

# Chapter 23

## NONIONIZING RADIATION

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## INTRODUCTION

This chapter updates Chapter 15, Nonionizing Radiation, in the previous edition of this book.<sup>1</sup> This update includes a discussion of new nonionizing radiation equipment and lasers that have been added to the Department of Defense (DoD) equipment inventory and are used daily in military operations. Physicians need to be aware of the unique hazards that nonionizing radiation poses and be able to detect signs of exposure and injury related to these exposures.

Electromagnetic radiation is a wave phenomenon consisting of oscillations in the electric and magnetic fields of space. Scientists and engineers commonly characterize electromagnetic radiation, like all wave phenomena, using two parameters, frequency and wavelength. These parameters, continuously varying from the sub-atomically small and unperceivably fast

to the cosmically large and glacially slow, are used to define what is known as the electromagnetic spectrum. The spectrum is divided up into frequency (or, interchangeably, wavelength) regions based on the physical processes that generate the radiation they contain and the manner in which that radiation interacts with matter. The most physically significant division in the spectrum is that between ionizing radiation and nonionizing radiation.

Ionization of matter occurs when an electron absorbs enough energy to overcome its attraction to the positively charged nucleus of an atom or molecule, and ionizing radiation refers to radiation energetic enough to ionize matter. Once ionized, atoms or molecules are known as ions, and because ions are charged particles, they are more chemically active than in their electrically neutral state (prior to ionization). Chemical

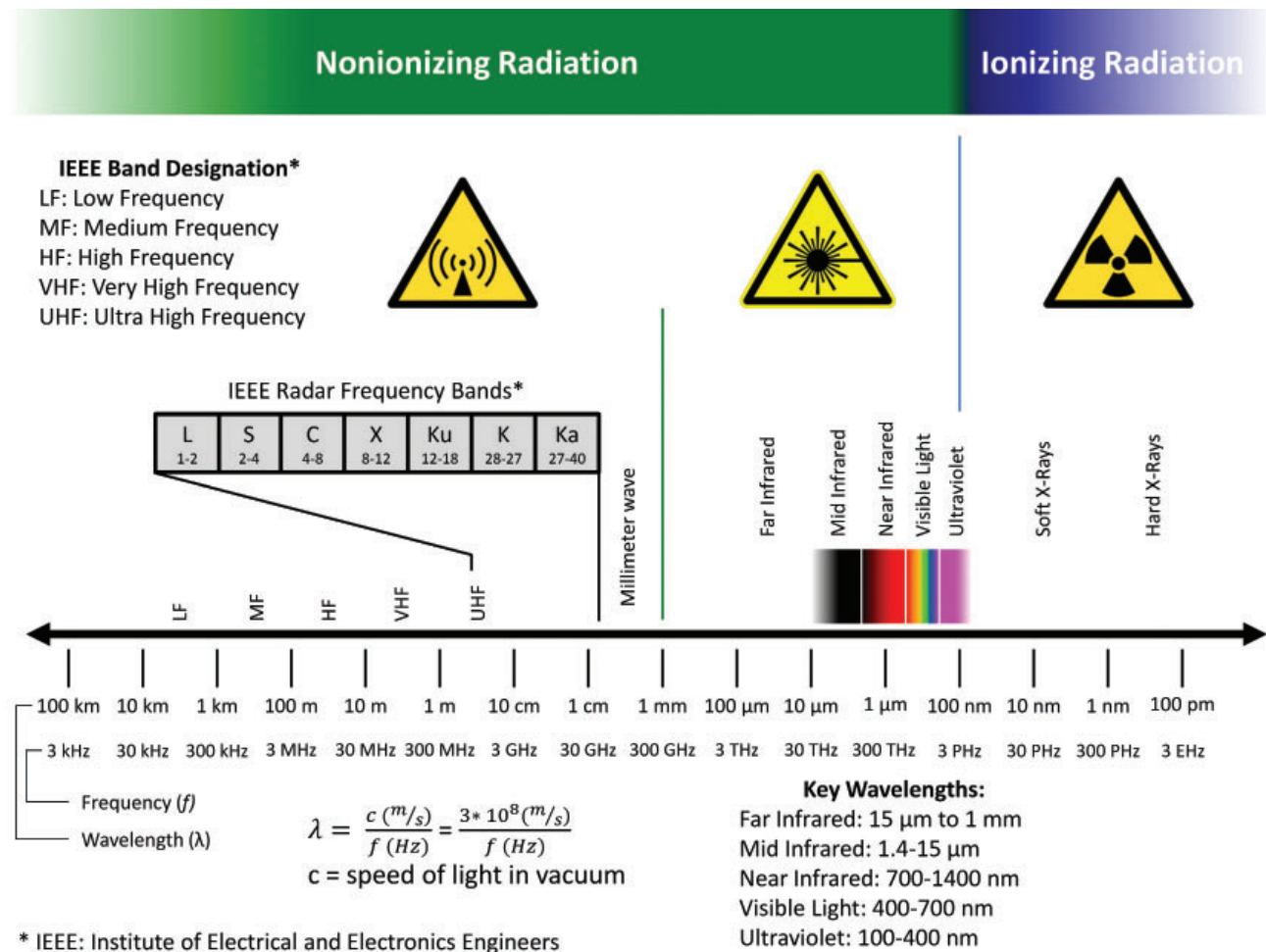


Figure 23-1. Nonionizing radiation electromagnetic spectrum.

changes that occur in biological systems because of ionization may be cumulative and can be detrimental or even fatal.

All other radiation is categorized as nonionizing. The division between the two categories falls within the ultraviolet (UV) frequency range, but the exact boundary varies with context. Laser safety standards, designed to control nonionizing radiation hazards, usually begin at a wavelength ( $\lambda$ ) of 180 nanometers (nm), corresponding to a frequency around 1.7 petahertz (PHz).

Another important division in the electromagnetic spectrum is at the wavelength of 1 mm between the optical and radio frequency (RF) radiation regions. These regions may be divided into smaller frequency bands ad infinitum. The radiation produced in this portion of the electromagnetic spectrum does not possess energy sufficient to ionize matter. This nonionizing radiation excites atoms by raising their outer electrons to higher orbitals, a process that may store energy, produce heat, or cause chemical reactions (photochemistry).

The biological effects of nonionizing electromagnetic radiation are caused by thermal stress (the ac-

cumulation of heat) and photochemical denaturation of proteins and other molecules in cells. When heat is dissipated, the effects of thermal stress do not persist (they are not cumulative). When the thermal stress is extreme, however, persisting injuries from RF radiation such as erythema, cataracts, or burns may occur. Extreme exposures to lasers and other optical sources may cause damage to components of the eye and burns to the skin.

Figure 23-1 shows the nonionizing radiation portion of the electromagnetic spectrum. The divisions of the electromagnetic spectrum are arbitrary, overlapping regions on a continuum. The generally accepted divisions are:

- x-rays;  $\lambda = 0.01$  to  $10$  nm
- UV;  $\lambda = 10$  to  $400$  nm
- visible light;  $\lambda = 400$  to  $700$  nm
- infrared (IR);  $\lambda = 700$  nm to  $1$  mm
- microwave;  $\lambda = 1$  mm ( $300$  GHz) to  $1$  m ( $300$  MHz)
- RF;  $\lambda = 1$  m ( $300$  MHz) to  $100$  km ( $3$  kHz)

## CHARACTERISTICS OF ELECTROMAGNETIC RADIATION

Two complementary concepts in modern physics describe electromagnetic radiation: the wave model and the particle model. The wave model simplifies the way in which electromagnetic radiation interacts with matter on a macro scale, for instance, with reflection and refraction. It characterizes electromagnetic radiation as the *propagation of energy through transverse oscillations of the electric and magnetic fields*. Electromagnetic waves are measured by four key parameters: wavelength, frequency, polarization, and amplitude (field strength). The *frequency* of a wave is its number of oscillations per second measured in hertz (Hz). The *wavelength* is the distance between successive waves, which correlate to any part of the wave, for example, peak to peak or trough to trough. The wavelength must be one full oscillation of the periodic wave. *Polarization* is the relative orientation of the electromagnetic field, commonly with respect to the electric field component. Waves may be linearly polarized (vertical, horizontal), or circularly polarized, when the orientation of the field rotates with respect to distance and time. The *amplitude* is the absolute field strength of the electromagnetic radiation, and is given in terms of volts per meter (V/m) for the electric field strength and amperes per meter (A/m) for the magnetic field strength.

Frequency and wavelength of an electromagnetic wave relate to each other through the following equation:

$$c = \lambda \cdot f$$

where  $c$  denotes the wave velocity,  $\lambda$  denotes the wavelength, and  $f$  represents the frequency. The velocity of the wave will change with propagation through various media, but will never exceed the speed of light in a vacuum ( $3 \cdot 10^8$  m/s). If a wave is propagating in free space, the respective wave velocity is simply the speed of light in a vacuum.

The particle model, on the other hand, proposes that electromagnetic radiation consists of particles, called *photons*, which possess only discrete amounts of energy (*quanta*). Photons only exist in motion, which for the photon is traveling at the speed of light. Photons may interact with other particles, exchanging energy and momentum through elastic and inelastic collisions. Higher frequency electromagnetic radiation has higher particle energy. Max Planck related the actual particle energy of a quantum to frequency of the radiation through the following equation:

$$E = h \cdot f$$

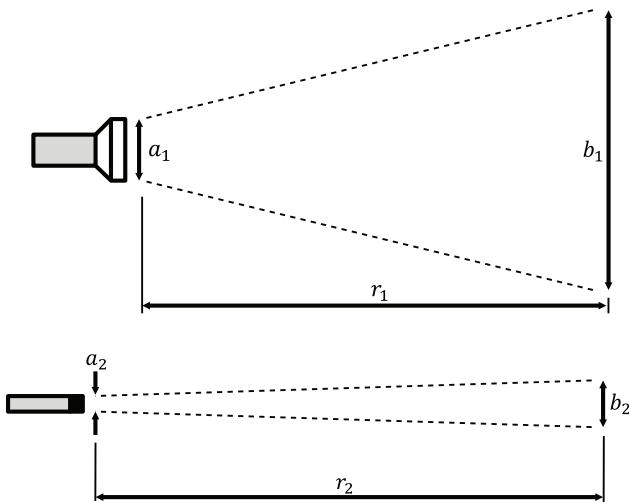
where  $E$  represents energy,  $h$  denotes Planck's constant (Js), and  $f$  denotes the frequency of the electromagnetic radiation. The particle model is useful in conceptualizing certain phenomenon such as scatter, and widely describes the phenomenon of *stimulated emission*. Stimulated emission is a quantum mechanical phenomenon that results in the emission of two photons

in the same direction with the same energy and spatial coherence when an incoming photon interacts with an atom or molecule in an excited state. This principle is the essence of the *laser*. Laser, or light amplification by stimulated emission of radiation, is a technology, not necessarily a type of radiation. However, current use of the term refers to both the technology and the highly collimated beam of nonionizing radiation it produces.

When measuring nonionizing radiation, energy and power are used to quantify its intensity. Energy, measured in joules (J), is the ability to perform work on a system. Power, measured in watts (W), is the ability to perform work on a system per unit of time; in other words, power is the rate at which energy is transferred. Thus, the power unit of the watt may be also expressed as joules per second (J/s). All types of electromagnetic radiation share certain properties that make them alike, but when the radiation interacts with matter their differences become evident. For example, a thin sheet of black paper absorbs visible light, but RF radiation passes through the sheet of paper as if it were transparent.

### Physical Properties

All types of electromagnetic radiation, both ionizing and nonionizing, share the properties of *divergence*, *interference*, *coherence*, and *polarization*.



**Figure 23-2.** Divergence calculation from nonionizing radiation sources.

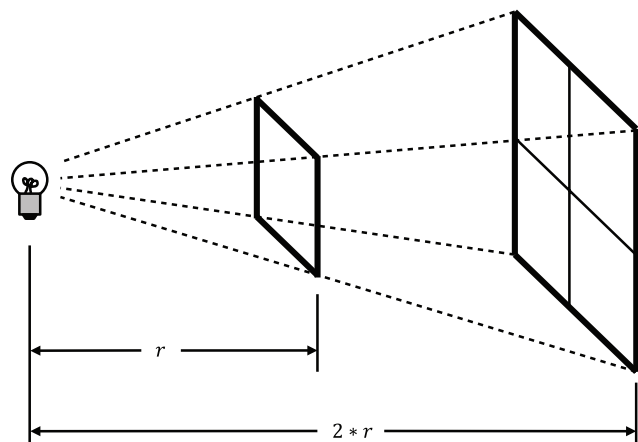
$$\varphi = (b-a)/r$$

The upper graphic depicts a common flashlight and represents its divergence for illumination. The lower graphic compares the measure of divergence to a laser, showing a much narrower beam, and thus, a much smaller divergence.

### Divergence

The term *divergence* describes how the radiation emission from a source spreads out with respect to distance. It may be visualized and calculated through the graphic and equation in Figure 23-2, the divergence calculation from nonionizing radiation sources, where  $\varphi$  represents the divergence (in radians),  $b$  represents the diameter of the radiation beam at a measurement distance,  $r$  from the source, and  $a$  denotes the diameter of the beam at the starting point of the measurement. Divergence is bounded from below by a value known as the diffraction limit. It is impossible for divergences of sources to be less than the diffraction limit, but with laser sources the divergence can very nearly equal it. Other factors that contribute to divergence include the source size, the geometry of the emission aperture, and the medium of electromagnetic propagation.

Isotropic and collimated radiation exemplify two contrasting concepts. By definition, radiation emitted from an isotropic source diverges uniformly in all directions surrounding the source. The intensity of the radiation decreases with the square of the distance from the source. For example, if the distance to the source were doubled, the radiation would decrease by a factor of 4. If the distance to the source were tripled, the radiation at that distance would decrease by a factor of 9. A common example of an isotropic radiation source is the sun. Light is emitted in all directions regardless of spatial orientation of the source. A standard household incandescent light bulb has a near isotropic intensity, lighting up a room regardless of spatial position of the source. Figure 23-3 shows the inverse-square relationship of the radiated power with respect to the distance to the source.



**Figure 23-3.** Inverse square law conceptualization.

Collimated radiation, however, has an asymmetrical or directional spatial radiation pattern. Automobile headlights are a good example of a somewhat collimated source, with the visible light directed forward toward the road ahead. Lasers are highly collimated sources and exhibit a very narrow beam of radiation for long distances; they have a very narrow, or tight, divergence.

### Interference

The principle of *superposition* maintains that amplitudes of intersecting waves will combine to produce a resultant wave. Therefore, the net effect of two waves of the same frequency will be either *constructive* (the resultant amplitude is larger than either two of the input waveforms) or *destructive* (the resultant amplitude is smaller than either of the two input waveforms; the two waves cancel each other out). Constructive interference occurs when two waves of equal amplitude are in phase (their crests/troughs overlap); the result is a single wave with twice the amplitude. Destructive interference occurs when the two waves are out of phase, for example,  $180^\circ$  (a peak overlaps a trough), where the result is no wave, since the energies cancel each other out point by point. A common physics experiment demonstrating interference is described along with the diffraction phenomenon in the **Interaction with Matter** section below.

### Coherence

Coherence is the measure of the degree of *phase correlation* within the electromagnetic radiating field from the transmitting source (either a light source or radio antenna) at different times and places along the propagating wave. Coherence is further described in two main forms: *temporal coherence* and *spatial coherence*. Temporal coherence, the time in which radiation remains in phase after emission, is essentially a measure of how monochromatic (consisting of a single wavelength) the radiation is. Spatial coherence, on the other hand, is a measure of the radiation's phase with respect to a given wave plane, and dictates the uniformity of the radiation over a unit in space.<sup>2</sup> Lasers emit nonionizing radiation in both temporal and spatial coherence. The radiation emitted by lasers is near monochromatic in nature, and all photons are in phase with one another across the radiation beam.

