3

Infrared radiation

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CONTENTS

INTRODUCTION

Infrared (IR) radiation is that part of the electromagnetic spectrum associated with energy levels such that thermal effects are produced when it is absorbed by matter. The IR region encompasses wavelengths from 0.78 to 1000μm, and most sources that emit ultraviolet or visible radiation will probably emit IR. This is important in considering the potential occupational hazards from the multitude of artificial radiation sources.

Over the past 50 years, human exposure to IR, formerly associated only with the glassmaking, metal smelting and foundry industries, has become more widespread and now includes exposure to welding arcs and to many specialized industrial heat sources. Consequently, increasing numbers of workers throughout the world are being exposed to broad bands of IR for long periods of time under unique conditions. The rapid growth in the development and application of IR devices has led to the awareness that meaningful biological information is lacking. While the obvious action sites or target organs (skin and eye) have been identified, questions persist concerning the mechanisms of damage in man, threshold levels for acute and chronic effects, effects on tissues and organs other than skin and eye, potential synergistic effects, and the role of heat stress.

PRODUCTION AND CHARACTERISTICS

The IR region has been subdivided by the International Commission on Illumination (CIE) into three biologically significant bands, IR-A (0.78–1.4μm), IR-B (1.4–3μm) and IR-C (3–1000μm) *(1)*.

Infrared radiation is generated by the vibration and rotation of atoms and molecules within a material whose temperature is above absolute zero. All objects emit IR as a function of their temperature. Physical matter emits IR in accordance with the black body radiation laws, but with the inclusion of a factor called the emissivity. This is a fraction of unity, except for a black body, for which it equals unity. Many IR sources emit a continuum of wavelengths (Fig. 1) and the wavelength of maximum spectral power is determined by:

$$\lambda_m = \frac{2898}{T}$$

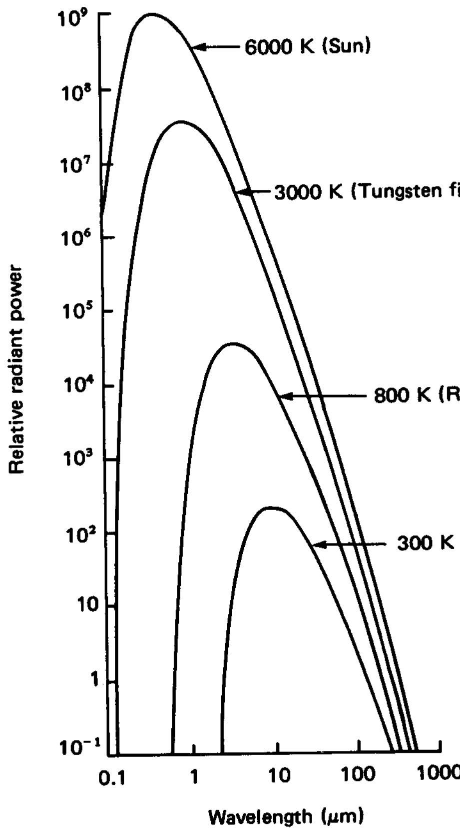
where T is the temperature (K), and λ_m is the wavelength in μm. Fig. 1 shows that, as the source temperature increases, the peak of the radiation curve moves towards shorter wavelengths while the intensity of the emitted radiation increases.

Infrared, like all types of electromagnetic radiation, can undergo a number of interactions, including reflection, absorption, transmission, refraction and diffraction. An understanding of all these interactions is required for measurement and control purposes, while the biological aspects are affected only by refraction, absorption and transmission.

SOURCES

All IR sources can be classified as either artificial or natural sources. Both types are encountered in the working environment. Artificial sources include various types of commercially manufactured incandescent, fluorescent, and high-intensity discharge lamps, flames, heaters and artificial black body sources. These are all broad-band sources and require the use of filters to limit the output to a particular wavelength band.

Fig. 1. Emission of optical radiation from black bodies at various temperatures



Numerous sources also occur in nature and cannot be directly controlled by man. The most significant natural source is the sun. The average total radiant power of the sun at the edge of the earth's atmosphere is approximately 1.35 kW/m^2, of which half is in the IR region. The sun resembles a black body source at a temperature of about 6000 K, reaching a peak near 500 nm, although the radiation extends from the near-UV through the visible radiation range well into the IR region.

Occupational exposure

A wide range of exposures under conditions involving large temperature differences occur in industry from both artificial and natural IR sources.

The occupations associated with potential IR exposures include the following:

Bakers and cooks	Glass skimmers
Blacksmiths	Heat treaters
Braziers	IR laser operators
Chemists	Iron workers
Cloth inspectors	Kiln operators
Construction workers	Lacquer dryers
Electricians	Motion picture machine operators
Farmers	Plasma torch operators
Firemen	Roofers
Foundry workers	Solderers
Furnace workers	Steam locomotive firemen
Gas mantle hardeners	Steel mill workers
Glassblowers	Stokers
Glass furnace workers	Welders

It must be emphasized that other employees may also be exposed when working conditions require them to occupy areas in close proximity to IR sources.

INSTRUMENTATION

When IR impinges on a medium, the energy absorbed produces either an increase in the temperature of the medium or a change in its structure. This change can be measured by means of secondary effects, such as the consequent variation in physical properties (volume, pressure, refractivity, conductivity, thermoelectricity, pyroelectricity, electron emission) or chemical properties.

The essential function of any IR detector is to convert the radiant energy into another form of energy that can be processed more readily. There are two types of IR detector: thermal and photonic. The first relies on an increase in temperature, which can be measured as a corresponding change in electrical resistance or other physical characteristics that provide a signal proportional to the radiant power absorbed. This type of detector responds to a broad spectrum, generally requires no cooling, has low sensitivity, and has a response time of the order of milliseconds to seconds. Thermal detectors are relatively inexpensive. The spectral response of such thermistor, bolometer, thermopile and pyroelectric detectors depends on the absorption properties of the detecting medium.

Most IR photon detectors are semiconductors in which photons interact to produce free charge carriers (e.g. photoelectric effect). These detectors respond to a relatively narrow range of wavelengths. In general, this type requires cooling and has a fast response time. The essential difference between the two types is that the photon detector determines the number of quanta per second absorbed whereas the thermal detector depends on the total power absorbed.

A special filter is often inserted in the incident beam so that only specific wavelengths are transmitted to the detector. Filters can be made by the vacuum deposition of thin films on to suitable transparent substrates. Almost any desired band width and peak wavelength can be obtained.

Various models of spectroradiometer are commercially available that will measure the spectral energy distribution of IR sources. However, most of these devices become expensive when spectral information is required beyond $1.2\mu m$. Radiometers can then be used with special filters. Additional information on IR detectors can be found in Keyes *(2)* and Wolfe & Zissis *(3)*.

When laboratory measurements and hazard evaluations are made, consideration of the effect of mechanical, electrical and thermal changes on the detector, changes in source emission levels, spectral response, aging of components, calibration, atmospheric conditions and contaminants, and reflections are of the utmost importance. In order to make accurate and reliable measurements, the investigator must be aware of the characteristics and limitations of the instrument used.

BIOLOGICAL EFFECTS

It is generally assumed that IR photons, because of their low energy levels, do not react photochemically in biological tissue. A review of the literature reveals that most research on the bioeffects of IR is on ocular effects. Far fewer studies have been concerned with skin and other effects.

