15.
20. R. A. Paquin, “Selection of Materials and Processes for Metal Optics,” in *Selected Papers on Optomechanical Design*, *Proc. SPIE*, Milestone Series, **770**:27–34 (1987).
21. D. Janeczko, “Metal Mirror Review,” in R. Hartmann and W. J. Smith (eds.), *Infrared Optical Design*, Critical Reviews of Optical Science and Technology, **CR38**, SPIE Optical Engineering Press, Bellingham, Wash., 1991, pp. 258–280.
22. M. H. Krim, “Mechanical Design of Optical Systems for Space Operation,” in P. R. Yoder, Jr. (ed.), *Optomechanical Design*, Critical Reviews of Optical Science and Technology, **CR43**, SPIE Optical Engineering Press, Bellingham, Wash., 1992, pp. 3–17.
23. P. R. Yoder, Jr. *Opto-Mechanical Systems Design*, 2d ed., Marcel Dekker, New York, 1993, pp. 1–41.
24. This analysis is the same as that used by many structural engineers such as the late G. E. Seibert of Perkin-Elmer and Hughes Danbury Optical Systems.
25. S. Timoshenko and S. Woinowsky-Kreiger, *Theory of Plates and Shells*, 2d ed., McGraw-Hill, New York, 1959, pp. 51–78.
26. P. K. Mehta, “Nonsymmetric Thermal Bowing of Curved Circular Plates,” in A. E. Hatheway (ed.), *Structural Mechanics of Optical Systems II*, *Proc. SPIE*, **748** (1987).
27. E. Pearson, “Thermo-elastic Analysis of Large Optical Systems,” in P. R. Yoder, Jr. (ed.), *Optomechanical Design*, Critical Reviews of Optical Science and Technology, **CR43**, SPIE Optical Engineering Press, Bellingham, Wash., 1992, pp. 123–130.
28. C. W. Marschall and R. E. Maringer, *Dimensional Instability, an Introduction*, Pergamon, New York, 1977.
29. R. A. Paquin (ed.), “Dimensional Stability,” *Proc. SPIE* **1335** (1990).
30. R. A. Paquin and D. Vukobratovich (eds.), “Optomechanics and Dimensional Stability,” *Proc. SPIE* **1533** (1991).
31. R. A. Paquin, “Dimensional Instability of Materials; How Critical Is It in the Design of Optical Instruments?,” in P. R. Yoder (ed.), *Optomechanical Design*, Critical Reviews of Optical Science and Technology, **CR43**, SPIE Optical Engineering Press, Bellingham, Wash., 1992, pp. 160–180.
32. *op.cit.* Ref 23, pp. 271–320, 567–584.
33. E. D. Palik (ed.), *Handbook of Optical Constants of Solids*, Academic Press, Orlando, 1985.
34. E. D. Palik (ed.), *Handbook of Optical Constants of Solids II*, Academic Press, Orlando, 1991.
35. D. W. Lynch, “Mirror and Reflector Materials,” in M. J. Weber (ed.), *CRC Handbook of Laser Science and Technology*, **IV**, Optical Materials, Part 2: Properties, CRC Press, Boca Raton, Florida, 1986.
36. J. H. Weaver, C. Kafka, D. W. Lynch, and E. E. Koch (eds.), “Optical Properties of Metals,” Pts. 1 and 2, *Physik Daten/Physics Data*, Nos. 18-1 and 18-2, Fachinformationszentrum Karlsruhe, 1981.
37. D. Y. Smith, E. Shiles, and Mitio Inokuti, “The Optical Properties of Aluminum,” in E. D. Palik (ed.), *Handbook of Optical Constants of Solids*, Academic Press, Orlando, 1985, pp. 369–406.
38. E. T. Arakawa, T. A. Callcott, and Y.-C. Chang, “Beryllium,” in E. D. Palik (ed.), *Handbook of Optical Constants of Solids II*, Academic Press, Orlando, 1991, pp. 421–433.