### Polarization

Polarization refers to the orientation in space of the oscillating fields of the electromagnetic wave, usually given as the direction of the electric field vector. For

example, a wave traveling in the z-direction may have an electric field oscillating along the x-direction, in which case it could be referred to as an x-polarized wave; this could also be considered horizontal or vertical polarization depending on how the coordinate frame is defined. More generally, waves polarized in this way (along one particular spatial dimension) are said to be linearly polarized. Waves may also be elliptically or circularly polarized, which means that the direction of polarization changes (rotates) as the wave propagates.

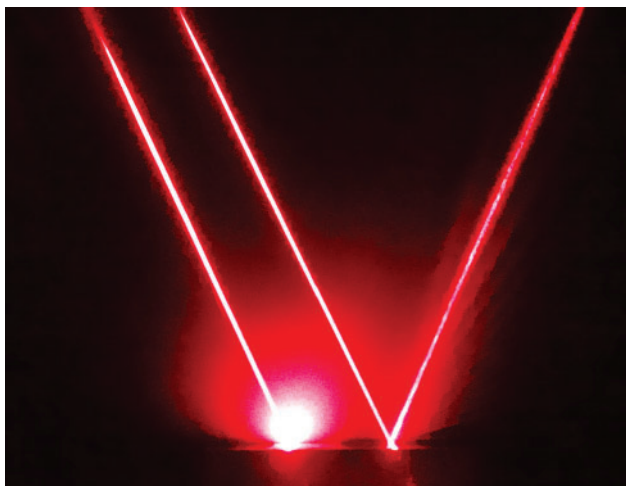
### Interaction with Matter

The polarization or orientation of the electromagnetic field components can greatly affect the radiation's interaction with matter, and can in turn be affected by that interaction. These effects are most evident in matter that exhibits a preferred direction of some kind on a spatial scale comparable to the incoming radiation's wavelength. For example, the physical orientation of a monopole antenna (like those on portable radios), whether vertical, horizontal, or any position in between, will correspond with the polarization it transmits and receives. Another example is ordered matter such as a crystal lattice, through which polarized light will propagate at different speeds depending on the direction of the polarization. Most sources of electromagnetic radiation do not exhibit a preferred orientation, and are therefore unpolarized. Electromagnetic radiation may gain a preferred direction of oscillation by reflection or transmission through a material, or through a transmitting antenna or radiation-producing aperture. For example, sunglasses with polarizing filters prevent glare by blocking the horizontally polarized light that reflects off glossy surfaces such as car hoods and windshields.

When electromagnetic radiation contacts matter, it interacts directly with the atoms and molecular structure of the medium. Behaviors of the incident energy may take the form of scattering, reflection, absorption, refraction, transmission, or diffraction. The resulting effect of the electromagnetic radiation on matter depends on numerous factors including the wavelength, transmission, and reception media; polarization of the radiation; and the angle of incidence.

### Reflection, Refraction, and Scatter

Reflection of an incident electromagnetic wave depends on the surface's roughness relative to the wavelength of the radiation. The smoother the surface relative to wavelength of the radiation, the better it



**Figure 23-4.** Diffuse versus specular reflections. The laser line to the left indicates a scattered diffuse reflection; incident beam qualities are lost upon interaction with the surface. The laser line to the right indicates a specular reflection where the incident beam reflects at the same angle of incidence with little distortion.

will reflect the incident wave. If the relative roughness of the medium interface is larger than the incident wavelength, scattering of the electromagnetic radiation occurs. If the reflection image of the incident radiation is scattered in all directions upon interacting with the surface, the image is described as a *diffuse* reflection. An example of a diffuse reflection is lighting up a room by shining a light at the ceiling or wall. If, however, the reflected image of the incident radiation is maintained with little or no distortion, the image is described as a *specular* reflection. An example of a specular surface for visible light is the ubiquitous silvered mirror. Figure 23-4 shows diffuse versus specular reflections of laser beams.

The speed of electromagnetic radiation in any medium depends on (a) its wavelength and (b) the medium’s physical properties of transmission. It is always slower than the speed of light in a vacuum. The change in velocity for a given material has the nonintuitive result that light changes direction when it passes into a material, a phenomenon known as refraction. This can be seen when light passes from air into another medium (such as acrylic or water) in which it slows down, as seen in Figure 23-5. Eyeglasses and other lenses also exploit refraction in order to direct the image (onto the back of the retina, in the case of eyeglasses).

Scattering mechanisms depend on the size of the particle composing the medium and the wavelength of the incident radiation. The radiation exhibits *Rayleigh*

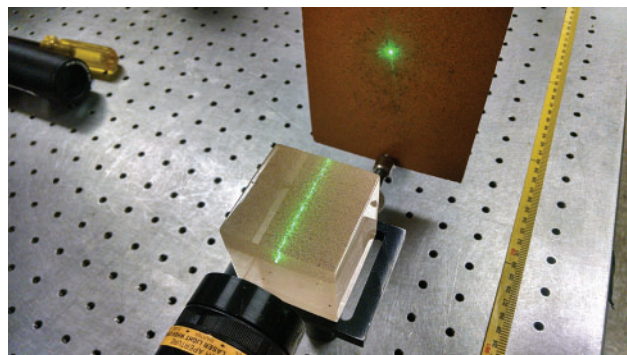


**Figure 23-5.** Refraction of laser light through a clear acrylic block. Although the acrylic is clear, a slight specular reflection occurs at each of the surfaces where the refraction occurs.

*scattering* when the size of the particle is on the same order as the incident wavelength. A good example of Rayleigh scattering is the reddening of the sky during a sunset on a clear evening. The scattering of light by larger-sized particles with respect to wavelength is referred to as *Mie scattering*. Mie scattering is not as dependent on the incident wavelength and may produce scattering both forward and backward with respect to the direction of radiation travel (Figure 23-6).

**Transmission**

The interactions of a given medium with electromagnetic radiation may be highly selective based on wavelength of the incident radiation. The material may



**Figure 23-6.** Mie scattering in acrylic showing the beam of a green helium neon laser. Small impurities or air bubbles in the block scatter the laser light both forward and backward to enable viewing of the beam path.

transmit all energy at one wavelength while completely absorbing another wavelength. For example, red-colored glass transmits light around the wavelength of 650 nm but absorbs the wavelengths of green (550 nm) and blue (450 nm). If the medium is not capable of transmitting energy at a given wavelength, it scatters or absorbs and dissipates the energy by other means, typically as heat.

### Absorption

When electromagnetic radiation interacts with matter and is absorbed, its energy is transferred to the medium. According to the particle model, an atom absorbs the incident photon and excites an orbiting electron to a higher energy state; the excited electron eventually decays back to its ground state either by giving off another photon or by nonradiative (mechanical, thermal, or photochemical) means. The wave-model description of absorption is that atoms and molecules are immersed in the oscillating field of a passing wave, and the electrons respond mechanically to the oscillation (by rotating or vibrating); this energy is then either re-radiated in the form of another electromagnetic wave, siphoned off as frictional heat, or stored via photochemical reaction. Each description uses different language and mathematical formalisms, but the observed physics (heating, photochemistry, and photon exchange) is the same.

The main effect of electromagnetic radiation on a medium is ultimately dictated by the radiation's wavelength, intensity, and duration of the exposure. By changing or increasing the intensity of the radiation, or the duration of exposure, the total energy absorbed in the matter will increase. At IR, visible light, and other short wavelength radiation regions, the photons have enough energy to excite electrons to high states, or molecules to high-energy vibrational modes, whereas longer wavelength photons are capable of inducing only the lower energy rotational



**Figure 23-7.** Single slit diffraction physics experiment showing the interference pattern of spatially coherent light.

modes of molecules. A common example of heating matter through molecule rotation is the microwave oven, which uses radio frequency radiation (2.45 GHz) to “flip” the polar water molecules in the food or drink being heated.

### Diffraction

Electromagnetic radiation will diffract when it encounters obstacles—that is, it will bend or move around particles, corners, edges, or apertures. The closer in size the obstacle is to the wavelength of the radiation, the more pronounced the effect. A classic physics example of this is single slit diffraction (Figure 23-7). In this example, monochromatic light from a helium-neon laser is incident upon a narrow slit, in this case the gap between two razors. Because the gap is on the same order as the wavelength of light, the laser light “bends” or diffracts around the razor edges and spreads out into the line seen in the figure. Also evident in the photograph is an interference pattern: light starting at different positions along the slit, but reaching the same point on the wall, will interfere either constructively or destructively in a periodic pattern as the differences in path length change by multiples of the wavelength. The nodes (locations at which the light is cancelled out) are seen in the dark regions. The antinodes (locations where the light adds together) are seen in the bright regions.

## RADIO FREQUENCY RADIATION

In 1864 James Clerk Maxwell proposed mathematically that energy could be transferred through electric and magnetic fields travelling together at a finite speed. Over 20 years later, in 1886, Heinrich Hertz constructed the first basic oscillator transmitter and receiver. Hertz's experiment consisted of two metal spheres connected to a high-voltage power supply to create a simple spark gap transmitter. The receiver consisted of a loop of wire with a miniature gap constructed in it to “tune” it to a desired frequency. With this basic equipment, Hertz conducted experiments that demonstrated the similar-

ties between radio and light-based waves, along with the polarization, refraction, and reflection of electromagnetic waves. Although Hertz's experiments utilized relatively short wavelengths (50–450 MHz), later developments in radio made use of longer and more tunable wavelengths.<sup>3</sup>

### Radio Communication and Radar Technology

Guglielmo Marconi used Maxwell's equations for electromagnetic waves and Hertz's experiment to put theories into practical use for communication systems.

In 1901 Marconi successfully demonstrated radiotelegraphy across the Atlantic Ocean. By 1907 wireless communication services had been established between North America and Europe through the telegraph. Marconi not only successfully demonstrated wireless communication between continents, but also conceptualized the use of radio waves for radio detection and ranging (radar). At the time, however, he was unsuccessful in attracting support for this application.

Later, Marconi's suggestions stimulated experimental work at the US Naval Research Laboratory, which resulted in the first radio detection of a wooden ship in 1922, and the first radio detection of an aircraft in 1930. In 1932, radio detection systems operating at 33 MHz were capable of detecting the presence of an aircraft at distances up to 50 miles. At the time, however, specific target position information such as range and bearing could not be determined.<sup>4(p856)</sup>

After the primitive radio detection equipment was developed in the 1930s, research and development efforts continued at a rapid pace. The US Army Signal Corps successfully tested its first radio detection assembly in 1936. Two years later, the Army introduced the first operational radio detection and ranging (radar) system for aiming anti-aircraft fire, the SCR-268. This radar was used in conjunction with searchlights due to the radar's poor angular position accuracy, although its range information was superior to comparable optical methods used at the time. Also used in the pre-World War II era was the SCR-270, a radar developed in 1939 for the Army as a long-range early warning radar for aircraft. This radar system detected the first signs of the Japanese attack on Pearl Harbor, Hawaii, in 1941, but unfortunately, they were ignored until after the bombing began. The SCR-268 was the standard fire control radar until early 1944, when it was replaced by the SCR-584, developed through research conducted at the Massachusetts Institute of Technology's radiation laboratory.<sup>4-6</sup>

### Microwave Radar

In 1936 the first efforts to develop radar in the microwave frequency range were published in two research papers that discussed replacing the conventional wire transmission line with a tubular waveguide.<sup>7</sup> The waveguide resulted in less transmission line loss than the wire-based transmission line. Secondly, a successful cavity magnetron was developed in Great Britain in 1940, which made it possible to generate substantial magnitudes of microwave radio frequency energy. In partnership with the Massachusetts Institute of Technology's radiation laboratory, magnetron units were shipped to the United States to promote research in the field of microwave frequencies for radar applications.

Most of this early work was directed toward the use of the newly invented magnetron in aircraft microwave radar applications, namely due to the smaller antenna aperture needed to transmit and receive the RF signals.

The term "radar" was applied to microwave RF-producing equipment, with which objects can be electronically "seen" by means of a transmitted electromagnetic radio wave. The targeted object reflects a percentage of the wave back to the receiver of the radar equipment, which then translates the input to range and position (azimuth and elevation). The use of microwave radar equipment revolutionized the older very high frequency (VHF) radio detection systems. By using higher frequencies, and thus, much smaller wavelengths, newer radar systems could be much smaller and have greater range and versatility.

### Radar During World War II

Although the radar used in the Battle of Britain operated at VHF, it provided accurate range and tracking data, and was able to function in spite of fog, clouds, and darkness, thus reducing the threat from Hitler's bombers. The introduction of microwave techniques not only sharpened these abilities, but also reduced the size and weight of the equipment and extended the applications of radar. Many radar systems at this time could now be installed on mobile platforms, without needing the support infrastructure of a base station to operate the radar system.

Until 1942, allied airborne antisubmarine radar, operating at a frequency of approximately 200 MHz, had neutralized the effectiveness of German submarines in the North Atlantic. At that time, many German submarines were equipped with listening receivers operating at VHF to detect the allies' operation of the radio detection units. A German submarine with a directional antenna could determine the direction of allied antisubmarine aircraft and estimate their range from the strength of the signal received. The effectiveness of allied antisubmarine aircraft decreased greatly because German submarines, warned of impending attack, were able to dive before the aircraft were positioned to drop depth charges.

However, allied aircraft then countered the effect of the submarines' receivers by using an attenuator inserted between the radar transmitter and the transmitting antenna. During the final phase of attack, the radar operator adjusted the attenuator to reduce the radiated signal level. The operator of the listening receiver in the submarine would then note a decrease in the signal strength and conclude that the aircraft was moving away, when in fact the aircraft was approaching for attack.



When the allied forces introduced microwave radar, the German forces mistakenly believed that some sort of IR equipment sensing heat from the submarines had replaced the VHF radio detection systems. Because the German military made no attempt to develop microwave listening receivers, allied antisubmarine operations increased in effectiveness. By 1943, microwave equipment operating at a wavelength of approximately 10 cm had replaced most of the VHF airborne detection systems.

During the next 2 years, new types of radar were developed, including airborne targeting radar and ground-controlled approach radar. Airborne targeting radar allowed bombers to accurately locate targets on the ground in overcast conditions. Ground-controlled approach equipment permitted operators on the ground to direct an aircraft to a safe landing under zero visibility conditions. Neither of these technologies had been practicable before the advent of microwave radar because the required antenna directivity was not possible using small VHF antennas.

Since World War II, microwave equipment has been used for various types of communication systems, including microwave relay installations that handle telegraph, telephone, and television signals. The wide microwave band affords significant data-handling capacity, offers flexible antenna gain due to a much smaller wavelength, and requires relatively low-power transmitting equipment.

### Physical Properties That Determine Energy Transfer

RF energy is typically transferred to the body through conduction, coupling, and absorption mechanisms, which are dependent on both the wavelength and the body's distance from the radiating source. Distances from the source in wavelengths and their corresponding mechanisms are:

- $0 \lambda$  = conduction (contact)
- $0 - \lambda/2\pi$  = coupling (currents induced by non-radiating fields)
- $> \lambda/2\pi$  = absorption (conversion to heat)

#### Conduction

Conduction occurs when the body makes contact with an RF source (for example, when an individual touches an antenna element or an exposed transmission line). This is no different than sticking a fork in an electrical outlet, although the frequencies involved are generally orders of magnitude higher. The detrimental effects associated with conducted energy are electrical

shock and burn, which comprise the most serious injuries associated with RF energy. As frequency increases, the conductivity of (and penetration into) human tissue decreases: at 60 Hz, the frequency associated with the US power grid, the threshold for a painful shock is 9 mA, whereas the threshold at 10,000 Hz is 55 mA. The threshold for shock and burn also increases with increasing surface area—a grasping contact with the entire hand reduces the energy density in tissue compared to single-finger (touching) contact, thereby reducing adverse effects.