Infrared radiation from all sources, including the sun and industrial IR sources, constitutes an important component of the microclimate, together with temperature, water vapour, pressure and air velocity. Traditionally, far-IR has been synonymous with radiant heat, and is usually associated with the older IR sources encountered in glassblowing, foundries, furnaces, etc. Occupational exposure to high levels of radiant heat from these sources may precipitate a thermal stress condition *(4)*. Quite apart from any specific effects of IR, therefore, there is an important effect of industrial IR on thermal stress in the workplace. It should also be appreciated that IR can be a major contributor to and cause of thermal stress; the normal precautions against such stress should therefore be borne in mind.

Ocular hazards

In general, the eye is as effective as the skin in protecting itself against IR. It has certain protective mechanisms, and these are adequate for the natural environment, since IR is usually accompanied by intense visible radiation. This evokes the blink and pupil reflexes, which limit the radiant exposure (dose) penetrating into the eye. However, with some industrial sources, IR can be present without intense light and those reflex mechanisms may not be activated.

One important feature of the eye is its focusing ability, which is, of course, not possessed by the skin. The optic media focus the incident radiation so that a significant concentration of energy is produced.

In 1962 Boettner & Wolter *(5)* carried out a comprehensive study of the transmission characteristics of the separate ocular components, using nine enucleated human eyes. Subsequent investigations into the transmission properties of the eye have been limited. In 1968 Geeraets & Berry *(6)* examined the transmittance of 28 intact human eyes in a similar manner. The results of these two studies are compared in Fig. 2, from which it can be seen that the difference between the upper and lower curves is substantial. This difference remains a problem. Sliney *(7)* has suggested that it is probably due to the measuring techniques used to obtain the total spectral transmission of the eye as opposed to the transmittance of each of the ocular media separately, and to the correction factors used for scatter.

Previous work by Fischer et al. *(8)* and Franke *(9)* led Ruth *(10)* to propose that the aqueous humour, lens and vitreous humour should be collectively termed the "inner eye" and that their absorption should be viewed compositely, as illustrated by Fig. 3. This figure, in turn, is extremely useful in that it can be used to relate the absorption of the eye to the spectral distribution of the various IR sources, as shown by Fig. 4 and 5. When Fig. 3 is used, it must be remembered that it does not take into account the absorption by the cornea; this must be considered whenever IR is evaluated relative to ocular absorption. The part of the IR spectrum that might be hazardous to the eye is confined to the near-IR region.

Effects on the eyelid

The presence of the eyelid and its associated blink reflex protects the eye from excessive radiation exposure and replenishes the liquid on the anterior surface of the eye. This dual action aids in cooling the organ by shielding it from radiant energy. Investigations into the degree of transmission of IR by the eyelid have not been reported in the literature. Since the anatomical structure of the eyelid is more or less similar to that of body skin, it is possible to estimate the transmission of IR radiation. This estimate may be important, since it is often assumed by safety personnel that protection against near-IR is provided by closure of the eyelids.

Effects on the cornea

Since exposure to high intensities of far-IR can produce corneal pain, the eyes are reflexively closed and the head averted. Sliney *(7)* has stated that the sensory nerve endings in the cornea are quite sensitive to small temperature elevations and that a temperature of 45 °C (corresponding to approximately 100 kW/m^2 absorbed in the cornea) elicits a pain response in humans within a small fraction of a second. Hence, he suggests that a thermally mediated response is initiated before the actual pain stimulus. For this reason, burn lesions are not commonly seen in the usual industrial exposures *(7)*. If a burn does occur from an intense radiation source that is limited to the corneal epithelium, the normal repair process will generally preclude any permanent

Fig. 2. Spectral transmittance of the ocular media of the human eye

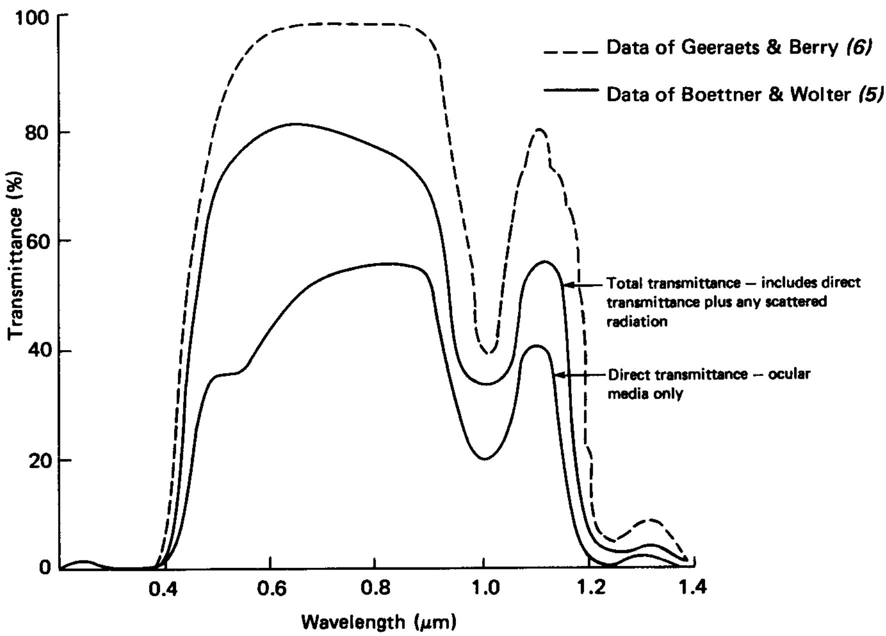
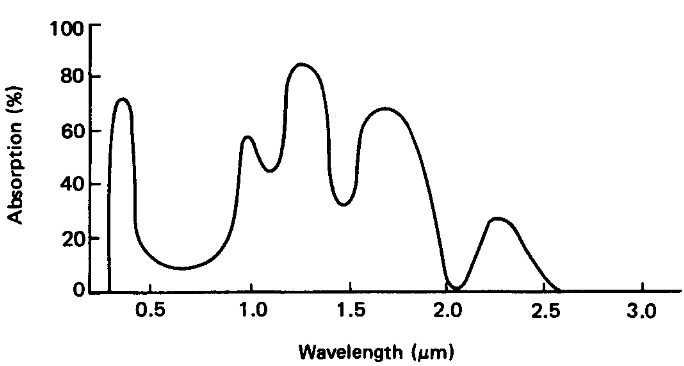
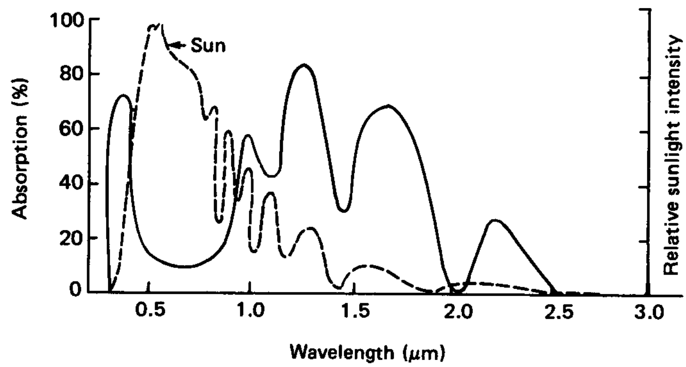


Fig. 3. Composite absorption of optical radiation by the deeper tissues of the eye (aqueous humour, lens, vitreous humour) after passage through the cornea



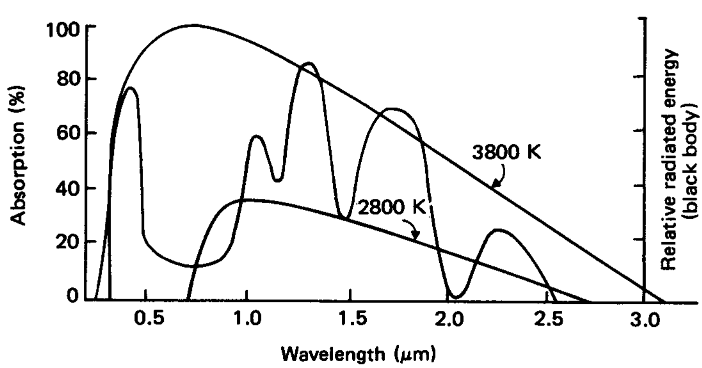
Source: Ruth *(10)*.