39. D. W. Lynch and W. R. Hunter, in E. D. Palik (ed.), *Handbook of Optical Constants of Solids*, Academic Press, Orlando, 1985, pp. 275–367.
40. D. W. Lynch and W. R. Hunter, in E. D. Palik (ed.), *Handbook of Optical Constants of Solids II*, Academic Press, Orlando, 1991, pp. 341–419.
41. W. J. Choyke and E. D. Palik, “Silicon Carbide,” in E. D. Palik (ed.), *Handbook of Optical Constants of Solids*, Academic Press, Orlando, 1985, pp. 587–595.
42. J. H. Weaver, D. W. Lynch, and R. Rossi, “Optical Properties of Single-Crystal Be from 0.12 to 4.5 eV,” *Phys. Rev. B* **7**:3537–3541 (1973).
43. J. C. Stover, J. Rifkin, D. R. Cheever, K. H. Kirchner, and T. F. Schiff, “Comparison of Wavelength Scaling Data to Experiment,” in R. P. Breault (ed.), *Stray Light and Contamination in Optical Systems*, *Proc. SPIE* **967**:44–49 (1988).
44. C. L. Vernold, “Application and Verification of Wavelength Scaling for Near Specular Scatter Predictions,” in J. C. Stover (ed.), *Scatter from Optical Components*, *Proc. SPIE* **1165**:18–25 (1989).
45. J. E. Harvey, “Surface Scatter Phenomena: a Linear, Shift-invariant Process,” in J. C. Stover (ed.), *Scatter from Optical Components*, *Proc. SPIE* **1165**:87–99 (1989).
46. J. C. Stover, M. L. Bernt, D. E. McGary, and J. Rifkin, “An Investigation of Anomalous Scatter from Beryllium Mirrors,” in J. C. Stover (ed.), *Scatter from Optical Components*, *Proc. SPIE* **1165**:100–109 (1989).
47. See also papers in the “Scatter from Be Mirrors” session in J. C. Stover (ed.), *Optical Scatter: Applications, Measurement, and Theory*, *Proc. SPIE* **1530**:130–230 (1991).
48. Y. S. Touloukian and D. P. DeWitt, “Thermal Radiative Properties, Metallic Elements and Alloys,” vol. 7 in Y. S. Touloukian and C. Y. Ho (eds.), *Thermophysical Properties of Matter*, IFI/Plenum, New York, 1970.
49. Y. S. Touloukian and D. P. DeWitt, “Thermal Radiative Properties, Nonmetallic Solids,” vol. 8 in Y. S. Touloukian and C. Y. Ho (eds.), *Thermophysical Properties of Matter*, IFI/Plenum, New York, 1971.
50. J. S. Browder, S. J. Ballard, and P. Klocek in Paul Klocek (ed.), *Handbook of Infrared Optical Materials*, Marcel Dekker, New York, 1991, pp. 155–426.
51. C. M. Egert, “Optical Properties of Aluminum, Beryllium, Silicon Carbide (and more)” in *Proc. of Al, Be, and SiC Optics Technologies Seminar*, MODIL, Oak Ridge National Lab., 1993.
52. W. D. Kimura and D. H. Ford, Absorptance Measurement of Metal Mirrors at Glancing Incidence,” *Appl. Optics* **25**:3740–3750 (1986).
53. M. Bass and L. Liou, “Calorimetric Studies of Light Absorption by Diamond Turned Ag and Cu Surfaces and Analyses Including Surface Roughness Contributions,” *J. Appl. Phys.* **56**:184–189 (1984).
54. W. D. Kimura and T. T. Saito, “Glancing Incidence Measurements of Diamond Turned Copper Mirrors,” *Appl. Optics* **26**:723–728 (1987).
55. M. Bass, D. Gallant, and S. D. Allen, “The Temperature Dependence of the Optical Absorption of Metals,” in *Basic Optical Properties of Materials*, NBS SP574, U.S. Govt. Printing Office, Wash. D.C., 1980, pp. 48–50.