Even if the induced thermal current from RF conduction is not sufficient to create a thermal injury, it can stimulate the nervous system and cause a response similar to that invoked by an electrical shock. The individual may jerk involuntarily or reflexively, and the resulting movement could cause an injury to the victim or to someone nearby.<sup>8</sup>

Maximum permissible exposures (MPEs), quantified in standards, are intended to limit induced and contact RF-current flow through the body for frequencies less than 110 MHz and reduce RF shocks and burns.<sup>9</sup> From 100 kHz to 110 MHz, the MPE limits the RF current through each foot, and at the point of a grasping contact, to 100 mA. The current limit through both feet is simply double, 200 mA. These limits are conservative enough that even if currents at these levels were to enter through a single fingertip, it would not be enough to produce RF shock or burn. The RF current limits in mA per foot below 100 kHz are equivalent to the frequency in kHz; for example, at 40 kHz the limit is 40 mA for one foot, or 80 mA for both feet.

The MPE drops with frequency to accommodate the increased penetration depth of the current and correspondingly higher probability of interaction with the heart and central nervous system. At frequencies lower than approximately 3 kHz, the biological effects associated with RF current flow in the body are clearly discernable and the physiological effects are well understood. They include (in addition to shock and thermal injury) electronarcosis, ventricular fibrillation, and involuntary movement. However, allegations of low-level effects (below the respective MPEs) have been made regarding the frequency region lower than 3 kHz with the largest cluster of questions presently concerning the 60 Hz power-line frequency.<sup>9-11</sup>

#### Coupling

During transmission, energy is stored around the antenna in nonradiating electric and magnetic fields in the region known as the reactive near field, which

spans from the source to a distance of  $\lambda/2\pi$  (approximately  $0.159\lambda$ ). A second conductor introduced into this region (for example, another antenna or a human) will “couple” with the source conductor through either the magnetic or electric field. This is referred to as inductive and capacitive coupling, respectively, and the effect in either case is the penetration of an electric field into the introduced conductor. Exposure levels resulting from electromagnetic coupling are difficult to calculate using field strength probes alone because the probes themselves will couple with the antenna, significantly affecting the results. Similarly, electrical properties of the transmitting antenna (such as impedance) will also be altered by the presence of a second conductor in the reactive near field. Therefore, instead of a direct external field measurement, induced currents and electric fields in realistic models of humans (in both shape and electrical properties) are measured.<sup>12</sup>

The reactive near field of an antenna transmitting at a frequency of 1 GHz ends within 2 in. of the radiating surface, meaning that coupling effects are usually associated with transmission on the lower frequency end of the spectrum, especially when considering human-sized conductors. Specifically, coupling with reactive near fields below 5 MHz can, like direct RF conduction, result in nonthermal electrostimulation effects more serious than thermal effects, including involuntary movement, pain stimulation, and ventricular fibrillation. It is important to protect against induced currents with frequencies up to about 110 MHz.

### Absorption

At distances greater than  $\lambda/2\pi$ , radiated electromagnetic fields dominate over reactive (nonradiating) fields, so the primary means of energy transfer of this radiation is absorption. Just as coupling is associated with low frequencies, radiation absorption becomes a concern as frequency increases, when reactive fields have retreated close enough to the antenna to no longer be practically accessible. Measurements of radiated fields beyond the reactive near field are relatively easy to measure, and conductors immersed in them have no impact on the transmission properties of the antenna being measured. Heating of tissue is the only direct effect potentially hazardous to people from absorption of radiation.

### Direct Biological Effects

The common theme in all the previously discussed energy transfer mechanisms is the transformation of energy from electric and magnetic fields into one or

more types of energy modes in the target material. When translational modes (movement) are excited, the ambient cell temperature rises due to the heat generated by friction. If the temperature rise is sufficient, proteins denature and a burn results.

Depositing RF radiation energy into the body increases its overall thermal load. The thermoregulatory system responds to the increased thermal load by the usual means: transfer of energy to the surrounding environment through convection, evaporation of body water, and radiation (primarily IR). When RF radiation causes localized heating of certain organs, such as the eyes, prolonged exposure can directly damage that organ. However, short-duration exposure to RF-induced thermal load will usually not cause damage and the heat will be dissipated. For this reason, RF radiation exposure is not cumulative, unlike ionizing radiation exposure. The biological effects of RF radiation are thoroughly treated in textbooks such as the *Handbook of Biological Effects of Electromagnetic Fields*.<sup>13,14</sup>

Burns caused by exposure to nonionizing radiation are different from conventional and electrical burns in that contiguous tissues are not necessarily affected; which tissue will be affected depends on the frequency of the incident radiation. For example, microwaves tend to excite thermal modes in water molecules, and tissues with high water content, such as skin and muscle, are affected more severely than tissues with low water content, such as fat. Therefore, microwave-induced burns tend to damage skin and muscle preferentially, and (relatively) spare the subcutaneous fat layer that separates these two structures. In addition, tissue interfaces such as organ capsules and fascial planes tend to be more susceptible to microwave damage. Also, with electrical burns, charring is minimal and usually localized to the site of the current's entry. *Nuclear streaming* (when cellular nuclei align along the direction of current flow) is characteristic of electrical burns but not radiation burns.<sup>15</sup>

The lens of the eye is recognized as the most sensitive site for thermal damage. Studies on rabbits show that cataracts can be induced above a certain time-power threshold, down to a minimum power density, by frequencies from the low MHz to several GHz.<sup>16</sup> Attempts to establish a similar relationship in other nonhuman models (including rats, dogs, and monkeys) have been less successful. Several epidemiological studies of military and industrial workers have yielded no evidence of increased risk to these populations. One of the only known potentially credible cases of human exposure to RF resulting in cataract formation, analyzed by Hirsch,<sup>17</sup> involved

an electronics technician under nearly continuous occupational exposure to power densities from 1,000 to 9,000 W/m<sup>2</sup>.

### Low-Level Effects of Radio Frequency Electromagnetic Radiation

Popular controversy surrounds the possibility that electromagnetic radiation may cause harmful biological changes in the absence of demonstrable thermal effects. Thermal effects occur following measurable increases in temperature and at energy levels at least 10-fold greater than the officially mandated MPEs.<sup>18</sup> RF environments in the US Army are relatively safe, but medical officers must realize that thermal effects can range from nuisance, to minor discomfort, to serious injury, to death. Serious effects such as extensive burns are obvious, but low-level effects may not be so clear cut.

Effects of low-level RF radiation, actual or alleged, have involved temperature increases that are (a) too small to measure, (b) transient, or (c) too localized to distinguish.<sup>19</sup> The significance of these effects on health is a subject of much debate among scientists, public health officials, and various special interest groups. The relatively recent proliferation of cell phones and local area wireless networks has made these technologies the target of the most common allegations of low-level exposure effects, but less ubiquitous sources such as “smart” utility meters and radiofrequency identification readers have also triggered concern. Earlier, power grid transmission lines and cathode ray tube video display terminals were cited as examples of chronic low-level exposure.

Although thermal effects are the basis of the current RF radiation exposure standards, scientific investigations during the last 20 to 30 years have focused on effects of low-level exposure. Cancer, birth defects, behavioral changes, and other detrimental effects have been investigated using low-level (below current MPEs) RF energy. These investigations include epidemiological studies, animal studies, and other research efforts. No conclusive evidence substantiates claims of low-level RF radiation effects.<sup>9</sup>

### Indirect Biological Effects

Although most manufacturers carefully design sensitive healthcare devices (intended to be used in a fixed setting such as a hospital) to operate satisfactorily in conventional RF environments, RF radiation indirectly poses a threat to health through electromagnetic interference (EMI) with electronic devices by disrupting their normal operation. EMI affects medical personnel by causing interference with sensitive healthcare

devices (such as electrocardiograph equipment, operating-room monitors, or cardiac pacemakers), and affects military personnel by causing electronic weapons platforms (such as helicopters) to fail.

Currently, the US Army Medical Department is only addressing concerns associated with the interference of medical devices, specifically from EMI sources produced and operated by the DoD. These evaluations determine system characteristics such as *rise time* (the time required for the RF pulse to reach peak intensity), modulation, duration, and peak amplitude of the RF radiation. The US Army Public Health Center (USAPHC) is tasked with studying EMI problems with healthcare devices at Army hospitals. The USAPHC maintains special measuring equipment capable of detecting very low EMI threat levels. Typical EMI threat levels may be 7 to 10 orders of magnitude below the MPE associated with direct biological effects.

Implantable electronic devices such as cardiac pacemakers may be subject to EMI-related failure in certain RF radiation environments, such as near electromagnetic pulse (EMP) generators. Most implanted pacemakers provide a stimulating pulse to the heart only when the heart’s own pacemaker fails to do so. The implanted pacemaker monitors the biological pacemaker, but the artificial pacemaker is sometimes susceptible to EMI. Fortunately, the device’s shielding and the surrounding tissue act to reduce the threat of EMI.

During 1987 to 1989, a citizen group protested the use of an EMP generator that supposedly posed an EMI threat to implanted cardiac pacemakers.<sup>20</sup> The Army and other military services used this generator to test the susceptibility of electronic weapons platforms to the effects of EMPs. A thorough study of the alleged threat was conducted in response to the protest, and the results showed that EMPs could indeed interact with modern implanted cardiac pacemakers. Individuals who work close to the EMP source are at risk and require radiation protection controls; however, the EMP levels actually encountered by the public will not produce EMI interactions.

Presently, although the Army’s RF environments pose no known uncontrolled EMI threats to pacemakers or similar medical devices, pacemaker wearers are denied access to controlled areas that might pose an undetermined threat. Such devices and sources of EMI are continually evaluated through the US Army Radiation Protection Control Program.<sup>21-24</sup>

### Radio Frequency Radiation Protection

Protection of personnel from RF electromagnetic fields is mandated and implemented through Department of Defense Instruction (DoDI) 6055.11, *Protecting*

*Personnel from Electromagnetic Fields.*<sup>25</sup> DoDI 6055.11 adopts the Institute of Electrical and Electronics Engineers (IEEE) C95 series standard for applicable MPE and localized exposure limits (IEEE C95.1-2005).<sup>9</sup> The IEEE C95.7-2005 standard provides recommended practices for developing an RF radiation safety program (discussed later in this chapter). DoDI 6055.11 also established a DoD hotline for electromagnetic field injuries (Exhibit 23-1), as well as the Transmitted Electromagnetic Field Radiation Protection Working Group, which provides technical guidance and recommended policy for RF electromagnetic field safety.

Within the Army, several regulations and pamphlets provide information for the protection of personnel from RF radiation (Table 23-1). Army Regulation (AR) 40-5, *Public Health*, outlines overall public health policies and their use within the Army, from chemical, biological, and ionizing radiation hazards to nonionizing radiation (RF and laser/optical radiation). AR 385-10, *The Army Safety Program*, implements requirements of the Occupational Safety and Health Act of 1970 and provides policy on Army safety management procedures with emphasis on responsibility hierarchy and organizational concepts. Department of the Army Pamphlet (DA PAM) 385-24, *The Army Radiation Safety Program*, focuses specifically on implementation of the radiation safety program established by AR 385-10. Included in the DA PAM are sections for both ionizing and nonionizing radiation, from RF to visible light and near UV. The pamphlet also provides guidance for implementing RF radiation protection measures outlined in DoDI 6055.11.

### Exposure Limits

MPEs (formerly known as permissible exposure limits) have greatly changed in the past 50 years since the creation of a standard for RF control. After the dawn of mainstream RF sources in the 1960s, permissible exposure limits were initially published through the American National Standards Institute (ANSI) and the IEEE (before the creation of the C95 series documents). The exposure limit was a constant 10 mW/cm<sup>2</sup>, applicable to the public and military alike. Since then, as a result of studies and research papers, the standards began to account for the effects of frequency and temporal characteristics (pulsing) of the incident energy. Current RF limits set forth in the IEEE C95.1-2005 adopt an MPE and localized exposure limit that is frequency dependent, based on the diverse studies on the effects of RF radiation to the human body. Additionally, a two-tier approach to the limits are implemented for the action level (general public) and upper tier (controlled environment) settings depending on how the RF system is used.

## EXHIBIT 23-1

### MILITARY SAFETY PROGRAM AND EMERGENCY CONTACT INFORMATION

*Department of Defense Laser Injury Hotline:*  
1-800-473-3549

The US Army Public Health Center Nonionizing Radiation Division can provide assistance in the identification of and protection against radiofrequency and laser/optical radiation hazards.

5158 Blackhawk Road  
ATTN: MCHB-PH-NIR  
Aberdeen Proving Ground, MD 21010-5403  
Radio Frequency Radiation phone: 410-436-3353;  
DSN: 584-3353  
Laser/Optical Radiation phone: (410) 436-3932;  
DSN 584-3932  
fax: (410) 436-5411; DSN 584-5411  
email: usarmy.apg.medcom-phc.mbx.nonionizing@mail.mil

The US Air Force School of Aerospace Medicine Occupational/Environmental Health Division manages the Tri-service Laser Incident Hotline and provides assistance in the identification of and the protection against laser hazards from lasers used by the Air Force.

USAF School of Aerospace Medicine  
2947 Fifth Street  
Wright-Patterson Air Force Base, OH 45433  
phone: 1-888-232-ESOH (3764) or (937) 938-3764;  
DSN: 798-3764  
email: esoh.service.center@wpafb.af.mil

The US Air Force Research Lab Optical Radiation Branch can also provide assistance in the identification of and the protection against laser hazards in the Air Force.

Chief, Optical Radiation Safety Team  
Air Force Research Laboratory  
Optical Radiation Branch (RHDO)  
4141 Petroleum Road  
Joint-Base San Antonio, TX 78234-2644  
phone: (210) 539-8205  
email: usaf.jbsa.711-hpw.mbx.usaf-laser-safety@mail.mil

The US Navy Naval Surface Warfare Center Code G71 Lead Navy Technical Laboratory for Navy and Marine Corps Laser Safety can provide assistance in the identification of and the protection against laser hazards in the Navy and Marine Corps.

NSWCDD  
Code G71  
Dahlgren, VA 22448  
phone: (540) 653-1060/1149/2442; DSN: 249-1060  
email: lasers@nswc.navy.mil

**TABLE 23-1**  
**US ARMY GUIDANCE ON RADIO FREQUENCY RADIATION PROTECTION**

Regulation	Title	Purpose
AR 40-5	<i>Army Public Health Program</i>	Regulation to establish the Army Radiation Safety Program
DA PAM 40-11	<i>Army Public Health Program</i>	Department of the Army Pamphlet to give guidance on execution of the regulation
AR 385-10	<i>The Army Safety Program</i>	Regulation to provide guidance on radiation safety within the Army
DA PAM 385-24	<i>The Army Radiation Safety Program</i>	Provides guidance on execution and initializing a working radiation safety program from Army-wide to installation and commands
DoDI 6055.11	<i>Protecting Personnel from Electromagnetic Fields</i>	Establishes protection standards for radio frequency electromagnetic fields, and instructs personnel to use MPE limits and practices from the IEEE C95 series standard
IEEE C95.1	<i>IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz</i>	Provides the frequency-dependent MPE limits and guidelines on protecting personnel from overexposure, contact and induced currents, and discharge contact voltages
IEEE C95.6	<i>IEEE Standard for Safety Levels with Respect to Human Exposure to Electromagnetic Fields, 0–3 kHz</i>	Provides MPE limits and guidelines on protecting personnel for sub-radio frequency fields in the range of 0–3 kHz. Main protection is from electrostimulation, contact voltages, contact and induced currents, and magnetic field strength
IEEE C95.7	<i>IEEE Recommended Practice for Radio Frequency Safety Programs, 3 kHz to 300 GHz</i>	A useful tool for radiation safety officers and safety personnel on development and implementation of a radio frequency safety program

IEEE: Institute of Electrical and Electronics Engineers  
MPE: maximum permissible exposure

Current MPEs are derived from specific absorption rate limits, known as the basic restrictions (BRs), which are defined as the maximum allowable RF (or electromagnetic) power deposited per unit mass of biological tissue, in units of watts per kilogram (W/kg). Often, for low frequencies, exposure is best directly compared to the BR using dosimetric methods. As the frequency of the radiation increases, the energy is deposited closer to the surface, and comparison to the derived MPE values via measurements of external fields becomes more practical. External field power densities are given in the units of watts per square meter ( $W/m^2$ ), or milliwatts per square centimeter ( $mW/cm^2$ ) in older versions of the IEEE C95 standard. Electric and magnetic field components of any incident RF radiation are given in units of either volts per meter (V/m) for the electric field, or amps per meter (A/m) for the magnetic field. In all frequency ranges, the BRs are the most fundamental restriction: the MPE may be exceeded provided the BR is not, but the reverse is never true.