Fig. 4. Comparison between the energy absorption of the deeper tissues of the eye and the spectral distribution of sunlight



Source: Ruth *(10)*.

Fig. 5. Comparison between the energy absorption of the deeper tissues of the eye and black body radiators at different temperatures



Source: Ruth *(10)*.

adverse effect. However, if the underlying proteinaceous stromal layer is damaged, corneal opacities can occur *(11)*.

Effects on the aqueous humour

The aqueous humour, being located between the cornea, iris and lens, will absorb IR radiation and increase in temperature. This increased temperature could contribute to the temperature rise of the ocular components, most notably the lens.

Effects on the iris

The effects of IR on the iris have been summarized by Duke-Elder *(12)*. In his view, the iris is very susceptible to IR because of heavy absorption by its pigment. Moderate doses result in constriction of the pupil (hyperaemia miosis) and the formation of an aqueous flare.

Effects on the lens

The lens of the eye is optically clear up to early adulthood. It is a unique body tissue, being both avascular and lacking innervation. Furthermore, the lens is a growing and actively metabolizing tissue throughout life. Probably as a result of disturbances in this continuing metabolic activity, the optical clarity can become progressively reduced as a result of a number of factors, including metabolic disorders, ocular inflammation, blunt trauma and different types of electromagnetic radiation. This reduction in optical clarity is caused by different types of opacity, generally referred to as cataract, which do not, however, necessarily result in lowered visual acuity. Such opacities should be defined as dark spots visible against the light reflected from the fundus of the eye, e.g. with an ophthalmoscope but not with a slit lamp. Cataracts interfering with vision to such an extent that surgical intervention is necessary occur mostly in those over 65 years of age. The frequency in a European population of that age group is up to 5 per 1000 per year.

In the literature prior to 1920, a number of reports suggested that glassblowers and furnace workers had a higher incidence of cataracts than the non-exposed population *(8,13,14)*. Modern epidemiological studies have confirmed these results among glassblowers *(15)*. The beginning of the twentieth century brought intense interest and debate as to the etiology of this kind of cataract *(16–20)*. These investigations do not show any specific type of cataract, true capsule exfoliation being the only specific sign. On the basis of animal experimentation and theoretical analyses, two theories have been advanced to account for the formation of what are now recognized as IR cataracts *(16,17,20,21)*. These theories suggest that cataract formation is due to direct absorption of IR in the lens, or is secondary to heating of the aqueous humour and iris by absorption of IR. Data from Pitts & Cullen *(22)* and Wolbarsht *(23)* indicate a photochemical type of lens damage with a constant dose relationship based on reciprocity between time and power. This is for acute *in vivo* exposures only, spanning hours, days or even weeks. How this relates to low-level chronic exposures over a period of years in industrial situations remains to be seen. Wolbarsht *(23)* has also shown that acute high-level exposures direct to the iris only can produce cataracts in the areas of the lens behind the exposed iris, presumably through heat transfer. It should be pointed out, however, that many other factors such as heredity, race, drug use, disease, and immunological and nutritional factors can predispose towards cataractogenesis, or be synergistic among themselves or with other factors. These synergistic effects are supported somewhat by the data, as all the epidemiological studies show an increased number of cataracts in older age groups.

Effects on the retina

Difficulties arise concerning the effects of IR on the retina. Since absorption by the retina of the shortest IR wavelengths differs only slightly from that of visible radiation, it is difficult to see that there are any specific IR effects apart from the thermal effects usually attributed to visible radiation.

Experimental threshold exposures

Another area of uncertainty has been the determination of the minimum energy level (threshold) at which tissue damage occurs. Past investigations have sought to establish the lowest dose level (acute exposure) at which the stated damage criterion occurs. Such studies have been made on the cornea, iris, lens and retina. The more significant experimental broad-band threshold studies for the above ocular structures are indicated in the work of Jacobson et al. *(24)*.

It must be remembered, in addition, that laboratory threshold experimentation has usually involved acute exposure. This poses a problem for the determination of the radiation energy level that causes cataracts in industry, since their development involves long latent periods and chronic exposure. Furthermore, it is debatable whether experimentally determined damage thresholds can be correlated with those occurring in industry. This is especially difficult because of the lack of extensive research in industrial situations to establish the energy level at which cataracts are produced. Fewer problems occur in determining the damage thresholds for the cornea and retina, since experimental conditions coincide fairly closely with those of the occupational acute exposures required to cause damage.

Industrial exposures

Typical data from the literature for worker exposure levels are given in Table 1. While damage thresholds determined experimentally are based on exposure to the lowest single dose causing the damage, determinations of industrial damage thresholds should be based on many exposures to the lowest dose over many years that will produce such damage. In the past, there has been a failure in industrial research to take into account irradiance and exposure duration. Nevertheless, some investigators have attempted to make some sort of threshold estimation under industrial exposure conditions for the cornea, lens and retina. The occurrence of lens damage in the form of "glassblowers' cataract" following exposure to IR has long been recognized. Unfortunately, the earlier studies do not include any data on the absolute temperature of the source, the wavelength region, or the irradiance level.

A more recent study *(25)* of glassblowers exposed for a number of years to an irradiance level of approximately 1.4 kW/m^2 has shown no evidence of cataract formation. In addition, Keatings et al. *(26)* were unable to find any posterior cortical changes in the lens of iron-rolling millworkers exposed to irradiance levels of 0.8–4.2 kW/m^2. However, they did report a higher incidence of posterior capsular opacities originating in the capsular plane and extending to the cortex. This differs from what has been defined as cataract.

In a recent large-scale epidemiological investigation, Wallace et al. *(27)* studied 1000 workers in a large steel mill, 900 of whom were exposed to IR; exposure was classified as high, intermediate, low and no-risk (scored as 3, 2, 1 and 0, respectively). Different job classifications were scored according to relative exposure. The exposure index was multiplied by the number of years of risk to arrive at a total exposure estimate in "exposure-years". Wallace et al. defined cataract type III (of which no cases were found) as that producing gross disturbance of vision and requiring surgery. Type II cataracts were defined as posterior polar subcapsular saucer-shaped cataracts capable of producing some interference with visual acuity. Type I cataracts were not true cataracts but small inhomogeneities which did not interfere with visual acuity. Fig. 6, which is based on the data of Wallace et al., shows the percentage of people with bilatral cortical cataract of type I as a function of age in this population.

When Wallace et al. *(27)* compared the percentage of type I cataracts with the number of "exposure-years" for the whole population, they found that there was a slight increase in such type I cataracts with increasing exposure, as shown in Fig. 7. While it appears as though the incidence of IR cataracts caused by the older industrial sources, e.g. in the glass industry, has decreased over the years, recent investigations of other industrial sources (both old and new) give rise to some concern. In 1971, Hager et al. *(29)* found several cases of "fire" cataract among locomotive firemen at temperatures of 1300–1500 K and wavelengths in the range 0.8–1.4 μm. Irradiance levels were found to be 0.5–1.8 kW/m^2. New sources of worker exposure to IR include welding arcs and industrial "heating" lamps. A comprehensive study by Hubner et al. *(28)* of different welding processes revealed irradiance levels as high as 34 W/m^2 in the IR. Despite these high radiance levels, however, there have been very few reported cataracts from welding operations. Another source of worker exposure is provided by the IR lamps used in paint and enamel drying operations. In 1975, Ruth *(10)* reported on what were designated as eye risk levels of 9–500 W/m^2 for various types of heating lamp for which most of the spectral distribution was in the near-IR region. To date, the literature indicates little or no incidence of cataracts from exposure to these newer industrial sources. It may be that the lack of information on the effects of welding and heating lamps is due to the comparative paucity of investigations into these questions and also to the possibility that IR cataractogenesis may have a long latent period.

