**CHAPTER 11 –NON-IONIZING RADIATION**

**Introduction**

One hallmark of the technological change since WWII has been the increasing use of the electromagnetic spectrum.

This chapter presents the basic principles of electromagnetic fields and radiation and how to protect people from the hazards associated with energy.

**Electric and Magnetic Fields**

** electric fields**

All matter is made of atoms, which are divided into the nucleus (containing protons and neutrons), and electrons (that orbit around the nucleus).

The protons in the atomic nucleus carry a unit of positive charge, and the electrons orbiting the nucleus carry a negative charge.

Usually, objects are electrically neutral because the amount of positive and negative charge in the matter is equally balanced so the net charge is zero.

Objects can become charged when this balance is altered:

 objects with an excess of electrons have a negative charge;

 objects with a deficit of electrons will likewise have a positive charge.

- negative charges attract positive charges (cancel out) and repel other negative charges;

- positive charges attract negative charges (cancel out) and repel other positive charges.

Any charged object creates a powerful *electric field*, whether the object is stationary or in motion.

The charge state is called *polarity* (+ or -).

The electric force exerted by a charged object on another charged object depends on:

 the amount of charge on both the objects;

 the polarity of the charges on the objects; and

 the distance between them.

Note: An atom or molecule carrying an electric charged is called an *ion*.

Larger objects that have a charge imbalance are said to be *electrostatically charged*.

The force on the charged objects is directly proportional to the amount of charge and decreases with distance according to an inverse square relationship described by *Couloumb’s law*.

The force between two point charges can be stated as:

$$F\_{e}= k\_{e}  \frac{q\_{1}q\_{2}}{r^{2}}$$

where: *Fe* = electric force between the objects

 *q*1 = net charge on first object

 *q*2 = net charge on second object

 *r* = distance between the objects

 *k*e = constant (SI: 9  109 *Nm*2/*C*)

Note: The inverse square relationship causes the electric force to fall off rapidly with increasing distance (e.g., at 2X distance, force is ¼, at 3X distance, force is 1/9).

** magnetic fields**

The electric force exists regardless of whether the charges are stationary or not.

However, a moving electric field creates a *magnetic field* that exerts a force on other moving charges.

Imagine electric charges are moving in some direction, such as electrons flowing through a wire.

The amount of charge flowing past a given point in a defined period of time is called the *electric current*.

Magnetic fields exist in a direction perpendicular to the direction of the current flow.

The magnetic field lines can be visualized by pointing the thumb of the right hand in the direction of the current flow in the wire and them curling the fingers around the wire.

The magnetic field lines will follow the curl of the fingers, forming a series of closed loops surrounding the wire.

Thus, magnetic fields don’t radiate out into space as electric field lines do; instead, they return to the other pole

A magnetic field exerts a force on moving electrically charged particles in a direction perpendicular to both the field and the direction of motion.

The force is proportional to the amount of moving charge (the current flow) and the distance between the system carrying that current and a charged object.

When a magnetic field changes in time, it causes non-moving charges to move, and induces a current flow in objects that conduct electricity, including the human body.

Thus, a person in a changing magnetic field experiences current flows in loops inside the body.

People are usually unaware of this internal current flow, but it is always happening because they are immersed in magnetic fields that change with time (time-varying fields) arising from the transmission and use of alternating current (AC) electricity.

On AC electricity, the polarity (direction) and strength of the current flow deeps alternating between positive and negative.

Note: In the U.S. and Canada, polarity changes occur 60x/sec (50x/sec in Europe and elsewhere).

**- Ohm’s Law**

Resistance describes the proportionality between the current flow in a conductor and the potential difference (voltage) across the conductor.

According to Ohm’s law, the source voltage equals the current flow in a circuit times the resistance

*V = R  I*

where: *V* = voltage

 *R* = resistance (in ohms, *Ω*)

 *I* = current (in amperes, *A*)

The volt is a measure of the energy available per unit charge, so the power (*P*) used in the circuit is the product of the voltage times the current, expressed in units of watts.