### **Radiation Control**

When assessing the hazard severity of an RF-producing source, certain operating parameters must be known: transmit frequency, transmit power (and possibly duty cycle), and antenna gain. The transmit frequency of the source is used to look up the proper MPE limit in the IEEE C95.1 standard tables. Transmitter power is then used (along with the antenna geometry) to determine the near field power density for comparison with the MPE. If a given RF source exceeds the MPE in the near field, the (far field) antenna gain can be used along with the transmitter power to calculate a standoff distance for personnel to maintain while the system is transmitting. The standoff distance, typically given in meters or feet, is the distance from the antenna beyond which the calculated or measured power density falls below the MPE. Engineering-based controls and administrative procedures may be used to restrict access to areas where the MPE is exceeded.

## Emission of Radio Frequency Radiation

A typical RF system has three basic components to convert electrical power and a modulated signal into the electromagnetic waves that propagate from an antenna. First, the RF oscillator generates the necessary waveform within the RF spectrum. The intensity of the waveform is then increased to the required level by an amplifier. These two components are collectively referred to, in this context, as the transmitter. The transmission line then “guides” the energy from the transmitter to an antenna for propagation. A transmission line, which may take on many forms, must be able to transfer energy effectively to the antenna. Third and last is the antenna. The function of the antenna is to match electrical parameters from the transmission line to free space, effectively coupling the energy to a free-space radiating wave.

### The Transmitter

The RF oscillator is a means to convert electrical power in a circuit to a time-varying waveform. Typically, the oscillator is the fundamental component of an RF transmitter. Included within the transmitter is an amplifier, which amplifies the RF-generating source and provides an output matching the impedance of the transmission line or the antenna itself. There are many types of oscillators and amplifiers, the details of which are outside the scope of this publication, but amplifiers may be broadly divided into two categories: solid-state and vacuum tube based. Solid-state amplifiers are common among radio communication systems and some radar assemblies, while vacuum tube-based designs are still ubiquitous in high power applications such as long-range search radars and radio/television broadcast towers. RF safety concerns for personnel at the transmitter are usually minimal and, as before, are dictated by transmitter power and frequency. When hazards do manifest, the connection point between the transmitter and the rest of the system (ie, transmission line or antenna) is the most likely culprit.

### The Transmission Line

The purpose of the transmission line is to guide the RF energy from the transmitter to the antenna. Some systems couple the transmitter directly to the antenna, omitting a transmission line completely. The many types of RF transmission lines may be divided into two main categories: conductor-based lines and waveguides.

The more familiar of the two, conductor-based transmission lines, are so called because the energy is primarily stored as electrical current within conduct-

ing wires (strands of metal or metal alloys) during transit. Examples include single wire conductors, parallel or ladder lines, and coaxial cables; applications include commercial power transmission lines (cross-country transmission wires), older “rabbit ears” and “bow tie” type television antenna hookups, and modern cable television coaxial hookups (Figure 23-8). The diameters of a coaxial cable typically denote the operating power, with larger diameters able to handle more power. As frequency increases, the losses in conductor-based transmission lines also increase. Coaxial cable can be used at frequencies well into the millimeter wave band, but if efficiency is important, waveguides should be used.

Waveguides become practical at a frequency around 1 GHz. Waveguides make use of a single conductor in the shape of a hollow metal tube and, instead of RF power being transferred through voltages and currents on conductors, a propagating wave develops on the interior walls of the tube. Waveguides are rectangular for linear polarization modes and circular for circular polarization modes. Most modern microwave RF systems make use of waveguides to transfer energy from the transmitter to the antenna; however, coaxial cables may still be used in specific circumstances. The cross section dimensions of the waveguide (length and width or radius of the interior) determine the operation frequency. Therefore, as the frequency increases, the dimensions of the waveguide decrease. Figure 23-8 shows various waveguide sizes.

Potential hazards for the transmission line of an RF system may be either overexposure or electric shock or burn. An RF shock or burn can occur on a



**Figure 23-8.** Assortment of conductor and waveguide transmission lines. The brown two-wire transmission line was salvaged from an old television set-top antenna. The light green cable handles the smallest amount of power transmission, while the coaxial cable section on the far left handles the most power. The waveguides increase in frequency from left to right.

conductor-based transmission line where the voltages and currents exceed limits set forth in the current IEEE C95.1 standard. This includes both a contact voltage and contact current along any conductor of the transmission line. Waveguides pose a problem of potential overexposure if the transmitted power is high enough because the RF energy propagates as a coupled electromagnetic wave down the waveguide. RF radiation may leak out into the surrounding area if the transmitter waveguide is cracked or open during transmission.

### *The Antenna*

The antenna is the final constituent of an RF free space-radiating system. The antenna's purpose is to couple the energy from the transmission line to free space. Like transmitters and transmission lines, antenna design and safety concerns are a function of frequency and power, but the antenna introduces a third factor: beam shape. When transmitting, the antenna does not radiate electromagnetic waves in a sphere of perfectly uniform intensity (isotropic radiation), but instead concentrates the radiation in certain areas. The degree to which an antenna's radiation pattern (or beam shape) departs from that of an isotropic radiator is known as its directivity; the more concentrated the beam is, the higher its directivity. Directivity is frequently combined with other antenna efficiency factors and compared to a lossless isotropic antenna—the resulting quantity is referred to as the gain of the antenna.

Antennas take on many forms, from conductor-based designs (like the set-top antennas found on over the air broadcast televisions) to high-gain aperture horn antennas used when high directivity is desired. An example of a typical low-gain antenna is the monopole whip antenna on many vehicles. The RF radiation emitted from these antennas is omnidirectional; the energy is radiated from all directions broadside to the antenna. An example of a high-gain antenna is a parabolic dish antenna. An electrically conductive parabolic dish typically has a waveguide horn aperture positioned at the dish's focal point to yield a high gain.

### **Military Applications**

The subtopics below provide some examples of common US Army RF radiation-producing systems and the potential hazards to operating them. For a more complete list of systems and their respective technical parameters, consult the Communications-Electronics Command technical bulletin 43-0133.<sup>24</sup>

### *VHF/UHF Radio Communications Systems*

VHF and ultra-high frequency (UHF) radio systems are ubiquitous in the Army for voice and data communication and coordinating operations. Radios take on numerous forms but are essentially grouped into three main categories: handheld or manpack systems, vehicular radio systems (Figure 23-9), and systems used in a base station or tactical operations center. Many radios are also capable of operating within some or all of these categories, depending on their configuration. For example, the AN/PRC-154 Rifleman radio is a handheld radio that can be mounted into a docking station in a vehicle. The docking station may also provide additional amplification to the initial 5-W power output to cover a greater distance. Another example is the AN/PRC-155 radio transceiver. The radio itself may be used in all three configurations, and depending on the antenna configuration. Handheld and manpack radios typically do not pose a hazard from RF radiation emitted by the antenna; however, they may pose a risk of shock or burn if the antenna or transmission line is bare wire or has metal surfaces. Vehicular radio and base station radio sets generally transmit more power than portable radio systems, and therefore may require additional precautions against radiation hazards, shock, and burn. A common single-channel ground and airborne radio system transmits about 50 W into its antennas, and may require standoff distances during transmission.



**Figure 23-9.** A mine-resistant, ambush-protected (MRAP) vehicle provides a variety of radio frequency communication systems. The most prevalent are the omnidirectional very high frequency (VHF) and ultra-high frequency (UHF) antennas. US Army photo by Specialist Elisebet Freeburg, Joint Sustainment Command–Afghanistan, PAO. Reproduced from: <https://www.army.mil/e2-images/2009/10/23/53959/index.html>

### Very Small Aperture Terminal Communication Systems

Very small aperture terminal (VSAT) communication systems are ubiquitous in the US Army today for maintaining communications in the field. The main goal of a VSAT is to communicate with a geosynchronous satellite network, providing ground connections to the secure and nonsecure internet protocol routing networks (SIPR/NIPR) and other networks. Transmit power of a typical VSAT can range from a few watts to systems capable of 200 to 300 W, as in the AN/TSC-208, pictured as the trailer-mounted VSAT in Figure 23-10a. As technology has progressed and microwave electronic devices have become more affordable, smaller VSAT configurations have become available in a manpack form for greater portability. The VSAT pictured in Figure 23-10b is part of the AN/TSC-203 Global Response Intelligence Terminal.

These two different forms provide similar communications, but may pose different hazards. Specific equipment may differ, but when the transmit power is greater than approximately 20 W, personnel should avoid the region between the antenna feed and reflector. This recommendation typically applies to the bigger VSATs such as the AN/TSC-208 trailer-mounted system. Also, although VSAT systems are capable of a maximum specified transmit power, in most cases they will use only enough power to establish reliable communication with the satellite. Therefore, transmit power may be a fraction of the full rated power of the system while in operation on the satellite network. Additionally, VSAT systems are directed to the sky toward satellites in geosynchronous orbit.

### Microwave Radars

The main purpose of microwave radar systems is to acquire and track targets, either on the ground or in the air. The radar system transmits high-energy pulses of RF radiation using the antenna to direct the energy in a specified pattern. Range is computed by the time it takes for the transmitted pulse to reach the target, reflect, and be received back at the radar. The antenna is typically mounted on an electromechanical positioner to direct it to potential points of interest. It may scan 360°, or only oscillate in a given direction, depending on application. Common transmitter peak power for microwave radars ranges from a few hundred watts to several hundreds of kilowatts. Despite the high peak power of a radar transmitter, the average power may be quite low, due to the duty cycle (on/off time) of the transmitter when operating.

Areas of concern with microwave radar assemblies include the main beam of the antenna, the region between the antenna feed and reflector, and the waveguides that supply the transmitter power to the antenna. Additionally, if the radar transmitter uses a vacuum tube-based amplifier, special consideration must be taken to guard against high voltage and potential x-ray generation. Most if not all systems today have interlocks built into the enclosure and critical components to prevent hazard to individuals. Figure 23-11 shows a typical acquisition and tracking radar for aerial applications. When the radar is in operation, personnel should be advised not to occupy the



**Figure 23-10.** Two common very small aperture terminal (VSAT) deployments for portable operations: (a) a trailer-mounted AN/TSC-208; (b) a part of the AN/TSC-203 Global Response Intelligence Terminal.





**Figure 23-11.** A microwave radar system installed at an Army depot. The waveguides feed the radio frequency power through the arm at the top of the antenna.

platform via administrative procedures (signs, warning lights), or prevented from accessing the platform through engineering controls (fences and barriers).

### *Phased Array Antenna Systems*

Phased array antenna systems operate in a similar fashion to parabolic reflector microwave antennas; however, the main radiating beam is not geometrically dependent on the antenna. Rather, in a phased array system, the antenna plane consists of many antenna elements that essentially work together to create a desired radiating pattern. By altering the phase of the RF signal at each antenna element, the radiation is electrically steered (in contrast to mechanical steering, used in traditional microwave systems). This allows the radiating beam to transmit from the antenna at oblique angles to the phased array plane and change the radiation pattern at an extremely fast rate. Phased array radars can track targets by scanning the radiation beam in a two-dimensional pattern. If a target of interest is designated, the phased array antenna may dwell, or “stare” at the target, to acquire more precise location information than is possible with a quick sweep of the scanning beam. Phased array systems are typically stationary or mounted on a slow-moving positioner.

For high power phased array systems, the potential hazard area is broader because of the electrical steering of the beam; the antenna plane does not necessarily denote where the radiation comes from. Additionally, personnel working around the system may not know

the radiation pattern of the antenna. The hazard zone of a high power phased array system may be a semi-circle or hemisphere on the front of the antenna. Figure 23-12 depicts a phased array antenna radar system.

### *Exposure Incidents*

The severity of any suspected personnel overexposure to RF radiation determines the extent of both the medical and technical investigations. When a suspected RF overexposure occurs, the local medical department activity must examine the patient and complete a Special Telegraphic Report of Selected Condition (Requirement Control Symbol MED-16), as required by AR 40-5, *Army Public Health Program*, Section 3-20, Public Health Information Systems, 3-21: Records Management. The report must be sent to the Office of The Surgeon General’s Preventive Medicine Division. The medical evaluation initiates a technical evaluation to analyze the following RF radiation parameters and incident data:

- operating (transmit) frequency,
- antenna gain,
- average and peak power output of the transmitter,
- transmission line losses between the antenna and transmitter,
- distance from the antenna or waveguide to the location of the suspected overexposure, and
- duration of the exposure.

The initial technical evaluation of the suspected overexposure permits investigators to determine the exposure level an individual may have encountered. However, an incident is not classified as an overexposure



**Figure 23-12.** A trailer-mounted phased array radar system. Note that there is no defined parabola dish on the antenna. There is a red covering on the antenna for absorbing radio frequency radiation that attenuates the output power during maintenance or repair work; it is removed during operation.

only if the power density level exceeded the MPE. According to current IEEE standards, in most frequency ranges, a 6-minute timer period is used to average the exposure. A safety factor of 10 is also incorporated into the MPEs for further protection. If the technical evaluation indicates that an individual may have been exposed to RF radiation greater than 5 times the MPE, the following procedures must be followed: (1) medical personnel will administer a complete medical evaluation (however, the only manifestation of overexposure that the evaluation will diagnose is thermal injury); (2) the USAPHC will conduct an investigation; and (3) an investigation report will be published. The investigation report includes:

- on-site interviews,
- evaluation of the RF radiation source,
- measurements at the incident site from the source,
- consideration of other evidence to establish the extent of the overexposure, and
- recommendations for improving potential deficiencies in the nonionizing radiation safety program.

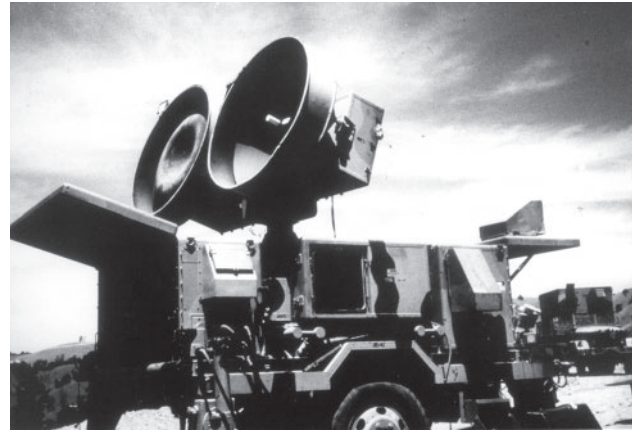
Below are two case studies of exposure investigations.

### Case Study 23-1

One RF radiation exposure incident involved a soldier working near a high power illuminator radar (HIPIR) unit that was tracking aircraft (Figure 23-13). The soldier was dismantling a tent 35 to 40 m from the HIPIR when he reported feeling localized heating on his back. As the soldier turned around to discern the heat source, he noticed the HIPIR directed toward him. Immediately, he entered a nearby equipment shelter, which put the HIPIR out of sight (thus making the soldier feel safe). The soldier soon began to notice sunburn-like reddening on the backs of his arms and on his upper back.