As a result of worker exposure to certain industrial sources (welding arcs, arc lamps, xenon arcs, etc.) retinal injury in the form of burns and/or other lesions may occur because of the focusing effect of the cornea and the lens on the retina. These injuries are most probably due to radiant energy in the visible region of the optical radiation spectrum. Moreover, the size of the image on the retina and the absorbed irradiance are the predominant factors, as discussed by Sliney *(7)*.

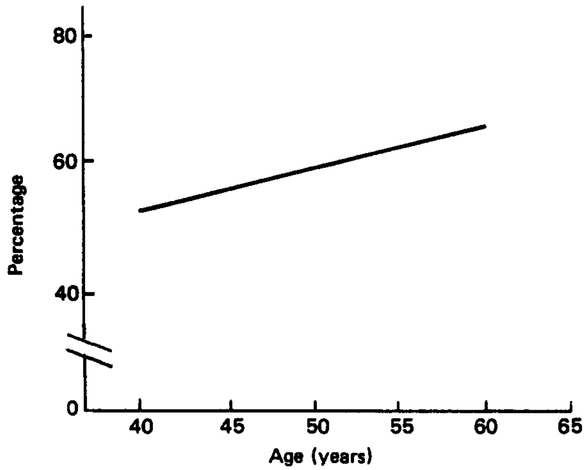
Sensintaffar et al. *(30)* have reported a case of conjunctivitis and decreased lachrymation associated with exposure to near-IR from an IR heating device. The effective wavelength of the radiation from the heating device was 980 nm. The total irradiance from the device at the eye position was

Table 1. Data for ocular infrared radiation hazards

Study and source	Subject and exposure time	Effect	Wavelength (nm) (black body radiator temperature)	Radiant exposure (kJ/m^2)	Irradiance level (kW/m^2)
Goldmann, 1933 *(21)*: electric furnace	Man:	Increase in temperature of aqueous humour (above 36 °C) of:	760–72 500 (1733 K with peak at 1 500)		
	30 seconds	3 °C		42	1.4
	231 seconds	9 °C		322	1.4
	Rabbit:				
	90 seconds	11 °C temperature increase behind pupil		408	4.53
	30 seconds	1.5 °C temperature increase behind lens		272	9.06
Dunn, 1950 *(25)*: glass furnace	Glass workers, 20 years	None reported	1 500 (peak) (2000 K)	—	1.4
Keatings et al., 1955 *(26)*	Iron-rolling mill workers, 17 years	Lens posterior capsular opacities	—	—	0.84–4.18
Hubner et al., 1970 *(28)*: welding arc	Welders	Not investigated	400–2 000	—	to 0.034

Hager et al., 1971 *(29)*: glass and locomotive furnaces	Glass workers (G) and locomotive firemen (F), 10 years:	Cataract	800–1 400		
	G		(1300 K)	3 050	0.50
	F		(1300 K)	3 220	0.22
	G		(1400 K)	5 980	0.98
	F		(1400 K)	6 170	0.43
	G		(1500 K)	10 740	1.75
	F		(1500 K)	11 160	0.76
Wallace et al., 1971 *(27)*	Steel workers	Increase in opacities	—	—	—
Ruth, 1973 *(10)*: molten brass	Man, 15 minutes	Increase in temperature of aqueous humour and lens of:	760–2 500 (1 250 K with peak at 1 800)		
		3.9 °C		900	1.00
		6.4 °C		1 490	1.65
		8.5 °C		1 980	2.20
		All cases had lens opacities			
Lydahl, 1984 *(15)*: IR heating lamps, automobile paint and enamel dryers		Not investigated	400–3 200	—	0.009–0.5

Fig. 6. Percentage of people with bilateral cortical cataract (type I) as a function of age



Source: Wallace et al. *(27)*.

650 W/m^2 and the radiance between 400 and 1400 nm was 30 kW/(m^2$\cdot$ sr). Other reports *(31)* mention conjunctivitis and decreased lachrymation. It is clear that exposure to IR will increase evaporation of the tear film and therefore aggravate pre-existing deficiencies in accessory lachrymation ("dry-eye").

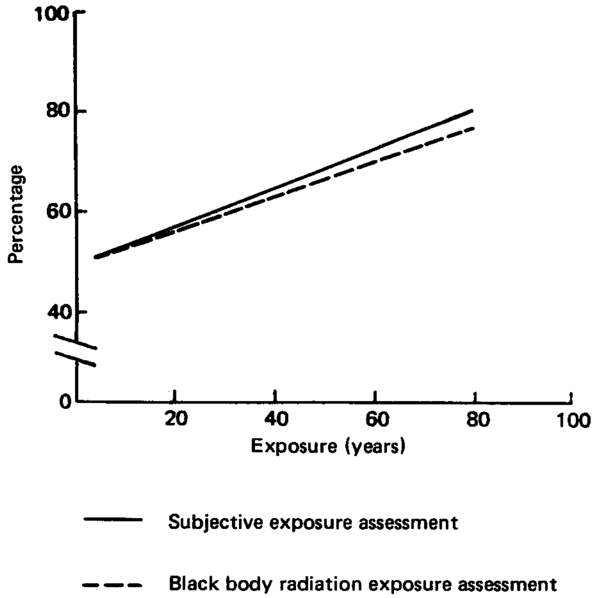
In recent years, a great deal of experimental research has been carried out in an attempt to establish the threshold for retinal damage; this has been summarized by Clark *(32)* and Sliney *(7)*. Unfortunately, laser sources were used in most of these studies and the results are thus appropriate only to laser hazards (see Chapter 2).

Skin hazards

To understand the effects of IR on skin, it is necessary to be familiar not only with the optical and thermal properties of skin but also with other related characteristics. Because of its high water content (60–70%) skin may be regarded as having absorption properties similar to those of water.

The skin is one of the largest organs of the body. In an adult "standard" man it comprises 4% of the body weight with a surface area of 1.6–2.0 m^2 *(33)*. It is generally 1–2 mm thick, although some areas may be as thick as 6 mm *(34)*. The skin is composed of an outer and thinner layer (epidermis) and an inner and thicker layer (dermis). The epidermis is an epithelium and varies from 0.07 to 0.12 mm in thickness over most of the body, except for

Fig. 7. Percentage of people with bilateral cortical cataract (type I) as a function of exposure assessment



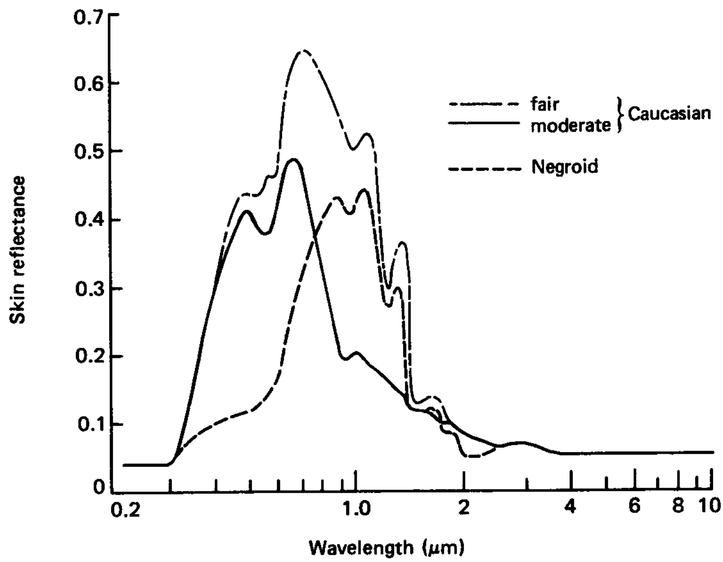
Source: Wallace et al. *(27)*.

the palms and soles where it is thicker. The dermis may be collectively viewed as consisting of loose and dense connective tissue (collagenous bundles) containing hair and follicles, sebaceous and sweat glands, diffuse blood vessels, nerve endings and muscle. The thickness of the dermis is approximately 1–2 mm; it is thinner on the eyelids and much thicker on the palms and soles. (See Chapter 1, Fig. 9.)