*P = V  I*

**- Joules’ Law**

Applying the units described here shows that the power (in watts) is also equivalent to the energy dissipated.

It follows that the power dissipated in an electrical circuit due to resistance is proportional to the square of the current (i.e., the power lost is proportional to the square of the current).

This relationship is described by Joules’ law:

*P = R  I2*



**Electric Power Transmission**

*Electric power transmission* is the bulk transfer of electrical energy from generating power plants to electrical substations located near demand centers.

This is distinct from *electric power distribution*, which refers to the local wiring between substations and customers.

Transmission lines, when interconnected to each other, become *transmission networks*.

The combined transmission and distribution network is known as the *power grid*.

In the early days, electric power was transmitted at the same voltage as used by lighting and mechanical loads, which restricted the distance between generating plants and consumers.

In 1882, generation was with *direct current (DC)*, which could not easily be increased in voltage for long distance transmission.

Different classes of loads (e.g., lighting, fixed motors, traction (railway) systems) required different voltages, and so, used different generators and circuits.

Altogether, early electric power transmission and distribution resulted in a myriad of interlaced conductors (see images below).

Electrical engineers in the early 20th century faced a problem figuring out how to transmit electric power to distance points.

The power losses became prohibitive when large direct currents were transmitted over long wires.

The solution to the problem was to transmit electric power over the wires using a high voltage and a small current so that the power losses were smaller.

This approach required that the high voltage be converted back down to a lower voltage (and corresponding higher current) at the place where the electric power was being used.

The answer to this problem was to keep changing the polarity of the voltage and current and use the resulting changes in magnetic fields to induce another current.

The transformer and Nikola Tesla’s *alternating current (AC)* were essential for a combined AC distribution system for both lighting and machinery.

Regarded as one of the most influential electrical innovations, the universal system used transformers to step-up voltage from generators to high-voltage transmission lines, and then to step-down voltage to local distribution circuits or industrial customers.

By using common generating plants for every type of load, important economies of scale were achieved, resulting in reduced cost for consumer and increased overall use of electric power.

** transformers**

A *transformer* is a device that swaps current for voltage and *vice versa*, while maintaining an approximate constant power flow across the device.

A transformer couples two circuits; a primary circuit that feed in power and a secondary circuit where a load consumes the power.

A transformer consists of two separated coils of wire wrapped around a core.



**- induction**

When a fluctuating electric current (AC) flows through a wire, it generates a magnetic field around the wire.

Conversely, when a magnetic field fluctuates around a piece of wire, it generates an electric current in the wire.

The strength of the magnetism is directly related to the size of the electric current.

The coil that is energized is known as the *primary coil*.

If a second coil of wire (*secondary coil*) is placed near the first one (but not touching), and a fluctuating current is sent through the first, an electrical current will be induced (*induction*) to flow in the secondary circuit.

Note: Transformers do not work with DC, where a steady current constantly flows in the same direction.

**- step-up transformers**

Boost low voltage to a higher one:

If the secondary coil has twice the number of turns as the first coil, the secondary voltage will be twice the size of the primary voltage.



To calculate the change between the current in the secondary circuit vs. the primary circuit:

II° voltage ÷ I° voltage = # turns in II° coil ÷ # turns in I° coil

and

II° current ÷ I° current = # turns in I° coil ÷ # turns in II° coil

**- step-down transformers**

Step-down high voltage to a lower one:



** transmission lines**

Transmission line conductors are made of aluminum wire wrapped around a steel cable core (aluminum-conductor steel-reinforced – ACSR)

Aluminum is used because it has about half the weight of a comparable resistance copper cable, as well as being cheaper, while the inner, steel cables are included for strength.

The length of the conductor cable will change depending on air temperature, the weight of additional load such as ice cover, and heating resulting from resistance to the electrical current being carried.