Although the soldier's commanding officers did not direct him to a medical facility, he later visited the installation hospital for treatment of the burned areas and the general uncomfortable feeling he was experiencing. The burned areas, described as superficial burns, were 1 cm<sup>2</sup> on the arm and 3 cm<sup>2</sup> on the upper back. There was no generalized erythema. All vital signs were normal and the soldier was released after being treated with Silvadine (Monarch Pharmaceuticals, Bristol, TN) ointment (a 1% suspension of silver sulfadiazine in a hydrophilic base).

The hospital created a MED-16 report of the occupational injury because RF radiation was a possible cause. [The actual medical records, which would have told exactly what physical signs were present, were not available for this case report. Medical officers might ask (a) if the burns were first, second, or third degree, or (b) whether localized, rather than



**Figure 23-13.** The high power illuminator radar (HIPIR) is an acquisition radar of the Hawk air-defense system.

generalized, erythema were present. The use of Silvadine suggests that bullae characteristic of second-degree burns were present, but if so, the lack of erythema would be unusual.—Eds.]

In addition to the initial medical examinations, the Office of The Surgeon General requested that the US Army Environmental Hygiene Agency (now the US Army Public Health Center) conduct an investigation of the circumstances surrounding the incident. This investigation, which was performed within several weeks of the incident, included determinations of (a) the actual RF radiation levels to which the soldier may have been exposed, (b) the duration of exposure, and (c) the possible biological effects resulting from the exposure. The initial evaluation was conducted via telephone interviews. The preliminary findings indicated that the maximum RF radiation levels that the soldier may have experienced were between 110 and 150 mW/cm<sup>2</sup>. However, the actual exposure duration could not be determined. Because the RF radiation levels exceeded the MPE by more than 5-fold, the Environmental Hygiene Agency initiated a full investigation of the incident, including a visit to the incident location to obtain the actual power density measurements.

The investigation team dispatched to the incident site consisted of medical and engineering personnel. The team conducted extensive interviews with personnel associated with the operation of the HIPIR at the time of the incident, the soldier who allegedly was injured by radiation from the HIPIR, personnel who were working with the soldier at the time of the incident, and hospital personnel who examined the soldier. The interviews were used in an attempt to create an overall picture of the events surrounding the incident.

In addition, the team engineers conducted measurements of the actual RF radiation levels at 35 to 40 m from the HIPIR source. The measured values agreed with those predicted in the initial evaluation. The team also determined that the HIPIR was in a tracking mode at the time of the incident. When a HIPIR loses its target, the radar will coast (continue in the same direction with the same velocity) in an attempt

to reacquire the target. If the HIPIR does not reacquire the target within a few seconds, the radar will return to its primary target (the direction is preset by the operator), which, in this instance, was away from the tent. It is likely that the soldier was exposed to the main beam of the HIPIR during this coasting function.

The investigation team determined that no RF radiation overexposure had occurred. The MPE in the frequency range of the HIPIR is 10 mW/cm<sup>2</sup> when averaged over 6 minutes. The duration of the exposure could not have exceeded a few seconds. Therefore, the soldier was not exposed to RF radiation in excess of the MPE. The burn may have been caused by another heat source such as the sun. The sensation of heat from the RF energy may have exacerbated the soldier's injury, but RF energy did not cause it. Nevertheless, unauthorized personnel will not be permitted within the RF radiation control range established for the HIPIR.

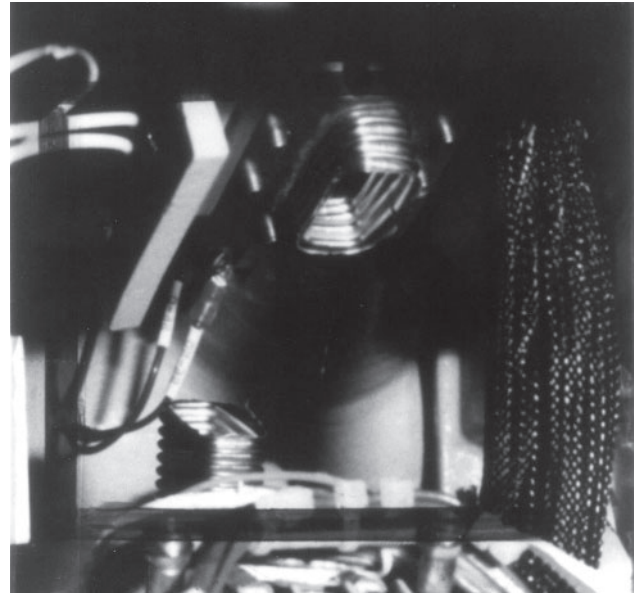
The soldier continued to report fatigue and chest pains. A series of examinations including liver function tests, blood counts, pulmonary function tests, and ophthalmic examinations were conducted over the next 6 months. All these examinations found no abnormalities. Later examinations included an electroencephalogram and a computed tomography scan. These examinations also found no abnormalities. The attending internist recommended regular neurological evaluations, which also found no abnormalities.

### Case Study 23-2

Another RF radiation exposure incident involved two soldiers performing maintenance operations on a HIPIR. They were attempting to determine why the antenna's arc detector crystal, located inside the transmitter housing, repeatedly burned out. While the radar was transmitting, the two soldiers removed the transmitter housing cover and visually examined the inside. After having examined the inside for 10 minutes, they noticed that a rigid waveguide was positioned incorrectly. They shut off the radar to remove the antenna pedestal head assembly. Upon further inspection after removing the assembly, they found the source of the repeated crystal burnout: a section of flexible waveguide that transfers high-power RF radiation to the antenna had been severed (Figure 23-14).

Within hours of discovering the severed waveguide, the two soldiers independently reported nausea and general malaise, and they reported the incident to the radiation safety officer (RSO). The RSO used an RF radiation meter to attempt to determine the actual power density levels to which the soldiers may have been exposed. The measured levels exceeded the 100 mW/cm<sup>2</sup> limit of the meter, and therefore the RSO requested the services of the US Army Environmental Hygiene Agency.

On the day after the incident, before the US Army Environmental Hygiene Agency investigation team arrived, the soldiers received ophthalmic examinations. The examinations included tests for visual acuity, a slit lamp evaluation of the crystalline lens, ophthalmoscopy, and an intraocular pressure test. The examinations revealed no abnormalities in either of the soldiers' eyes. The soldiers also reported that their initial nausea had subsided.



**Figure 23-14.** A broken radio frequency (RF) transmitter waveguide may leak RF energy into the surrounding environment during transmit modes. It is important to periodically check the waveguides and flanges for breaks and to replace them before transmitting with an RF device.

The US Army Environmental Hygiene Agency medical and engineering investigation team conducted an investigation. They interviewed the two soldiers, the RSO, and medical personnel at the installation. In addition, they measured the actual power density levels in the regions where the soldiers were trouble-shooting. The RF radiation levels ranged from 50 to 250 mW/cm<sup>2</sup>. Assuming that at least the minimum exposure level was experienced for a maximum of 6 minutes, there is no question that the soldiers were exposed to RF radiation more than 5-fold greater than the MPE (10 mW/cm<sup>2</sup>).

The primary recommendation of the investigation team was to test the HIPIR to determine why the flexible waveguide section had broken (this was apparently not the first time the waveguide had broken in this manner). The investigation team also recommended that maintenance personnel should always perform visual inspections around the transmitter housing with the power to the transmitter turned off.

### The Radio Frequency Radiation Safety Program

The installation or activity RSO is responsible for ensuring that a comprehensive nonionizing radiation safety program is in place and implemented in accordance with Army regulations (see Table 23-1). The safety program should include information on nonionizing radiation-producing sources, environments, control procedures, and points of contact in case of emergencies. No personal protective equipment is used by the DoD for RF radiation protection.<sup>25</sup> The USAPHC Nonionizing Radiation Program can provide

assistance in the identification of and protection against RF radiation hazards (contact information is provided in Exhibit 23-1).

### *Inventory of Radio Frequency-Producing Sources*

The installation or activity RSO must maintain an inventory list of all nonionizing radiation sources that exceed the respective MPEs. The threat classification of the source should be included on the inventory. Using the inventory, the RSO can recommend appropriate engineering controls or administrative procedures to further protect personnel from exposure.

### *Radio Frequency Controls and Administrative Procedures*

Engineering controls include any device or subsystem that modifies the design, construction, or operation of the RF system to prevent undesired radiation or hazards. Examples include safety interlocks on cabinets and couplings, and termination (dummy) loads to dissipate power instead of radiating the power through the antenna. Azimuth and elevation sector blanking switches, couplers, or attenuators provide additional interlocks to prevent antenna radiation in unintentional locations. Engineering controls may also restrict access to locations that exceed the MPE by the placement of fences or structures to limit or mitigate exposures. For example, the placement of an aircraft scanning radar may be put on a tower (with restriction to the tower itself) to mitigate the exposure of personnel on the ground. Secondly, the door to access the radar platform may also be installed with an interlock to disable the antenna rotation and transmission once the door is opened.

When physical barriers and other engineering controls are not feasible to integrate into the radiation safety program for the system, administrative procedures provide alternative methods to protect personnel. RF signage, caution tape (or simple ropes or chains), flashing lights, and warning sirens are some examples of administrative procedures that warn personnel of

the potential hazards for a given system or location, but do not necessarily prevent an exposure from occurring (unlike an engineering control, which turns off the transmitter or shuts down the system). Administrative procedures rely on individuals to ensure their own radiation protection through observing the environment (signs, lights, etc) and documents such as standard operating procedures. RF signage signal words such as “caution,” “warning,” and “danger” convey the severity of the hazard, along with the coloring of the sign. The IEEE C95.7 standard includes a recommended practice for sign signal words based on the severity of the potential RF exposure in terms of the MPE.

### *Training Programs*

Personnel who should receive radiation safety training include those responsible for operating, maintaining, and repairing RF sources capable of exceeding the MPE. This training should be conducted when the individual is first employed and annually thereafter. It is the RSO’s responsibility to maintain records containing an outline of the training material (or material itself) and a list of personnel who received the training. Training material should include:

- exposure potential associated with specific equipment used;
- biological effects associated with overexposure to power density levels exceeding the MPE;
- proper use of protective equipment and tools such as signs, indicators, barriers, and cones;
- accident-reporting procedures and points of contact in the event of an emergency;
- routine radiation safety program surveys; and
- procedures for maintaining an operational and maintenance log for recording radiation safety-related events (such as radiation hazard zone violations, overrides of warning lights or safety interlocks, failure to post signs during testing).

## **LASER AND OPTICAL RADIATION**

In 1913 Niels Bohr published his model of the hydrogen atom, proposing that atoms could (a) only exist in discrete energy states, and (b) radiate light of well-defined wavelengths in transitions between these energy states. In 1917, while studying the theory of black body radiation, Albert Einstein theoretically proved that emission of monochromatic light (light consisting of a single wavelength) was possible by showing that a process of stimulated

emission of radiation was necessary to account for the black body’s radiation spectrum. However, it was not until 1958 that Charles Townes first demonstrated microwave amplification by stimulated emission of radiation (maser). In 1960 Theodore Maiman experimentally constructed the first laser using chromium-doped aluminum oxide (synthetic ruby crystal) as the solid-state laser gain medium.<sup>26</sup> It was first called an “optical maser” because the

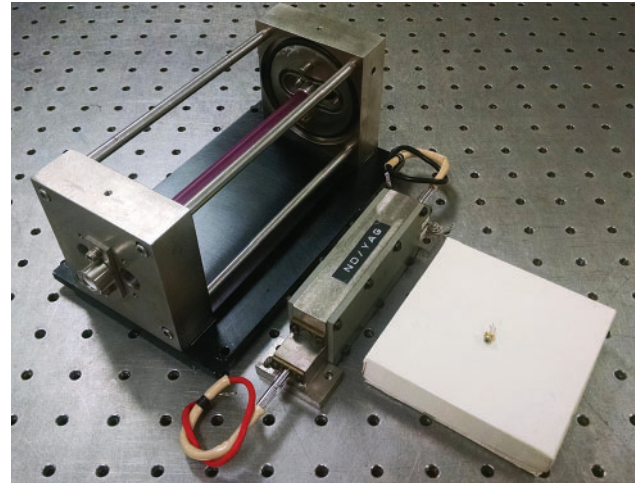
ruby transitioned at a wavelength of 694 nm (red light); the name changed to “laser” soon after optical masers became common.

The current inventory of fielded laser systems in the Army consists primarily of two types: solid-state and semiconductor-based. In the wider world of physics and engineering, semiconductor devices would be considered a subset of solid-state devices, but semiconductor-based lasers are different enough from other solid-state lasers (as well as all other lasers), in both design and beam properties, that the two domains are commonly redefined into non-overlapping categories. Solid-state lasers use solid-phase materials, usually crystals or glasses, such as neodymium doped yttrium aluminum garnet (Nd:YAG), and erbium doped glass (Er:Glass). Semiconductor-based laser diodes are similar to light-emitting diodes, and are typically referred to by their elemental composition; for example, two common semiconductor lasers in use by the Army are gallium arsenide and indium gallium arsenide.

Prototype ruby laser range finders were introduced in the late 1960s. The first vehicles to utilize the ruby laser range finder in the early 1970s were the M55A1 Sheridan vehicle and the M60A2 missile-firing tank shortly after. During the 1980s, a transition was made to Nd:YAG in infantry, armor, aviation, and artillery units, due to the increased lasing efficiency of Nd:YAG versus ruby laser technologies. Further development occurred in the late 1980s, and use of semiconductors for light emitting diodes and laser diodes became widespread. Semiconductor laser diodes are able to achieve higher efficiencies than Nd:YAG and produce comparable laser power output in a much smaller package. Today, semiconductor lasers have become the default choice for many of the most common laser roles (such as pointing and illuminating) and are not uncommon as rangefinders or light detection and ranging (LIDAR). Nd:YAG remains the laser of choice in high power, low divergence applications such as laser designation for the precision guidance of smart munitions, as well as for the production of high intensity green light. Figure 23-15 shows three stages of laser technology.

### Specific Properties of Lasers and Optical Sources

Stimulated emission, in theory, can be used to generate electromagnetic radiation of any frequency. In practice, stimulated emission sources cover a spectral range from x-rays to kilohertz frequencies, with various gaps along the way. Stimulated emission devices emitting at radio and microwave frequencies are known as masers, and although masers are considered the predecessor of the laser, they are not any different from lasers in principle. Masers have a more limited



**Figure 23-15.** Three examples of laser technology: the ruby laser (left), the Nd:YAG laser (center), and a common red laser pointer diode (right, on the white box). Note the size of each laser core and how technology has progressed in the development of more powerful and efficient laser designs.

scope of application than lasers because radio frequencies are more easily produced by traditional means. Stimulated emission on the short wavelength extreme of the spectrum, ionizing x-rays and extreme UV, is generated by devices that are still considered lasers but, like masers, are found only in highly specialized environments. Hence, current laser safety standards address devices operating in a spectral range of 180 nm to 1 mm, also known as the optical radiation range.

Lasers operating in this spectral range generally share three features: a lasing medium, a pumping system, and a resonant cavity. The lasing medium (also known as the gain medium) is the material in which the beam initially forms, and can be a solid, liquid, gas, or plasma. One special class of lasers uses an electron beam to generate the radiation (Exhibit 23-2). Lasers are typically referred to by the kind of lasing medium they use, for example, Nd:YAG and ruby. The pumping system (or pump) is the means by which energy is transferred into the lasing medium. Electric currents, flash lamps, and secondary lasers are all common types of pumping systems. The resonant cavity, while not technically required to create a laser, is what makes most laser designs practical. The simplest kind of resonant cavity consists of two mirrors, each facing the lasing medium at either end. In this way, the medium can be reused to amplify the beam repeatedly as it bounces between the two mirrors.