Physiologically, skin functions are complex and diverse, and include functions as different as protection, excretion and sensation. Skin also plays an important role in maintaining fluid and electrolyte balance and body temperature. It is apparent that skin cannot be considered merely as "water", but rather is an extremely inhomogeneous tissue. This is an important factor in the determination of its optical and thermal properties, especially in the near-IR region.

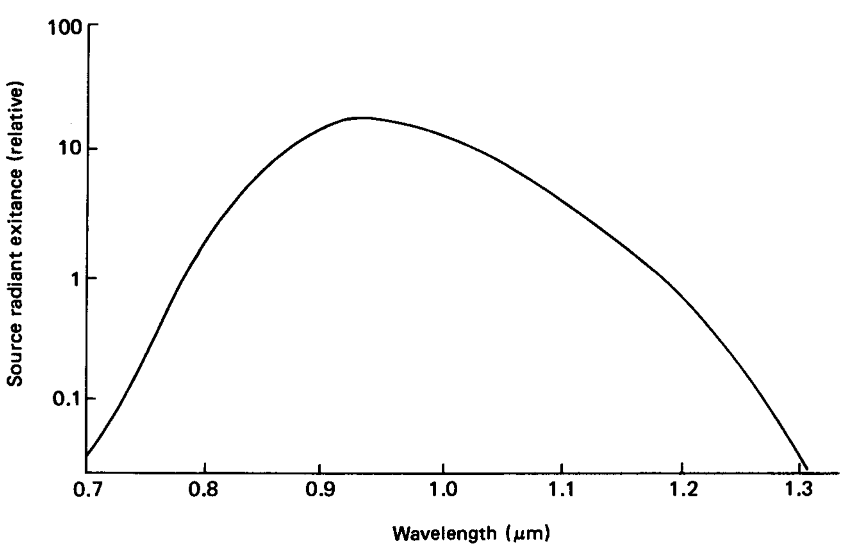
The reflection and absorption characteristics must be considered in evaluating skin bioeffects. The reflection curves for human skin, as determined by Jacques et al. *(35)*, are shown in Fig. 8. Beyond 2μm the reflectivity is variable and depends largely on skin pigmentation and blood flow. The maximum reflectivity occurs between 0.7 and 1.2μm, which is comparable to the wavelength of maximum intensity for some IR heating devices (Fig. 9). The spectral reflectance curve of skin is close in shape to the spectral

Fig. 8. Human skin reflectance as a function of wavelength for different pigmentation



Source: Jacques et al. *(35)*.

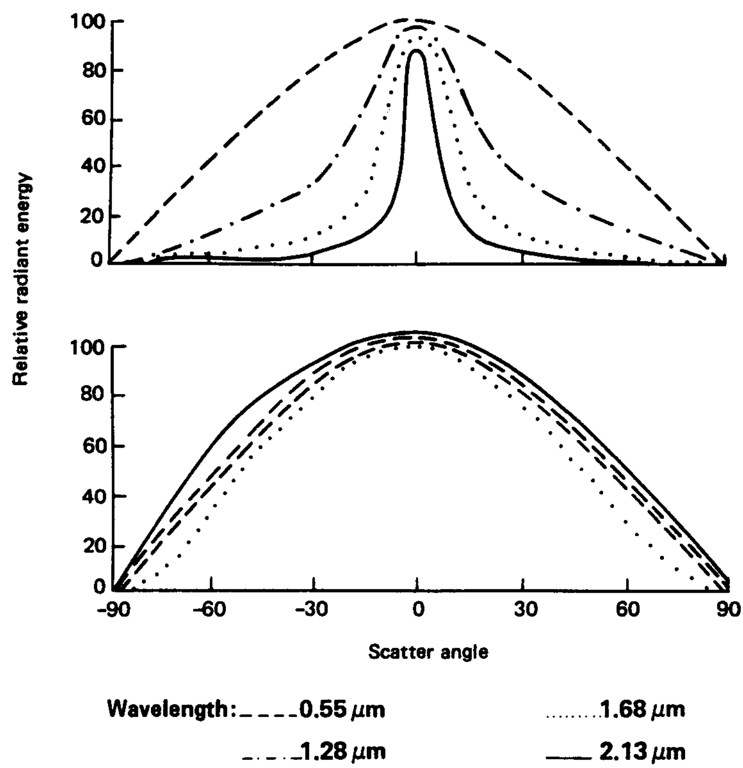
Fig. 9. Emission curve for high-temperature infrared heater



irradiance curve for the sun (Chapter 1, Fig. 4). This explains why the skin can reflect solar radiation effectively and yet have substantial thermal emissivity in the far-IR so that body heat can be gained or lost by thermal radiation. Furthermore, Fig. 8 shows that exposed skin surfaces in the darkly pigmented individual may be heated more by solar radiation than those of the fair-skinned individual. This difference can, however, be minimized by clothing. Beyond 1.5μm skin pigmentation does not affect reflectivity.

The second important optical factor is the depth of penetration of IR into skin. As previously mentioned, the skin is a dynamic and nonhomogeneous tissue and will scatter transmitted radiation. This effect, shown by Hardy et al. *(36)*, is illustrated in Fig. 10. The curves given

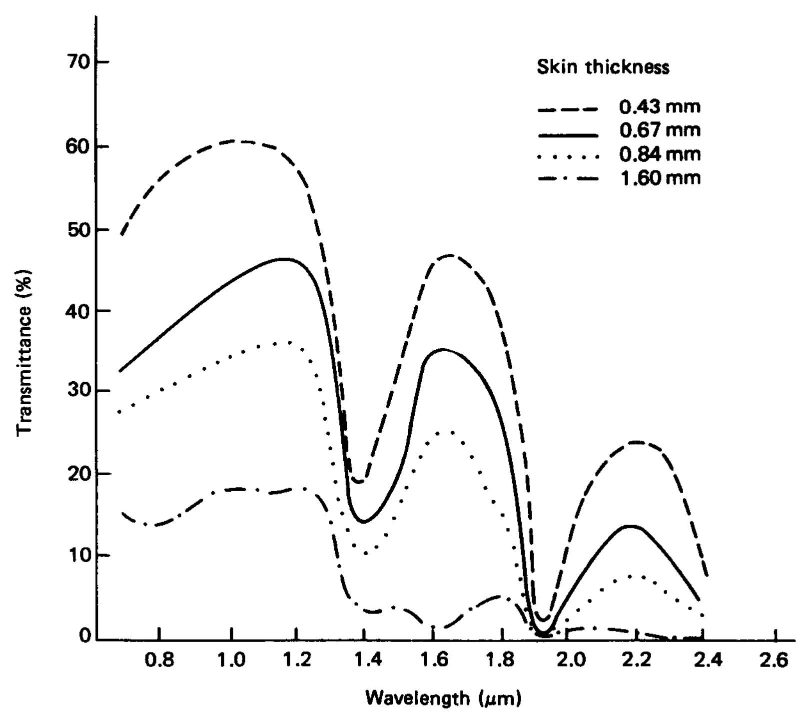
Fig. 10. Scattering of transmitted energy under normal incident radiation with skin samples 0.43 mm thick (top) and 2.1 mm thick



Source: Hardy, et al. *(36)*.