Note: A minimum overhead clearance must be maintained for safety.

**- conductor size**

**Pouillet’s Law**

The resistance of a given material will increase with the length, but decrease with increasing cross-sectional area.

$$R= \frac{pL}{A}$$

where: *p* = resistivity of material current is flowing through

 (in *Ω /* *d* (distance))

 *L* = length of conductor

 *A* = cross-sectional area of conductor

Example: Assume transmission of a current over a distance of one mile through a 3-inch and a ½-inch copper conductor.

To bring units into a common form, first convert the distance in miles to distance in inches:

$$1 mi  \frac{5280 ft}{mi}  \frac{12 in}{ft}=63360 in$$

Next, calculate the cross-sectional area of both conductors: ($A= π  r^{2}$)

4-inch conductor: $A= 3.14  2 in^{2} $

$A= 3.14  3 in^{2}$

$$A=9.0 in^{2}$$

0.5-inch conductor: $A= 3.14  0.25 in^{2}$

$A= 3.14  0.0625 in^{2}$

$$A=0.20 in^{2}$$

Next, perform the final calculations: $R= \frac{pL}{A}$

4-inch conductor: $R= 4.27  10^{-10}Ω/in  \frac{63360 in }{9.0 in^{2}}$

 $R= 3.01  10^{-6} Ω/in$

0.5-inch conductor: $R= 4.27  10^{-10}Ω/in  \frac{63360 in }{0.20 in^{2}}$

 $R= 1.35  10^{-4} Ω/in$

 **Resistivity of Common Materials**

 **Material Resistivity (*Ωm*) Resistivity (*Ωin*)**

Silver (Ag) 1.59  10-8 6.26  10-7

Copper (Cu) 1.68  10-8 6.61  10-7

Gold (Au) 2.44  10-8 9.61  10-7

Aluminum (Al) 2.82  10-8 1.11  10-6

Iron (Fe) 1.00  10-7 3.94  10-6

Carbon Steel 1.43  10-7 5.63  10-6

Stainless Steel 6.90  10-7 2.72  10-5

Sea Water 2.00  10-1 7.87

Drinking Water 2.00  102 7.87  103

Wood (damp) 1.00  103 3.94  104

Glass 1.00  1013 3.93  1014

Hard Rubber 1.00  1013 3.93  1014

Wood (dry) 1.00  1015 3.93  1016

 Air 2.30  1016 9.06  1017

**Electromagnetic Radiation**

So far, we have discussed electric and magnetic fields as single entities.

There is a common phenomenon where the two exist together: *electromagnetic radiation (EMR)*.

** frequency**

A time-varying magnetic field is able to induce an electric potential in a conductive object.

This effect is described by Faraday’s law, and is the operating principle behind many electric generators.

The number of times the fields change polarity and return to the beginning polarity in a given unit of time is called the *frequency*.

The frequency (*f*) is usually specified in full cycles of polarity reversals and returns that occur in one second: cycles per second.

In the SI system, one cycle per second is also called 1 hertz (*Hz*), and 1000 cycles per second equals 1 kilohertz (*kHz*).

Not only do the electric and magnetic fields change polarity and strength with time in a propagating electromagnetic wave, but they are mutually coupled together.

If the electric field is pointing in some direction, then the magnetic field must also exist in a direction perpendicular to the electric field, and the wave must travel in yet another direction perpendicular to the other two.

Note: In air and a vacuum, the speed of electromagnetic radiation is about 186,000 *mi/s* (299,792,458 *m/s*); the speed of light.

** wavelength**

An important way of expressing the distance the wave travels through one cycle is the wavelength (*λ*).

The amount of time elapsed during once cycle is called the *period* (which is the inverse of the frequency), in *Hz*.

The frequency times the wavelength must equal the speed of light, so as frequency increases, wavelength decreases (and *vice versa*).

Note: Depending on the reason for the examination, EMR is usually examined in terms of its frequency or its wavelength.