The specific properties of laser radiation are a direct result of the physics of stimulated emission. A simple way of understanding this process is to say the photons

## EXHIBIT 23-2

### THE FREE ELECTRON LASER

The stable, monochromatic nature of laser light is perhaps its most well-exploited feature, but it also makes individual lasers inflexible. Because of this, broadband, tunable laser sources have been an important area of laser research. Impressive strides have been made by taking advantage of vibronic electron energy states in crystal lasers and other state-dense gain media, but ultimately these solutions are limited by the physical structures containing the electrons. The free electron laser (FEL) addresses this limitation by using a beam of free electrons, traveling through a vacuum, as the emission source. Free from the electromagnetic background of atoms and molecules, the electron beam can be manipulated by artificially produced electromagnetic fields to emit wavelengths over a huge, continuous spectrum ranging from a 10th of a nanometer to several millimeters. FELs have already been used in some surgeries, where their tunable output enabled precision ablation with minimal collateral damage. The Office of Naval Research has an FEL program, with the hopes of eventually producing a megawatt class weapon.

in a laser are “cloning” themselves. An initial photon, in most lasers the product of spontaneous emission in the laser medium, encounters an atom or molecule within the medium that has been excited by the pump system, and stimulates it to emit a photon that is its exact match in direction, frequency, phase, and polarization, with some wiggle room for quantum randomness. On the macro scale, these properties correspond (respectively) to a highly directional, monochromatic, coherent, and polarized radiation beam. The two photons then continue onward, encountering more atoms or molecules and creating more copies of themselves, until they have exhausted the laser medium. Mirrors then reflect the beam back to the gain medium to be further amplified after the medium has been re-excited by the pump system. Note that stimulated emission merely lends itself to these properties, and some lasers may violate any one of them. For example, some lasers are designed to emit a broad range of wavelengths comparable to traditional light sources.

Other optical sources rely entirely on spontaneous emission to generate radiation, and are in general much less complicated than lasers and other stimulated emission devices. They can be divided into two categories: incandescent and luminescent. Incandescent light is the result of spontaneous emission from

electrons that have been excited by an increase in temperature. Glowing hot metal, filament light bulbs, and stars all emit incandescent light. Luminescence is a catch-all term that simply means “not incandescence,” and therefore contains the other two familiar modern light sources: fluorescent lamps and light-emitting diodes. Regardless of category, spontaneous emission optical sources emit with random direction, phase, and polarization. Spontaneous emission spectra are, like lasers, dependent on the emission medium, but because the photons are not “clones,” their spectra are much broader.

### Direct Biological Effects

Biological effects associated with exposure to the optical region of the electromagnetic radiation spectrum involve the skin and the retina, lens, cornea, and conjunctiva of the eye. The mechanism of injury for most effects is either photochemical or thermal. Thermal (heating) effects continue to dominate through the IR part of the optical spectrum, as they do in the microwave region. Photochemical (causing a direct chemical change) effects become important starting in the visible spectrum and continue to dominate throughout the UV range.

Because the nature and degree of injuries vary with wavelength, it is useful to consider the effects in the seven optical spectral bands that the International Commission on Illumination (*Commission Internationale de l'Éclairage*) has adopted (Figure 23-16). Actinic UV radiation (UV-C, 100–280 nm, and UV-B, 280–315 nm, which produce photochemical changes) characteristically produces erythema and photokeratitis (welder's flash). UV-A, 315–400 nm, can also produce these effects, but to a far lesser extent. Unless the exposed individual is also being treated with photosensitizers, which make people more sensitive to UV-A, exposure to UV-A (for example, UV-A black lights such as those used in industry) seldom produces an adverse effect. The recent identification of the injurious wavelengths (the *action spectrum*) associated with UV cataracts concluded that only radiation of 295 to 325 nm was effective in producing a temporary or permanent lenticular opacity for acute exposures.<sup>27</sup>

Lasers energetic enough to damage skin thermally have become much more common in Army applications over the last 2 decades, but gross thermal damage is still only possible with special lasers. One relatively common fielded laser that emits in excess of the skin MPE is the Green Laser Interdiction System, or GLIS, which has a skin hazard distance of around 2 m. Blocking the GLIS beam near the exit port with a finger or hand has been likened to the sensation of a pinprick.

CIE BAND	UV-C	UV-B	UV-A	VISIBLE	IR-A	IR-B	IR-C	
WAVELENGTH (nm)	100	280	315	400	760	1400	3000	10 <sup>6</sup>
INTERACTION MECHANISM	PREDOMINANTLY PHOTOCHEMICAL			PREDOMINANTLY THERMAL				
ADVERSE EFFECTS	PHOTOKERATITIS				RETINAL BURNS		CORNEAL BURNS	
			← CATARACT			CATARACTS		
	ERYTHEMA				←	COLOR VISION NIGHT VISION DEGRADATION		

**Figure 23-16.** International Commission on Illumination (CIE) spectral bands with corresponding adverse effects. The direct biological effects of optical radiation are frequency dependent. In the visible and infrared (IR) regions, the interaction mechanism is primarily thermal. In the ultraviolet (UV) region, the interaction mechanism is predominantly photochemical, although thermal injury is also present. The biological effects for IR radiation are corneal burns and cataracts. The biological effects for visible radiation are retinal burns, cataracts, and degradation of color and/or night vision. The biological effects for UV radiation are photokeratitis, cataracts, and erythema. UV-A and UV-B are also known causes of skin cancer.

For hazard analysis, effects on the eye are the greatest concern. There is an obvious interest in defining the sites of principle absorption, such as the retina, lens, or cornea. Another consideration is not only how much energy is absorbed in tissue, but also its relative biological effectiveness once absorbed. This is particularly important *outside* the spectral region where thermal effects predominate, at wavelengths shorter than 400 nm in the ultraviolet spectrum.

**Mechanisms of Injury**

Distinguishing the category of injury mechanism is of paramount importance in proposing exposure limits and in predicting the potential long-term, delayed, or chronic effects of exposure.

**Photochemical injury.** UV effects and blue-light retinal injury are considered photochemical in origin. Photochemical processes involve breaking or forming molecular bonds, or both, and result from stimulation of electronic energy modes. One property that aids in understanding photochemical injuries is *reciprocity* (the product of irradiance, or exposure rate, and the time necessary to produce an effect), which is constant over a wide range of exposure durations. The property of reciprocity is important in understanding photochemical processes: they obey the reciprocity rule for exposure duration from microseconds to hours. For example, 20 mJ/cm<sup>2</sup> of UV radiation produces the

same degree of erythema whether it is delivered as 20 kW/cm<sup>2</sup> for 1 microsecond, or as 20 μW/cm<sup>2</sup> for 1,000 seconds, provided the same wavelengths are employed. Exposure reciprocity is assumed to hold for up to 8 hours (one workday), and there appears to be very little (although measurable) additivity for multiple exposures if carried over one day. Exposure guidelines, such as the threshold limit values defined by the American Conference of Governmental Industrial Hygienists (ACGIH) or the MPEs for eye or skin exposure to UV radiation, are therefore expressed as *radiant exposure durations*.

**Thermal injury.** Reciprocity does not hold for thermal injury; therefore, it is always necessary to specify the exposure duration when studying a thermal injury. For thermal injury of the skin or eye from a pulsed source, it is the duration of the pulse that determines the threshold irradiance, threshold limit value, or MPE for a given wavelength and effect. The rate-process nature of thermal injury suggests that for exposure durations of less than approximately 10 to 100 microseconds, the rate of delivery of thermal energy to the tissue plays only a minor role because heat conduction cannot occur in so short a time.

Even the MPEs established for lasers tend to reflect this fact. For example, for ultrashort laser exposures of picoseconds, the biological effect is nonlinear and does not appear to be thermal. For the body to sustain thermal injury, exposure to a higher-intensity

laser for durations greater than 100 microseconds is required. However, because the body's blood flow and heat conduction away from the exposed site tend to provide some protection, if thermal injury has not occurred within a few seconds, it is unlikely to occur because a minimal critical temperature (perhaps 45°C) would not be reached through further exposure.

Laser beams may be capable of forming shock waves within tissue. The shock wave is believed to result from the rapid expansion of a plasma, which has been caused by the near-instantaneous heating of a tiny volume of tissue to approximately 10,000°F. Lasers are used in this manner to perform posterior capsulotomies in the treatment of cataracts, and to pulverize gallstones during laparoscopic surgery. Perhaps the clicking or popping sound anecdotally reported by people who have inadvertently gazed into a laser's beam can be attributed to such a shock wave.<sup>28,29</sup>

### *Recent Research on the Injury Process*

Until recently, the thermal-injury mechanism was thought to be associated with retinal injury sustained when individuals view bright light sources such as the sun. Researchers were puzzled that the calculated retinal temperature rise for an individual who stares at the sun was only 2° to 3°C for a 2-mm pupillary diameter. Laboratory studies of thermal retinal injury also showed that a 10° to 20°C temperature elevation in the 160-µm solar image was required to produce retinal injury within a few seconds. At this duration, short-wavelength light proved to be far more damaging than longer wavelengths, and reciprocity was maintained over a period of hours. Research thus concluded that the actual mechanism of retinal injury was photochemical, not thermal.<sup>30</sup>

The discovery of the blue-light retinal injury process and the theory of photochemical injury answered unexplained questions about solar retinitis (eclipse blindness). Researchers had not understood why individuals who gazed at the sun for 2 to 3 minutes during a solar eclipse at midday developed eclipse scotoma, but individuals who gazed for several minutes at the sun while it was low in the sky—and lacking in blue light—did not even sustain solar retinitis.<sup>30</sup>

UV light interacts with a number of different molecules in the skin and initiates several different signaling cascades that are still an area of active research. Consequently, the physiology behind UV erythema, photokeratitis, and blue-light retinal injuries is multifactored and multistaged, with the manifestation of injury delayed anywhere from hours to days.

### **Indirect Biological Effects**

Many laser systems used in both research and development and industry contain or are associated with potential ancillary sources of adverse biological effects such as chemical burns, loss of hearing, exposure to airborne contaminants, and electric shock.<sup>31</sup> These sources include chemical reactants and byproducts, target-generated contaminants, cryogenic fluids, dyes and solvents, ionizing radiation, noise, and high voltage. Consensus standards (such as those from the ACGIH, local and state agencies, and the Occupational Safety and Health Administration) govern many of these sources to limit exposure to contaminants with laser operation (Table 23-2). Potentially hazardous ancillary sources are listed below.

### *Voltage or Radiation During Maintenance*

Lethal voltage levels often are generated inside the laser-system enclosure. Personnel can be exposed to these voltages if the system covers are removed or if the electrical interlocks are defeated. Standard electrical safety precautions can reduce risk of electrocution. A potential for exposure to lethal voltages or other harmful radiation hazards might exist when protective covers are removed for service or maintenance. Safety precautions are provided in the appropriate technical manuals.

### *Fuels and Exhaust*

Many chemical fuels and exhaust products are associated with the operation of some laser systems (see Table 23-2). For example, the use of high-energy hydrogen fluoride or deuterium fluoride chemical lasers can cause atmospheric discharges of helium, oxides of nitrogen and sulfur, and several fluorinated compounds (including hydrogen fluoride and deuterium fluoride, which are corrosive and environmentally toxic). Normal ventilation techniques, such as dilution and local exhaust, and other engineering and administrative controls can reduce the concentrations of chemical reactants and their byproducts.

### *Targets*

The target of a laser operation can itself generate airborne contaminants during laser material processing, beam termination, and interactions with metal surfaces (such as arc welding). The ACGIH has recommended limits for welding fumes to provide protection from arc-welding contaminants. Control of airborne



**TABLE 23-2**  
**LASER-GENERATED AIR CONTAMINANTS**

Contaminant	Probable Source	OSHA Allowable TWA	OSHA Ceiling Value
Asbestos	Target backstop	0.1 F*/cc	—
Beryllium	Firebrick target	0.002 mg/m <sup>3</sup>	0.025 mg/m <sup>3</sup>
Cadmium oxide fume	Metal target	0.1 mg/m <sup>3</sup>	0.3 mg/m <sup>3</sup> (0.05 mg/m <sup>3</sup> )
Carbon monoxide	Laser gas	5 ppm	200 ppm
Carbon dioxide	Active laser medium	10,000 ppm	30,000 ppm <sup>†</sup>
Chromium metal	Metal target	1.0 mg/m <sup>3</sup> (0.5 mg/m <sup>3</sup> )	—
Cobalt, metal fume, and dust	Metal target	0.05 mg/m <sup>3</sup>	—
Copper fume	Metal target	0.1 mg/m <sup>3</sup> (0.2 mg/m <sup>3</sup> )	—
Fluorine	HF chemical laser	0.1 ppm	(2 ppm) <sup>†</sup>
Hydrogen fluoride	Active medium of laser	3 ppm	6 ppm <sup>†</sup> (3 ppm)
Iron oxide fume	Metal target	10 mg/m <sup>3</sup> (5 mg/m <sup>3</sup> )	—
Manganese fume	Metal target	1 mg/m <sup>3</sup> (1 mg/m <sup>3</sup> )	3 mg/m <sup>3†</sup>
Nickel and insoluble compounds	Metal target	1 mg/m <sup>3</sup> (0.05 mg/m <sup>3</sup> )	1 mg/m <sup>3†</sup>
Nitrogen dioxide	GDL discharge	(3 ppm)	1 ppm <sup>†</sup> (5 ppm) <sup>†</sup>
Ozone	Target and Marx generators	0.1 ppm	0.3 ppm <sup>†</sup> (0.1 ppm)
Sulfur dioxide	Laser exhaust	2 ppm (2 ppm)	5 ppm <sup>†</sup> (5 ppm) <sup>†</sup>
Sulfur hexafluoride	Saturable absorber	1,000 ppm	—
Uranium (soluble/insoluble)	Target	0.05/0.2 mg/m <sup>3</sup> (0.2 mg/m <sup>3</sup> )	0.6 mg/m <sup>3†</sup> (0.6 mg/m <sup>3</sup> ) <sup>†</sup>
Vanadium fume	Target	0.05 mg/m <sup>3</sup> (0.05 mg/m <sup>3</sup> )	—
Zinc oxide fume	Target	5 mg/m <sup>3</sup> (5 mg/m <sup>3</sup> )	10 mg/m <sup>3†</sup> (10 mg/m <sup>3</sup> ) <sup>†</sup>

Values in parentheses denote level recommended by American Conference of Governmental Industrial Hygienists.

\*fibers > 5 μm in length; †short-term exposure limits; —: no OSHA ceiling value

GDL: ground designator laser; HF: hydrogen fluoride; OSHA: Occupational Safety and Health Administration; TWA: time-weighted average

contaminants can also be achieved through local and dilution exhaust ventilation, and other engineering and administrative controls.

### *Cryogenic Fluids*

Cryogenic fluids such as liquid nitrogen are utilized to cool some lasers and many high-sensitivity photodetectors. When cryogenic fluids evaporate, they displace breathable oxygen and thus should be used only in areas of good ventilation. Another safety hazard associated with the use of cryogenic fluids is the possibility of explosion from ice collecting on a valve or a connector. Both protective clothing and face shields should be used when handling large quantities of liquid nitrogen. Workers using gas canisters and cryogenic Dewar flasks are required to follow numerous safety procedures (which are beyond the scope of this chapter) to prevent serious accidents.

### *Dyes and Solvents*

Organic dyes and solvents are used in older laser technology that is being replaced by safer alternatives, but they may still exist in some inventories. Solvents usually compose 99% of the dye solution by weight and are commonly flammable and toxic by inhalation or percutaneous absorption. Control measures for dyes and solvents include exhaust ventilation and proper storage and handling of flammable chemicals.

### *X-Rays*

Ionizing radiation (x-rays) are generated from some high-voltage power tubes and electron-beam lasers. This radiation can be controlled through proper monitoring and shielding procedures. Manufacturers

can successfully shield lasers to prevent x-radiation leakage if the lasers are operated with the shields in place.

### Noise

Certain high-energy lasers generate noise levels that exceed acceptable standards, although most lasers operate silently. However, hazardous noise levels occur only near the laser or its target, where personnel are not permitted. Other safety considerations thus obviate the need for noise-control measures.