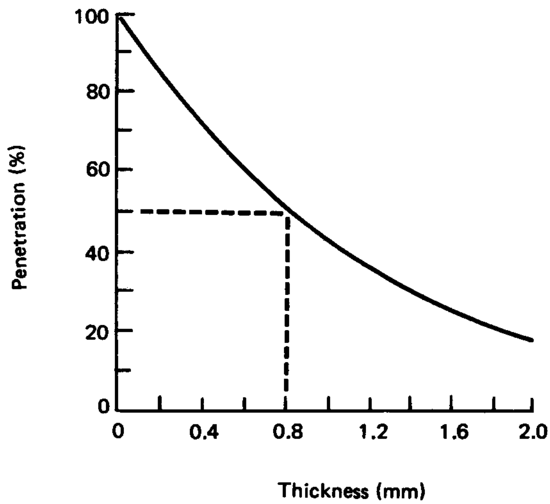
in Fig. 10 show the transmission for the indicated wavelengths through two samples of excised skin. As Hardy points out, if the skin were perfectly diffuse, the transmitted radiation would follow Lambert's cosine law for all wavelengths. However, it is apparent from Fig. 10, firstly that short wavelengths are scattered more than long wavelengths, and secondly that the differences due to wavelength are minimized as skin thickness increases. It is clear, therefore, that IR absorption by the skin depends not only on skin pigmentation, blood pigments and other substances that absorb specific spectral bands, but also on the degree of scattering due to the microstructures of the skin. The transmission spectrum of the skin, together with the absorption bands due to water, which is the principal IR absorber in biological tissues, are shown in Fig. 11. Although the skin is essentially opaque to wavelengths beyond 2μm, shorter wavelengths can penetrate a considerable distance below the skin surface. The maximum penetration is at a wavelength of approximately 1.2μm. Fig. 12 shows the average penetration of IR below the skin surface for both Negroid and Caucasian skin *(36)* and indicates that at least 50% of the radiation penetrates to a depth of about 0.8 mm, thus interacting with nerve endings and capillaries.

Fig. 11. Spectral transmittance of excised white human breast skin



Source: Hardy et al. *(36)*.

Fig. 12. Average percentage penetration into Caucasian and Negroid skin of near-infrared radiation (1.23 μm)



Source: Hardy et al. *(36)*.

In view of the foregoing, it appears that there are two spectral regions with different modes of action: the first is essentially confined to the near-IR with a peak at approximately 1.2 μm; the second is wavelength-independent beyond 2 μm and causes surface heating. The near-IR region is potentially more hazardous than the middle- and far-IR because of the ability to penetrate significantly into the dermal area of the skin and thus to cause greater injury. Caution should therefore be exercised in using high-intensity sources of near-IR. Because of the strong absorption of middle- and far-IR by skin, occupational exposure to high levels of radiant energy (e.g. from furnaces) may be hazardous if the heat load exceeds the capacity of the body's thermoregulatory mechanism.

The manifestation of excessive IR exposure and its effects on skin seem to be confined to the near-IR. The most obvious effects include burns, increased vasodilation of the arteriolar system, and a gradual increase in pigmentation. This increase may be due to chronic exposure, since it seems to persist for an extensive period of time. Moreover, the development of an "erythematous-like" appearance among certain occupational groups (glass workers, furnacemen, etc.) exposed to high intensities of IR may also be viewed as a chronic effect. Chronic exposure to low levels of IR has been reported to cause blepharitis *(37)*. Matelsky *(38)* reported that exposure of the eyelids to intense IR produced erythema, oedema and blistering similar to that from an ordinary burn. Tissue damage (denaturation) has been found to occur at skin temperatures of approximately 46–47 °C *(39)*. However, pain is induced at a mean skin temperature of 44.5 ± 1.3 °C *(40,41)*. Physiologically, the pain threshold is dependent on skin temperature alone and not on the rate of heating of the skin, nor on the rate of change of an internal thermal gradient.

Skin temperatures lower than 44–45 °C do not generally produce a burn *(37)*. Above this value, reddening of the skin (erythema) can occur. As the skin temperature is raised above the pain threshold, increasing intensities of pain are perceived. Raising the skin temperature to 70 °C will result in destruction of most enzyme systems. It is important to note that pain is primarily related to skin temperature alone, whereas tissue damage is dependent both on skin temperature and on the duration of the hyperthermic episode.

In the evaluation of industrial IR hazards, a number of variables must be considered, such as individual variability, environmental conditions, body surface area exposed, protective clothing and state of health. Typical industrial sources do not have sufficient radiant intensities to cause injury because of normal avoidance responses (pain). Those thermal burns that do occur in industry usually result from contact with hot objects rather than exposure to IR sources.

Other hazards

A number of reports have described specific effects of IR on man, animals and isolated cells. Some of these, however, can be explained as the result of associated environmental effects rather than of heat. Although in some cases these reports may not have been confirmed by independent workers, they are included here for completeness.

Studies by Krivobok *(42)* indicated that IR produced a limited level of organ and tissue degradation in areas remote from the eye. Changes such as vascular congestion in the spleen and kidneys were reported. A long-term decrease in the immunological reactivity (i.e. phagocyte count, phagocytic index and bactericidal properties of the skin) of foundry workers exposed to high-intensity IR at an irradiance of 0.2–0.7 kW/m^2 was reported by Zelencova *(43,44)*. However, these reports also indicated that, at lower intensity levels, IR stimulated the body's protective mechanisms.

Lehmann et al. *(45)* demonstrated that, when IR was applied to the ulnar nerve area at the elbow, an analgesic effect was found distally in the area supplied by this nerve. Lehmann states that this finding is in agreement with previous experimental evidence that nerve conduction can be temporarily blocked by application of IR.

A study by Borneff & Blumlein *(46)* indicated that the upper respiratory passages of iron foundry workers were damaged by exposure to intensive near-IR over many years. Chronic rhinitis (in most instances with polyps and hyperplasia of the mucous membranes), chronic laryngitis and sinus troubles were prevalent in almost 50% of the exposed workers. These disorders were claimed to be 5–10 times more frequent in the exposed group than in the control group.

Another organ located near the body surface and very sensitive to thermal insult is the testicle. The principal effect encountered from thermal insult in this organ is a temporary reduction in the sperm count. While little information is available on the relationship between IR and decreased sperm count, this interaction potential should not be completely overlooked. Episodes of apnoea (a transient suspension of respiration) have been reported in infants exposed to radiant warmers *(47)*. The relationship between changes in irradiance levels and the incidence of apnoea is not known.

Arima & Fonkalsrud *(48)* studied the incidence of post-operative intestinal adhesions and microscopic intestinal injury resulting from the use of overhead IR heating lamps. The safety of such lamps has been questioned because of their widespread use in neonatal operating rooms. A total of 45 rabbits were used in the study, the intestines being exposed to IR for two hours or longer. At a distance of 45.8 cm from the source, 87% of the rabbits developed adhesions; at a distance of 91.6 cm, 37% developed adhesions. The incidence and severity of the adhesions correlated directly with the period of intestinal exposure to IR. No histological evidence of intestinal injury was apparent in intestines exposed to the radiation under the conditions of this study. Although the results obtained may not be definitely applicable to the human infant, they do suggest that precautions should be taken when viscera are exposed to such external IR sources.