56. This discussion and Table 4 are based on the article: M. J. Berger and J. H. Hubbell, “Photon Attenuation Coefficients,” in D. R. Lide (editor-in-chief), *CRC Handbook of Chemistry and Physics*, 74th ed., CRC Press, Boca Raton, Fla., 1993, pp. **10**-282–**10**-286.
57. Op. cit., Ref. 49, p. 798.
58. D. R. Lide (editor-in-chief), *CRC Handbook of Chemistry and Physics*, 74th ed., CRC Press, Boca Raton, Fla., 1993, p. **10**-299.
59. Op. cit., Ref. 49, p. 792.
60. Op. cit., Ref. 58, p. **10**-298.
61. K. O. Ramanathan and S. H. Yen, “High-temperature Emissivities of Copper, Aluminum, and Silver,” *J. Opt. Soc. Am.* **67**:32–38 (1977).

62. E. A. Estalote and K. O. Ramanathan, "Low-temperature Emissivities of Copper and Aluminum," *J. Opt. Soc. Am.* **67**:39–44 (1977).
63. K. O. Ramanathan, S. H. Yen, and E. A. Estalote, Total Hemispherical Emissivities of Copper, Aluminum, and Silver," *Appl. Optics* **16**:2810–2817 (1977).
64. D. P. Verret and K. O. Ramanathan, "Total Hemispherical Emissivity of Tungsten," *J. Opt. Soc. Am.* **68**:1167–1172 (1978).
65. C. R. Roger, S. H. Yen, and K. O. Ramanathan, "Temperature Variation of Total Hemispherical Emissivity of Stainless Steel AISI 304," *J. Opt. Soc. Am.* **69**:1384–1390 (1979).
66. R. Smalley and A. J. Sievers, "The Total Hemispherical Emissivity of Copper," *J. Opt. Soc. Am.* **68**:1516–1518 (1978).
67. S. X. Cheng, P. Cebe, L. M. Hanssen, D. M. Riffe, and A. J. Sievers, "Hemispherical Emissivity of V, Nb, Ta, Mo, and W from 300 to 1000 K," *J. Opt. Soc. Am. B* **4**:351–356 (1987).
68. Op. cit. Ref. 5, p. 287.
69. Op. cit. Ref. 58, pp. **12-32–12-33**.
70. Y. S. Touloukian et al. (eds.), *Thermophysical Properties of Matter*, **1-13**, IFI/Plenum, New York, 1970–1977.
71. Y. S. Touloukian, R. K. Kirby, R. E. Taylor, and P. D. Desai, "Thermal Expansion, Metallic Elements and Alloys," vol. 12 in Y. S. Touloukian and C. Y. Ho (eds.), *Thermophysical Properties of Matter*, IFI/Plenum, New York, 1975, pp. 23 (Be), 77 (Cu), 125 (Au), 157 (Fe), 208 (Mo), 225 (Ni), 298 (Ag), 1028 (Al), 1138 (SS).
72. Y. S. Touloukian, R. K. Kirby, R. E. Taylor, and T. Y. R. Lee, "Thermal Expansion, Nonmetallic Solids," vol. 13 in Y. S. Touloukian and C. Y. Ho (eds.), *Thermophysical Properties of Matter* IFI/Plenum, New York, 1977, pp. 154 (Si), 873 (SiC).
73. C. A. Swenson, "HIP Beryllium: Thermal Expansivity from 4 to 300 K and Heat Capacity from 1 to 108 K," *J. Appl. Phys.* **70**(6):3046–3051 (Sep 1991).
74. Z. Li and C. Bradt, "Thermal Expansion of the Cubic (3C) Polytype of SiC," *J. Mater. Sci.* **21**:4366–4368 (1986).
75. C. Y. Ho, R. W. Powell, and P. E. Liley, *Thermal Conductivity of Selected Materials*, NSRDS-NBS-8, National Standard Reference Data System—National Bureau of Standards, Part 1 (1966).