### Laser Protection Standards

Until 1973, when the first ANSI standard (Z136.1)<sup>32</sup> pertaining to lasers was published, only general standards for the use of lasers existed. ANSI Standard Z136.1 laid the groundwork for a multitude of laser standards, including standards pertaining to laser use in industry and the military, performance standards, and environmental and international laws. The standard was originally updated triennially, but since 1980 updates have been done about every 7 years. There are eight additional ANSI standards encompassing other laser uses, such as lasers in healthcare and military settings. Although the US Army uses ANSI Standard Z136.1 directly, the US Air Force and Navy maintain their own standards: Air Force Occupational Safety and Health Standard 161-10<sup>33</sup> and Office of the Chief of Naval Operations (OPNAV) Instruction 5100.27.<sup>34</sup> The Army also maintains several regulations and technical bulletins pertaining to laser use (Table 23-3).

Title 21 CFR, Part 1040, dictates performance standards for all laser devices manufactured after 1976.<sup>35</sup> In July 2001, the Food and Drug Administration (FDA) issued guidance stating that some parts of the International Electrotechnical Commission 60825-1 standard may be substituted.<sup>36,37</sup> Additionally, some exemptions have been made for the military.<sup>35</sup> Soon after the FDA regulation was promulgated, the DoD obtained exemptions for tactical systems, outdoor training lasers, and lasers classified as in the interest of national defense. In addition, alternative design criteria were developed for the Army, Navy, and Air Force, which were published in Military Standard 1425A.<sup>38</sup> Military Standard 882E addresses safeguards from other, related potential hazards.<sup>39</sup>

Even certain environmental laws affect the use of lasers and laser facilities. Congress passed the National Environmental Policy Act of 1969 to minimize adverse environmental consequences of federal actions. Certain provisions of the act are incorporated into other federal regulations, including the National Historic Preserva-

tion Act of 1966 and the Endangered Species Act of 1973. Army Regulation 200-1, *Environmental Protection and Enhancement*, contains Army policy pertaining to these matters.<sup>40</sup> Because lasers can be used outdoors on a range, the effect of laser radiation on endangered species and other wildlife must be considered.

Lasers are also subject to state and international regulation. The United States is part of the North Atlantic Treaty Organization, which maintains a standardization agreement on laser radiation, Standardization Agreement 3606.<sup>41</sup> New York and Texas have also set restrictions for laser use.

Official standards do not yet address the use of high-intensity optical sources other than lasers. Safety guidelines for these sources are provided in the ACGIH publication, *Threshold Limit Values and Biological Exposure Indices*.<sup>42</sup> This document provides guidelines for the use of intense visible sources, which can produce retinal thermal injury; sources of intense blue light, which can produce retinal photochemical injury; and IR radiation, which can adversely affect the lens. These guidelines will probably provide a basis for future Army standards regarding these sources.

### Laser Hazard Classification

Lasers and laser systems are evaluated to determine the severity of hazard they are capable of posing. Each laser or laser system is classified in one of four basic hazard categories; class 1 is the least hazardous and class 4 is the most.<sup>35</sup> Class 1 lasers do not pose a hazard to personnel, even if all the energy emitted were focused into a person's eye. Most range finders, as well as the training mode on many military systems, fall into this category. If a laser system falls below the class 1 limit for unaided viewing, but would be classified as class 3R or 3B when optics such as binoculars are used, then it is considered a class 1M laser, with an associated hazard distance during the use of optics.

Class 2 lasers, which must be visible wavelength lasers, only pose a hazard if an individual overcomes the normal aversion response and stares into the laser for more than 0.25 seconds. Lasers less than 1 mW are categorized as class 2. If a laser system falls below the class 2 limit for unaided viewing, but would be classified as class 3R or 3B when optics such as binoculars are used, then it is considered a class 2M laser, with an associated hazard distance during the use of optics.

Class 3 is divided into two subclasses, 3R and 3B. Class 3R is the boundary category, in which lasers are considered to pose a remote hazard, but are given a hazard distance and some controls. The class 3R limit is five times the class 1 limit for lasers outside the visible spectrum, and five times the class 2 limit for lasers

**TABLE 23-3**  
**US ARMY GUIDANCE ON LASER USE**

<b>Regulation</b>	<b>Title</b>	<b>Purpose</b>
AR 40-5	<i>Army Public Health Program</i>	Regulation to establish the Army Radiation Safety Program
DA PAM 40-11	<i>Army Public Health Program</i>	Department of the Army Pamphlet to give guidance on execution of the regulation
AR 385-63	<i>Policies and Procedures for Firing Ammunition for Training, Target Practice, and Combat</i>	Regulation to provide procedures for operating lasers outdoors on a US Army range
TB MED 524	<i>Control of Hazards to Health from Laser Radiation</i>	Technical bulletin provides exposure limits and guidance, establishes responsibilities for personnel protection from optical radiation; applies to active US Army, National Guard, Army Reserve, and Corps of Engineers facilities
21 CFR 1040	Food and Drug Administration, Center for Devices and Radiological Health, Performance Standards for Light Emitting Products	Over-arching standard that the Army cites for standard implementation; states that ANSI/IEC standards may also be used for determining the MPEs and safety constraints of lasers and high intensity optical sources
ANSI Z136.1	Safe Use of Lasers	Provides the main information for setting the standard the Army uses for determining user hazards, based on accessible emission limit to personnel, of lasers and high intensity optical sources
ANSI Z136.6	Safe Use of Lasers Outdoors	Utilizes ANSI Z136.1 and expands upon guidance for using lasers outdoors and in a range environment
IEC 60825-1	International Standard for Safety of Laser Products	Provides guidance for manufacturers of lasers on safe emission limits from laser devices based on an international consensus and standard

ANSI: American National Standards Institute; IEC: International Electrotechnical Commission; MPE: maximum permissible exposure

within that spectrum. Class 3B lasers are capable of producing a permanent injury to the retina from even a momentary exposure, and therefore the Army requires 3B lasers to be inventoried and their operators trained in laser safety. The class 3B limit is 0.5 W.

Class 4 lasers are those with an average output power exceeding 0.5 W. Some are capable of producing thermal injuries on the skin; others pose hazards from combustion or diffuse reflections.

Many lasers may contain dangerous or powerful laser radiation within an enclosure of some kind, but only emit class 1 or 2 radiation into accessible areas. A laser system is classified based upon its accessible radiation, and therefore the classification of the device contained within an appropriately interlocked enclosure is not considered in the overall classification. For example, a laser etching system may employ a class 3B or 4 laser, but that laser is within an opaque box with an interlocked lid that only allows radiation not exceeding the class 1 limit to escape. Therefore, this laser etcher is considered a class 1 system.

### **Military Applications**

Using light for long-range, line-of-sight communications is not new. Paul Revere received a coded message in light before his ride in 1775. Morse code utilizing light was widely used during World War II. Current military uses of laser systems (both hand-held and mounted on vehicles and aircraft) include range-finding and distance measurement, tactical target designation, and simulation of ballistic characteristics for training purposes. Lasers can also be used as part of fire-control systems and in conjunction with night-vision and IR-sensing technologies. Many devices combine some or all of these lasers into a single device.

### **Laser Range Finders**

Laser range finders emit a single pulse or series of pulses toward a target. A counter is activated when the pulse is emitted. When light contacts the target, a diffuse reflector, it is scattered in all directions.

Optical sensors receive the light reflected back to the range finder and deactivate the counter. Thus, the distance from the range finder to the target can be calculated from the time of travel between the laser and target and the speed of light using the formula

$$r = (c \cdot t) / 2$$

where  $r$  is the range,  $c$  is the speed of light, and  $t$  is the time at which the counter is stopped (ie, the round-trip time of the laser pulse).

Most modern range finders have moved to wavelengths beyond 1,500 nm, where MPEs are more relaxed due to the eye's inability to focus light at that wavelength. The AN/PVS-6 Mini Eyesafe Laser Infrared Observation Set is a hand-held laser range finder first introduced in the 1980s, making it one of the first range finders to emit outside of the retinal hazard region. Laser target locators, including Vector 21 and Mark VII variants, are newer handheld or tripod-mounted range finders. The AN/PED-1 Lightweight Laser Designator Rangefinder is a larger, tripod-mounted system that incorporates a class 4 designator along with the range finder module. The AN/PSQ-23 Small Tactical Optical Rifle-Mounted Micro-Laser Rangefinder is, as the name suggests, a small-arms-mounted laser for target ranging and location. All of the range finders in these systems are class 1 and emit beyond 1,500 nm.

A related technology is LIDAR (light detection and ranging, also known as LADAR), which uses a rapidly scanning laser to create a picture of the scanned object or environment. While generally more powerful than typical range finders, LIDAR systems are usually rendered safe by the scanning motors. A scan failure, which causes the beam to "stare" at a single point, can result in potentially hazardous exposure. Special-purpose LIDAR systems, such as airborne terrain-mapping or water-penetrating LIDAR, may pose a hazard even after accounting for scan rate.

### *Designators and Markers*

Designators and markers (the terms are sometimes used interchangeably) include some of the most potentially hazardous lasers in military use, with both direct and indirect hazards. These devices continuously emit a coded laser pulse toward the target, and the scattered radiation is then picked up by the receiver on a missile, bomb, or artillery projectile. Guidance systems then maneuver the munitions toward the source of the scattered radiation. To achieve precision marking at long ranges, the laser beam must be both high power and low divergence, making it a potential

personnel hazard over long distances. Ocular hazard distances for laser markers frequently extend into the tens of kilometers.

Because of the performance requirements of laser designation, Nd:YAG, emitting at 1,064 nm, is still the lasing medium of choice for these systems. Systems currently in use include the aforementioned Lightweight Laser Designator Rangefinder, as well as the AN/PEQ-1 Special Operations Forces Laser Marker, another tripod-mounted designator. The Apache helicopter's target acquisition designation sight is a long-serving airborne designator. The handheld laser marker is a system designed for close-range target marking, with the intent that users will hand off the target to a longer-range marker before munitions are released. All of these lasers are class 4 and emit at 1,064 nm.

### *Pointers and Illuminators*

Some of the most commonly produced and issued lasers in the military today are small-arms-mounted pointing and illuminating devices. Most of these emit in the near IR, within the detectable range of night vision systems. Generally, a pointer is considered an elevation- and windage-adjustable laser with a narrow beam, while an illuminator is essentially a flashlight that illuminates only for those using night vision optics. Pointers are typically class 3R or 3B, whereas illuminators span from class 1 to class 4. Stationary illuminators meant to expose large areas (eg, over ranges) are generally classified as more hazardous than personal, rifle-mounted illuminators, but there are exceptions.

The multifunction aiming light family of lasers includes some of the most ubiquitous pointer/illuminator devices, such as the AN/PEQ-15 Advanced Target Pointer Illuminator Aiming Light (ATPIAL). The ATPIAL, which may be hand-held or weapon-mounted, integrates a visible aim pointer for daylight use, an IR aim pointer for use with night vision, and an IR illuminator. The AN/PEQ-15A Dual Beam Aiming Laser Advanced is similar in function; both devices are class 3B.

### *Directed Fire Simulator*

Lasers are used extensively in military training to simulate ballistic characteristics of live-fire weapons. The most frequently used laser training system is the Multiple Integrated Laser Engagement System, which uses laser diode technology. In most cases, the diode used is gallium arsenide, which emits a wavelength of about 905 nm. The laser diode is programmed to emit a code of pulses that lets the receiver, attached

to the trainee's target, determine which weapon is being simulated. Lasers developed for the program are required to be class 3R or below.

### *Countermeasures and Escalation of Force*

The increased interaction between the US military and foreign civilian populations brought about by the conflicts in Iraq and Afghanistan has spurred development of crowd control and escalation of force technologies. Ocular disruption lasers, such as the GLIS, are among those that have been fielded. These green beam devices are meant to flash-blind or startle targets without causing permanent injury. This gives soldiers the ability, for example, to determine the intent of a vehicle approaching a checkpoint by blooming its windshield with bright green light. These systems are almost all class 3B.

A conceptually related (but practically and technologically very different) technology is the laser countermeasure system. Primarily airborne, these lasers seek and track incoming guided munitions and send a beam directly into the munitions' sensors, blinding them. Because ocular safety is a minor concern in this scenario, these lasers are made as powerful as practical in order to maximize the blinding effect.

### *New Applications*

Research and development in laser technology has expanded rapidly within the military in the last 2 decades. Niche applications have prompted the creation of highly specialized lasers with limited production runs; maturing technology is allowing old ideas to finally become reality; and some laser technologies are being commercialized for the first time.

A recent trend has been toward longer wavelength lasers and optics. Night vision technology is being expanded to include so called "thermal" wavelengths, the parts of the spectrum in which warm objects, including people, radiate. New types of semiconductor diode lasers have enabled the creation of laser beams in this part of the spectrum as well. Looking even further into the future, novel high-efficiency solid-state masers hold the promise of closing the terahertz gap, a region of the electromagnetic spectrum in which few devices are capable of emitting.

The recent publicized success of naval laser weapons research hints at a future in which lasers take on an even more active role in warfare. Less celebrated, but just as significant, are the relatively portable high-powered lasers that have become practical solutions to in-the-field materials processing and ground-based directed energy weaponry. Such powerful systems

were formerly restricted to experimental setups in laboratories, where hazard control is much simpler.

Another formerly laboratory-confined technology that has recently seen advances in commercialization is the mode-locked laser. Although laser mode locking has existed since the 1960s, its implementation has been too complicated and delicate for use outside of the laboratory, and certainly for military applications, until recently. The key attributes distinguishing mode locking from other laser technologies are an extremely high pulse repetition frequency, extremely short-lived pulses, and broad frequency bandwidth. There is currently little experimental data on the biological effects of these ultrashort pulses.

There are no doubt many other novel laser applications to come over the next decades, unforeseen by the authors. Despite over 50 years of intense research and development in academia and industry, laser applications, and optical technology generally, continue along a kind of Moore's law trajectory, creating new challenges in clinical practice and injury prevention.

### **Laser and Optical Radiation Exposure Incidents**

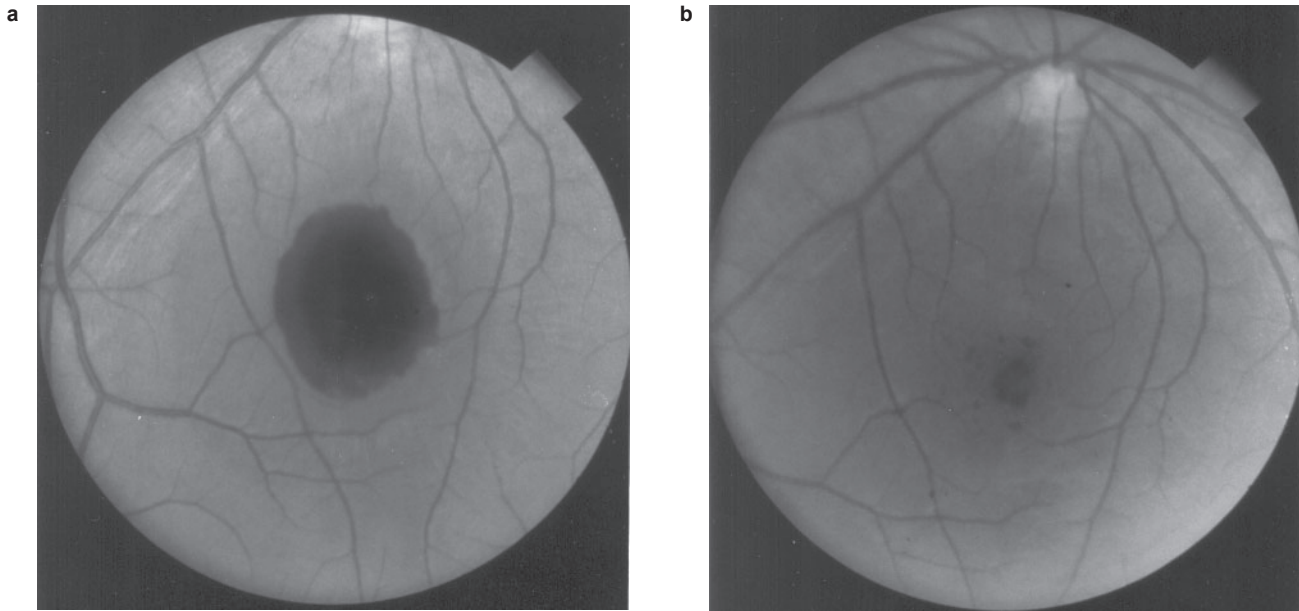
Unlike RF radiation overexposures, few incidents of potential laser and optical radiation overexposures have been reported since 1981, when the Army Environmental Hygiene Agency (now USAPHC) began investigating them. In 1988, a formal procedure was established for the investigation of laser and RF radiation exposure incidents. This procedure may involve a formal investigation followed by an official report, but only when directed by the Office of The Surgeon General.