The genetic effects of IR have been studied by Gordon & Surrey *(49)* using rat liver mitochondria. They postulate that the sites of ATP production were the primary target of IR, the occurrence of chromosome aberrations being a secondary phenomenon. In 1971, Gordon et al. *(50)* again demonstrated such effects using pig kidney cells irradiated with near-IR. Significant increases in chromatid breaks and exchanges were observed. Summarizing the work of other investigators in the field, Krell et al. *(51)* stated that near-IR acts to inhibit repair of spontaneous aberrations by interfering with chromosome hydrogen bonding by base pairing, either in the double-stranded DNA or in the complex structure of histone, enzymes and DNA or in both. The energy required to dissociate hydrogen bonds is 0.06 eV on average, which is within the capability of IR. If the radiation can cause such effects, mutagenesis can perhaps also occur. Inheritable changes due to IR, however, have not been demonstrated to date.

The significant number of reports in the literature of genetic effects following exposure of insects, plants and animal cells to IR must give rise to some concern that the radiation may be capable of affecting human cells.

As far as carcinogenesis is concerned, very little direct or indirect evidence exists at present to show that IR may be a causative agent *(52)*.

EXISTING STANDARDS

There are at present no standards for exposure of the skin or eye to IR non-laser "extended" sources. The only one available is standard Z-136.1 of the American National Standards Institute *(53)* which was developed for laser sources. It may be used for evaluating other sources, but it should be noted that the use of laser standards for setting "broad-band" IR industrial standards can be regarded only as a temporary measure. Since lasers operate with very narrow wavelength bands, comparison with the broad-band industrial sources is difficult. In addition, the lack of industrial exposure data makes it extremely difficult to determine conclusively the occupational thresholds for ocular damage. Fairly large safety margins are therefore used to compensate for this uncertainty.

Safe IR exposure levels in the eye have been suggested by a number of investigators. In 1968, Matelsky *(38)* stated that acute ocular damage from incandescent "hot" bodies can occur with radiant exposure of 40–80 kJ/m^2 incident on the cornea; however, this single radiant exposure concept ignores exposure duration. Based on the threshold data previously discussed, he recommended that a maximum permissible radiant energy of 4–8 kJ/m^2 would probably prevent the occurrence of chronic effects on the intraocular tissues. Sliney *(7)* has used experimental laser injury data to recommend that a safe level for chronic exposure to industrial IR sources should be limited to an average ocular irradiance of approximately 0.1 kW/m^2 with allowable incidental exposure for several minutes up to 1 kW/m^2.

The International Organization for Standardization (ISO) has proposed an IR exposure standard and the American Conference of Governmental Industrial Hygienists (ACGIH) has issued a notice of intent to establish a threshold limit value (TLV) for near-IR from broad-band sources *(54)*. The TLV for occupational exposure to IR for the eye applies to exposure in any eight-hour working day and requires a knowledge of the spectral radiance (L_λ) and total irradiance of the source as measured at the position(s) of the eye of the worker. The proposed TLV are:

1. To protect against retinal thermal injury, the spectral radiance of a lamp source weighted against the burn hazard function (Table 2) should not exceed:

$$\sum_{\lambda=400}^{1400} L_\lambda R_\lambda \Delta\lambda \leqq \frac{1}{\alpha t^{1/2}}$$

where L_λ is the spectral radiance measured in W/(m$^2\cdot$sr), R_λ is the dimensionless burn hazard function that changes with each increment of the band $\Delta\lambda$, t is the viewing duration in seconds, and α is the subtense of the source measured in radians. $\alpha = l/r$, where l is the length of the lamp and r is the viewing distance, both measured in metres.

2. To avoid possible delayed effects on the lens of the eye (cataractogenesis) the IR radiation ($\lambda > 780$ nm) should be limited to 100 W/m^2. For an IR heat lamp or any near-IR source where a strong visual stimulus is absent, the near-IR (780–1400 nm) radiance as viewed by the eye over an extended period should be limited to:

$$\sum_{\lambda=780}^{1400} L_\lambda \Delta\lambda = \frac{0.6}{\alpha}$$

This limit is based on a pupil diameter of 7 mm.

It should be noted that both formulae are empirical and are not dimensionally correct. (To make them dimensionally correct, it would be necessary to

Table 2. Spectral weighting function for assessing retinal hazards from broad-band optical sources

Wavelength, λ (nm)	Burn hazard function, R_λ
400	1.0
405	2.0
410	4.0
415	8.0
420	9.0
425	9.5
430	9.8
435	10.0
440	10.0
445	9.7
450	9.4
455	9.0
460	8.0
465	7.0
470	6.2
475	5.5
480	4.5
485	4.0
490	2.2
495	1.6
500– 600	1.0
600– 700	1.0
700–1050	$10^{(700-\lambda)/505}$
1050–1400	0.2

Source: ACGIH *(54)*.

insert a meaningless dimensional correction factor k in the right-hand numerator in each formula. In all cases, the numerical value of k will be unity.)

CONTROL MEASURES

The major areas of concern regarding occupational exposure to IR, especially in the near-IR region, are protection of the skin and eyes. This can best be accomplished by engineering means, i.e. by controlling the emission from the source. At distances comparable with the largest source dimension, the irradiance is inversely proportional to the distance from the source. With increasing distance there is a gradual change to the well known inverse square law. In this respect IR behaves in a similar fashion to all other radiation. Measures for controlling emissions have not been extremely sophisticated, yet their effectiveness, if used properly, can be very good. The high surface temperature of hot equipment can be reduced by insulation. However, this method is usually practicable only for equipment with low surface temperatures because of the thickness of the insulating material needed if it is to be effective. Engineering control measures involve the placing of an object between the source and the receiver to reflect and reduce the transmission of IR. Aluminium, because of its high reflectance, is widely used in the form of foil, sheeting or corrugated siding (sheets) as screening for the control of IR from furnaces and other IR sources in the industrial environment. The thickness of the material is not important and only the reflectance needs to be considered. If used, such a surface must be well polished and kept clean for maximum effectiveness. Other types of shield, such as glass, heat-exchanging aluminium cloth and absorbing plastic, use absorptive material to accept IR and give up heat by convection. Several shields may be used, cooled either by special ventilation or by water circulation. For convenience, such shields should probably be portable so that they can be removed in case of emergency repair or maintenance of machinery. Enclosures, e.g. baffled lamp housings, are employed to control the potential hazards from laboratory arc sources, such as spectroscopic equipment and optical calibration sources. Reflective booths and curtains have been used in welding operations to protect passers-by. Although the majority of welding curtains have been fairly effective in reducing the transmission of ultraviolet and visible radiation, recent investigations have shown that some transparent curtains transmit up to 80% of the IR *(55)*. The spectral transmission properties of such curtains should be examined before they are used for protection against IR exposure. In paint and enamel drying operations, where an intense array of heating lamps may be used, such enclosures may be provided with glass or metal doors and an interlock system. In addition, it is advisable to post warning signs.