76. C. Y. Ho, R. W. Powell, and P. E. Liley, *Thermal Conductivity of Selected Materials*, NSRDS-NBS-16, National Standard Reference Data System—National Bureau of Standards, part 2 (1968).
77. Y. S. Touloukian, R. W. Powell, C. Y. Ho, and P. G. Klemens, "Thermal Conductivity, Metallic Elements and Alloys," vol. 1 in Y. S. Touloukian and C. Y. Ho (eds.), *Thermophysical Properties of Matter*, IFI/Plenum, New York, 1970.
78. Y. S. Touloukian, R. W. Powell, C. Y. Ho, and P. G. Klemens, "Thermal Conductivity, Nonmetallic Solids," vol. 2 in Y. S. Touloukian and C. Y. Ho (eds.), *Thermophysical Properties of Matter*, IFI/Plenum, New York, 1970.
79. D. H. Killpatrick, private communication, Feb. 1993.
80. "CVD Silicon Carbide," Technical Bulletin #107, Morton International Advanced Materials, 1991.
81. Op. cit. Ref. 58, p. **12-133**.
82. E. A. Brandes and G. B. Brook (eds.), *Smithell's Metals Reference Book*, 7th ed., Butterworth Heinmann, Oxford, 1992, pp. **14-3–14-5**.
83. Y. S. Touloukian and E. H. Buyco, "Specific Heat, Metallic Elements and Alloys," vol. 4 in Y. S. Touloukian and C. Y. Ho (eds.), *Thermophysical Properties of Matter*, IFI/Plenum, New York, 1970.
84. *Metals Handbook*, **2**, 10th ed., Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, ASM International, Metals Park, OH, 1990, pp. 93–94 & 102–103 (Al), 265 (Cu), 704–705 (Au), 1118–1129 (Fe), 1140–1143 (Mo), 441 (Ni), 1154–1156 (Si), and 699–700 & 1156–1158 (Ag).

85. I-70-H Optical Grade Beryllium Block, Preliminary Material Spec., Brush Wellman Inc., Nov. 1990.
86. *Carpenter Invar* "36," Technical Data Sheet, Carpenter Technology Corp., Nov. 1980.
87. *Metals Handbook*, **5**, 9th ed., Surface Cleaning, Finishing, and Coating, American Society for Metals, Metals Park, OH, 1982, pp. 223–229.
88. *Engineered Materials Handbook*, **4**, Ceramics and Glasses, ASM International, Metals Park, OH, 1991, pp. 677, 806–808.
89. *Metals Handbook*, **1**, 10th ed., Properties and Selection: Irons, Steels, and High Performance Alloys, ASM International, Metals Park, OH, 1990, p. 871.
90. *Materials Engineering, Materials Selector 1993*, Dec. 1992, p. 104.
91. D. L. Hibbard, "Dimensional Stability of Electroless Nickel Coatings," in R. A. Paquin (ed.), *Dimensional Stability, Proc. SPIE* **1335**:180–185 (1990).
92. G. A. Graves, private communication, Feb. 1993.
93. Op. cit. Ref. 82, pp. **15-5–15-7**.
94. Z. Li and R. C. Bradt, "Thermal Expansion and Elastic Anisotropies of SiC as Related to Polytype Structure," in C. E. Selmer (ed.), *Proceedings of the Silicon Carbide 1987 Symposium* **2**, Amer. Ceram. Soc., Westerville, OH, 1989, pp. 313–339.
95. W. D. Rowland and J. S. White, "The Determination of the Elastic Constants of Beryllium in the Temperature Range 25 to 300°C," *J. Phys. F: Metal Phys.* **2**:231–236 (1972).
96. H. Ledbetter, private communication, Oct. 1987.
97. Op. cit., Ref. 82, pp. **15-2–15-3**.