The following four case studies of laser and optical radiation exposures have been selected to illustrate the range of incidents that the USAPHC investigates. The first two concern serious retinal injuries, while the third and fourth describe incidents in which the reported ocular effects were inconsistent with the potential laser exposure.

#### *Case Study 23-3*

On March 3, 1987, a civilian employee at Aberdeen Proving Ground, Maryland, was adjusting an Nd:YAG-pumped dye laser when he reported seeing a single orange flash. The laser was operating at a wavelength of 620 nm with a pulse-repetition frequency of 10 Hz. The individual was not wearing laser eye protection at the time because it inhibited his view, and viewing the beam is essential for performing adjustments.

During the eye examination conducted after the exposure, the individual reported seeing a central reddish scotoma approximately 2 ft in radius in his right eye when observing



**Figure 23-17.** (a) The retinal photograph of an accident victim's right eye shows macular hemorrhage. (b) The retinal photograph of the patient's right eye, taken 3 months after the accident, shows recovery to 20/20 vision.

a large object 20 ft away. The examination showed visual acuity of 20/x (not measurable) for the right eye, and 20/20 for the left eye. A fundoscopic examination showed a macular hemorrhage approximately 1.5 disc diameters wide in the right eye and a normal left eye. Retinal photographs were taken on the day of the injury and on follow-up eye examinations (Figure 23-17).

The examinations and investigation believe that the individual probably received a total intraocular exposure of approximately 550  $\mu\text{J}$ , which is 3,000-fold greater than the occupational exposure limit of 0.19  $\mu\text{J}$ . The injury was consistent with the exposure parameters. The individual did regain 20/20 vision in the injured eye, but continues to experience a slight visual degradation in his visual field when using the affected eye for monocular vision.

#### Case Study 23-4

On July 18, 1989, a US Army soldier stationed in the Federal Republic of Germany reported two laser exposures induced by an MX-9838 AN/GVS-5 laser IR observation set. The soldier claimed that he was exposed to the direct beam at 10 to 12 in. from the source. With each exposure, the soldier reported seeing a whitish flash, hearing a click, and then immediately seeing a dark spot in his visual field. Later, he reported seeing what appeared to be dark jellyfish tendrils in his field of view, which appeared red in high-level ambient illumination.

Because the GVS-5 is a single-shot laser range finder, a maximum of one injury is expected per exposure. The retinal examination, however, showed four separate lesions in and around the macula. The ophthalmologist, who examined the soldier the day following the injury, found the right eye

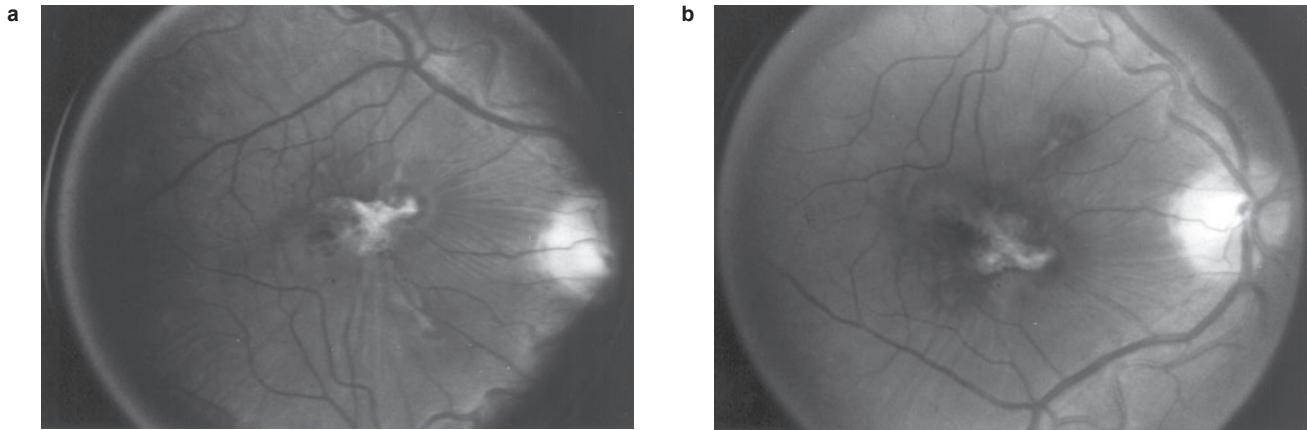
to demonstrate poor visual acuity (20/400), and the left eye to demonstrate 20/20 visual acuity (Figure 23-18). Although the ophthalmologist found the left eye to be normal, the right eye had sustained multiple macular and perimacular laser burns with edema, subretinal hemorrhages, rupture of the internal limiting membrane, and vitreal hemorrhage.

The eye examination and the Army Environmental Hygiene Agency investigation concluded that the maximum intraocular exposure for each pulse could be 15 mJ at 1,064 nm, if the exposed eye collected all the radiant energy emitted. The occupational exposure limit for a pulse less than 50 microseconds at 1,064 nm is 1.9  $\mu\text{J}$ . The potential exposure was therefore approximately 8,000-fold greater than this limit. Although the severity of the injuries was consistent with the exposure, the number of injuries was not consistent with the incident as reported.

#### Case Study 23-5

On October 4, 1984, an individual at Jefferson Proving Ground, Indiana, reported being exposed to a helium-neon laser for 1 to 2 minutes. The individual reported seeing a dark afterimage in a uniform circle, approximately the size of a golf ball. The afterimage gradually disappeared, and it had completely disappeared within 1 hour after the alleged exposure.

The individual had two eye examinations after the alleged incident. An examination performed 6 hours after the incident showed visual acuity of 20/30 for the right eye, and 20/20 for the left eye. The individual reported no visual disturbances. Six days later, a follow-up examination demonstrated 20/20 visual acuity in both eyes. Neither of the two examinations revealed any ophthalmoscopically visible retinal changes.



**Figure 23-18.** (a) This retinal photograph of the patient's right eye was taken three weeks after the incident. Little change is noted and vision has not improved beyond 20/400. (b) This retinal photograph of the patient's right eye was taken approximately 1 month after exposure to an AN/GVS-5 laser.

Like the eye examination, the Army Environmental Hygiene Agency investigation of the incident failed to prove that an overexposure had occurred. The investigation showed that at the time of the alleged exposure, the individual was located approximately 8.1 m from the transmitter. The laser was rigidly mounted and the direct beam's height was too far above the ground to expose the individual's eyes. If the individual had been exposed to the direct beam at this distance, he would have received a corneal irradiance of  $170 \mu\text{W}/\text{cm}^2$ . Approximately 1 minute of exposure to  $170 \mu\text{W}/\text{cm}^2$  is permitted, and similarly, 8 hours of exposure is permitted for  $17 \mu\text{W}/\text{cm}^2$ . The actual exposure was probably approximately  $1.7 \mu\text{W}/\text{cm}^2$ , which is far below the 8-hour limit. Therefore, the individual was not exposed beyond the occupational limit, and the persistence of the afterimage was not consistent with the exposure level.

### Case Study 23-6

On July 2, 1986, while inside the turret of an M60A3 tank at Fort Indiantown Gap, Pennsylvania, an individual performed a self-test on a ruby laser range finder operating at 694.3 nm. Within one-half hour of performing the self-test, the individual complained of an irritation in his left eye. Inflammation increased, becoming more intense over the next 4 days. When the individual returned to work after a holiday, he was sent for an examination. The civilian ophthalmologist's examination proved normal, except for a preexisting nevus on the fundus of the left eye, and episcleritis and keratitis of the left eye. The ophthalmologist did not attribute the nevus to laser exposure, but did attribute the episcleritis and keratitis to accidental laser exposure because the individual had been working with lasers at the onset of these conditions.

US Army ophthalmologists examined the individual's eyes and disagreed with the findings of the civilian ophthalmologist. The patient was then flown to Walter Reed Army Medical Center for examination 4 days after the initial eye examination. Army ophthalmologists there agreed with the clinical findings of the civilian ophthalmologist, but were more guarded about

attributing the other two findings to laser exposure. Contrary to the civilian ophthalmologist's conclusion, episcleritis is a relatively common inflammation of the anterior segment of the eye and its cause is usually unknown. Similarly, the civilian ophthalmologist's conclusion that a ruby laser induced the keratitis is inconsistent with scientific and clinical evidence suggesting that red light at 694.3 nm cannot damage the cornea unless it is of sufficient intensity to cause catastrophic injury to postcorneal ocular tissue. The onset of the episcleritis and keratitis after the laser self-test was coincidental. In addition, radiometric measurements verified that no laser radiation was present inside the turret during the self-test.

### The Laser Safety Program

The laser safety program adopts many aspects of the RF safety program. The installation or activity RSO is responsible for control of laser radiation sources within their organization. Lasers that are classified as class 3B or 4 need to be controlled and included in a comprehensive nonionizing radiation safety program. A typical laser safety program includes elements such as an inventory of all lasers within the organization that are classified as class 3B or 4, engineering controls and administrative procedures, laser safety training, and laser eye protection. Outdoor laser ranges must be in an approved setting designated by the organization RSO, with additional controls. See Exhibit 23-1 for the DoD laser injury hotline and service-specific safety program contact information.

### *Inventory of Laser and High Intensity Optical Sources*

A complete list of laser radiation sources should be available to the RSO. Included in the list should be laser specifics such as laser wavelength, output power

or energy, nominal ocular hazard distance (if necessary), laser eye protection optical density, location of the laser source, and the classification of the laser. Laser sources with classifications of 3B and 4 should be included in the inventory because they are capable of causing injury. Classes 1, 2, and 3R do not need to be listed because they do not require safety controls for operation.

### ***Engineering Controls and Administrative Procedures***

When dealing with the higher power class 3B and class 4 laser sources, care must be taken to ensure safe use of the device and prevent potential overexposures. The laser system must use engineering controls, such as remote interlocks, key control, emission indicators, and shudders/beam stops to prevent undesired laser radiation emission. CFR 1040.10 outlines specific engineering controls based on the laser classification. These controls are designed to prevent unintentional use or exposure by turning the laser off or placing it into a known safe state (not emitting radiation). Administrative procedures protect personnel through placement of signage (entry doors to laboratories, entering the laser approved range, etc) to alert personnel of the potential for laser radiation in a given zone. For lasers with relatively long nominal ocular hazard distance, the RSO should establish a nominal hazard zone.

If a laser system cannot meet all criteria for engineering controls set forth CFR 1040.10 or ANSI Z136.1, an exemption may be filed with the FDA. Typical exemptions are for signage, emission indicators, and key controls, or allowing a class 3B or 4 laser to omit a specific safety feature. For example, placing a standard laser aperture sign on the device may compromise camouflage and affect mission performance. FDA exemptions for lasers are only applicable to DoD laser systems, and the laser must be used in combat or combat training situations for the exemption to apply. Exempt military lasers, regardless of hazard class, must be included in the laser safety program and inventoried to satisfy the requirements of the DoD exemption.

### ***Training Programs***

Laser safety training is necessary for all personnel who operate potentially hazardous lasers and high intensity optical sources. This training should include instruction concerning the specific equipment, protection methods for prevention of overexposure, and emergency procedures if an incident does occur. Instructors involved in the training should receive

further instruction on basic optics, biological effects of lasers, laser safety standards, laser eye protection and protective garments, and preparation of laser range areas. Additionally, instructors or RSOs must familiarize themselves with the approved reporting channels in the event of a suspected laser incident or injury.

### ***Laser Eye Protection***

Laser eye protection is the last line of defense when operating class 3B or 4 lasers and protecting the eyes from potential overexposures. Laser eye protection provides attenuation to the incoming laser light, and dissipates the energy or power, dropping the exposure to below the applicable MPE. A note of caution: laser eye protection is wavelength specific, including certain dyes and materials within the lenses to attenuate the laser yet provide vision in wavelengths not emitted by the laser source. It is important to match laser emission to the wavelength and the relative stopping power (optical density) of the laser eye protection. For example, if using an Nd:YAG designator at 1,064 nm (near IR), make sure the laser eye protection has a significant optical density protection for a wavelength of 1,064 nm.

Currently, the only approved brand of laser eye protection is Revision Sawfly (Revision Military, Essex Junction, VT). Previous versions of laser eye protection, such as the ballistic/laser protective spectacles, are aging technology and are no longer procured by the DoD. The two current Revision Sawfly lens options offer two- and three-wavelength laser protection, and are interchangeable with regular safety glasses and sunglass lenses.

### ***Outdoor Ranges and Laser Range Controls***

General range control philosophy, and a general laser safety concept, is to prevent direct and collateral injury or damage to personnel or equipment resulting from laser use. Key elements to an outdoor laser safety range program include: (a) the use of backstops, both natural and manmade; (b) buffer zones defined by the pointing accuracy of the laser; (c) a limited line of sight to occupied areas; (d) maintenance of communication if down-range of the laser firing point; (e) avoidance of specular surfaces that may reflect the laser beam, such as water or metallic surfaces; and (f) appropriate warning signs and lights or sirens during the laser's operation. Individuals down range within the laser hazard danger zone are also required to wear laser eye protection when working with or observing targets. The ultimate goal of the laser range RSO is to follow the standard operating procedure for safe operation



of the laser on the range. He or she must also ensure that the danger zone is controlled so personnel are not exposed to laser radiation above the MPE limits (class

1). Control of the danger zone may be mitigated by terrain (firing the laser into a mountain or hill backstop) or delineated out to the nominal ocular hazard distance.

## SUMMARY

Electromagnetic radiation may be ionizing or non-ionizing. Nonionizing radiation includes electromagnetic radiation with wavelengths greater than around 100 nm, which is divided into the categories of UV radiation, visible light, IR radiation, terahertz radiation, microwave radiation, and RF radiation. Nonionizing radiation possesses a variety of physical characteristics, such as divergence, interference, coherence, and polarization, which, together with the media with which the radiation interacts, determines how the radiation is scattered, absorbed, reflected, transmitted, refracted, or diffracted. It can interact with tissue in a variety of ways, the most medically important being absorption in tissue and photochemical reactions in the blue light and UV wavelength regions. Optical radiation effects occur to the eyes and the skin. RF radiation can affect all organs of the body; however, the eyes and skin are generally the most sensitive.

The protection of Army personnel from overexposure to nonionizing radiation is accomplished through a comprehensive radiation protection program. The implementation of the program is the responsibility of the installation or activity commander. To this end, consensus standards for occupational exposure to nonionizing radiation have been developed and are enforced through Army regulations. Procedures have been established for the investigation of alleged overexposure incidents. The incidence of accidental exposure to nonionizing radiation in excess of established limits has been rare, especially considering the number and variety of sources in use today and the types of environments where they are used. The best medicine is preventive. In the event of an accidental overexposure, it is the responsibility of the attending physician to determine if an injury has occurred and to prescribe the treatment. An eye examination should be performed at the minimum.

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