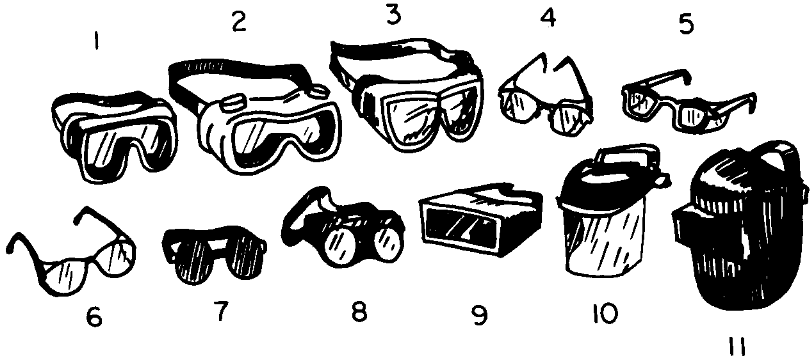
Pre-employment medical examinations, with particular attention to eye and skin lesions, can be an important means of preventing the assignment of susceptible workers to work associated with intense IR.

If engineering controls are absent or inadequate an alternative method, but one which is probably the least effective, is the use of personal protective devices. For protection of the skin, lightweight cotton clothing is recommended. Additional protection can be afforded by the wearing of reflective aluminized aprons, coats or gloves. For excessive radiant heat loads, reflective suits may be necessary.

As regards protection of the eye, the filters used in welding goggles, and in furnace inspection goggles for glass, steel and foundry workers, were originally developed empirically. However, optical transmission characteristics for the near-IR region are specified by various standards *(56–58)*.

The various types of goggles and spectacles fitted with suitable filters are shown in Fig. 13. In a recent study, Campbell *(59)* found that only one of 55 shade models of welding filter plates failed to meet the ANSI specifications for IR transmittance up to 2.6μm. However, in absorbing the incident radiation, filter plates may be heated to such an extent that corneal heating with accompanying pain occurs, prompting the worker to remove

Fig. 13. Recommended eye protectors



Note. 1. Goggles, flexible fitting, regular ventilation. 2. Goggles, flexible fitting, hooded ventilation. 3. Goggles, cushioned fitting, rigid body. 4. Spectacles, metal frame, with sideshields. 5. Spectacles, plastic frame, with sideshields. 6. Spectacles, metal-plastic frame, with sideshields. 7. Welding goggles, eyecup type, tinted lenses. 8. Welding goggles, coverspec type, tinted lenses. 9. Welding goggles, coverspec type, tinted plate lens. 10. Face shield (available with plastic or mesh window). 11. Welding helmet.

the goggles or spectacles. Reflective metal coatings deposited on the front surface of the absorbing filter should not aggravate this situation if the incident energy is really reflected. Fortunately, electric welding arcs emit relatively little radiation in the far-IR region. Hubner et al. *(28)* recommended that filter specifications for the degree of transmittance in the near-IR region should be made more severe; they could be less stringent for the middle- and far-IR regions (except for high-temperature welding). As far as furnace inspection goggles are concerned, however, they recommended that the eye protection specifications should be made considerably more stringent under all circumstances. In foundries where cobalt-blue glass is used when estimating the temperature of the melting metal, it is advisable to use heat-absorbing glasses as well.

An important factor in the design of eye protection devices is comfort. No matter how effective the filter may be, if goggles are not reasonably comfortable they will not be worn. In reality, a compromise must be reached between comfort and safety. However, in the future, safety may have to be emphasized more strongly because of the rapid increase in new, near-IR radiation emitting sources, plus the rise in the number of potentially exposed workers.

PROBLEMS AND RECOMMENDATIONS

In general, the data presented in the early literature, which comprises the greater part of that available on the bioeffects of IR radiation, are of doubtful value due to lack of information on instrument sensitivity and source spectrum. There is therefore a need for further research to determine threshold limits, irradiance values, the effect of time, and the epidemiology of effects due to IR radiation exposure.

Skin hazards seem to be confined essentially to radiation of wavelength 1.1–1.2μm. Possibly the near-IR region is potentially more hazardous than the middle- and far-IR regions because of the ability to penetrate well into the dermis. Caution should therefore be exercised in situations where individuals may be exposed to high-intensity occupational sources, i.e. the newer sources, which emit in the near-IR region. The reported effects include acute skin burn, vasodilation of capillary beds, and an increased, long-lasting pigmentation. Extensive research on the effects of low-intensity chronic exposure is lacking. The research reported, however, has revealed only an erythematous-like appearance and some eyelid inflammation in certain occupations. It is self-evident that the skin has an inherent natural protective mechanism that enables it to "sense" the warming effect of IR before the skin temperature reaches the pain or burn threshold. In addition, the body has a fairly effective heat dissipation mechanism for protection against the potentially damaging effects of IR. Some injury, however, may occur in the future from excessive exposure to high-intensity near-IR sources, but at present such cases have been infrequent. The effect of middle- and far-IR as a factor in causing heat stress may decrease in the future because of the use of newer sources that emit predominantly in the near-IR region.

There are infrequent references to the occurrence of discomfort similar to that of chronic conjunctivitis as a result of exposure to IR. The increased evaporation of the tear film could, of course, result in an abnormal state of the conjunctiva and cornea. Where the tear film is reduced as a result of malfunction, mainly of the accessory lachrymal glands, a state known as "dry-eye" is produced. In cases of "dry-eye", it may be assumed that IR exposures would aggravate the disease; exposures of such persons to IR should therefore be avoided.

Threshold limits for the occupational exposure of the cornea, lens and retina to IR do not exist at present. Although limited experimental thresholds for damage to ocular structures have been established, there are still insufficient data for comparative purposes.

There is a great need for research to establish exposure standards, determine irradiance levels, and evaluate the role that exposure duration plays in causing damage to the eye and skin. Data collected should include not only the area and spectral distribution of the source but also the working conditions, protective measures and working distance, so that a more precise estimation of the radiation dose incident on the eye and skin can be made.

Although present knowledge of IR bioeffects is insufficient for the conclusive determination of threshold levels, it appears that a more conservative standard of 0.1 kW/m^2 would be prudent, especially when a comparison is made with man's natural environment.

CONCLUSIONS AND RECOMMENDATIONS[a]

Conclusions

All people are exposed to IR radiation from sunlight, artificial light and radiant heating. Exposures to IR are quantified by irradiance (W/m^2) and radiant exposure (J/m^2) to characterize biological effects on the skin and cornea. However, near-IR exposure to the retina requires knowledge of the radiance ($W/(m^2 \cdot sr)$) of the IR source. With most IR sources in everyday use the health risks are considered minimal; only in certain high radiant work environments are individuals exposed to excessive levels.

Comprehensive measurements for hazard evaluation should include *(a)* spectral irradiance and radiance of the source, *(b)* exposure duration, and *(c)* frequency of repeated exposures. However, if the source is not too intense, it may suffice to measure only the total irradiance and radiance to assess the hazard.

The interaction of IR radiation with biological tissues is mainly thermal. IR radiation may augment the biological response to other agents. The major health hazards are thermal injury to the eye and skin, including corneal burns from far-IR, heat stress, and retinal and lenticular injury from near-IR radiation.

Recommendations

Control measures should include education and training of all personnel working with IR sources. Engineering controls include the proper layout of working areas, construction of baffles and enclosures, a separation distance from the source, and good ventilation to reduce the risk of heat stress. Personal protection may consist of special eyewear and appropriate clothing and protective garments.

Individuals chronically exposed to high levels of IR, such as glass workers, should wear IR-absorbing protective lenses.

Further research on the health hazards of exposure to IR does not seem urgent at present, but this position may change following understanding of the fundamental mechanisms of the interaction of heat with biological systems.

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[a] These conclusions and recommendations are those pertaining to infrared radiation made by the WHO Working Group on Health Implications of the Increased Use of NIR Technologies and Devices, Ann Arbor, USA, October 1985.

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