Since this course is primarily interested in potential health effects resulting from the energy of EMR, frequency will primarily be used.

**Electromagnetic Spectrum**

Electromagnetic radiation spans an immense range of frequencies.

We arrange the electromagnetic waves into an increasing order of frequencies.

Similar types of radiation cluster together (i.e., certain frequencies/wavelengths tend to behave similarly – infrared, visible, ultraviolet).

This arrangement is known as the *electromagnetic spectrum*.

Frequency is extremely important because the energy of a discrete parcel of electromagnetic radiation (photon) is directly proportional to its frequency.

The electromagnetic spectrum is divided into four parts in this chapter:

- subradiofrequency - 0 – 3 *kH*z

- radiofrequency/microwave (RF/MW) - 3 *kHz* – 300 *GHz*

- optical radiation - 300 *GHz* – 3  1015 *Hz*

- ionizing radiation - > 3  1015 *Hz*

The strength of the electric and magnetic fields in a free, propagating electromagnetic wave are related to one another.

The ratio of the two is a constant that represents the resistance of the medium in which the radiation is travelling.

The two fields together transmit power away from the source through an area of space that can be expressed in watts of power passing through an area of space or striking a given surface area.

It is customary to adjust the units to milliwatts of power per square centimeter of area (*mW/cm*2).

Radiofrequency and microwave specialists call this *power density*; laser and optical specialist call it *irradiance*.

These two terms have the same unit and the same meaning.

**When are Fields Important and When Is Radiation Important**

This question is important in the radiofrequency and microwave portion of the spectrum for two reasons:

 The strengths of the fields in radiation are rigidly related to each other so only one field must be measured (usually the electric field).

Both the electric and magnetic field must be measured where radiation does not exist.

 Radiation obeys the inverse square law unless the source happens to be a laser, so ta field strength measurement at one location can be used to calculate the field strengths at other distances in the same direction from the source.

Note: Separate electric and magnetic fields are commonly found at lower frequencies (longer wavelengths) or when measurements are taken “close to the source.”

Radiation is commonly found at higher frequencies (shorter wavelengths).

As a rule, “*close to the source*” is interpreted in terms of the wavelength so that separate fields are found with on e to a few wavelengths of a source.

Light has wavelengths ranging between 400 *nm* and 760 *nm*, so light is always found as radiation.

A 60 *Hz* wave has a wavelength of 3100 miles, so it follows that fields, rather than radiation, are found around power lines.

** near fields**

Found close to sources.

Near fields are divided into:

- *reactive near fields*

Electric fields created by the voltages and magnetic fields created by current flows in the source.

- *radiating near fields*

Electric and magnetic fields combine to form radiation that travels away from the source.

Note: The relationship between electric and magnetic field strengths in near fields is not rigid, so both fields must be measured separately.

** far fields**

Places where radiation is found.

Note: It is customarily assumed that separate fields exist when the wavelength is more than about 1 *m* (frequency of 300 *MHz*), and that radiation exists at shorter wavelengths or higher frequencies.

As a result, separate electric and magnetic field surveys are usually needed for frequencies of 300 *MHz* and less.

**Parts of an Electromagnetic Device**

Any electromagnetic device can be visualized as having three parts:

 a source;

 a transmission path; and

 a receiver.

Note: Particular attention should be paid to the transmission path, which could pass through open air, or be contained in an enclosed passageway that could leak at joints or connections, or be in a fiber-optic cable that could be cut or broken.

**Subradiofrequency Fields: 0 – 3000 *Hz***

Because the distance where radiation is dominant is longer than about one wavelength, fields (rather than radiation) are considered.

The wavelength of the highest frequency, 3 *KHz*, is 100,000 *m*, or about 61 *mi*.

The subradiofrequency portion of the spectrum includes the *extremely low frequency (ELF)* band, which includes AC fields and radiation up to 300 *Hz*, and the voice frequency band, which includes frequencies from 300 to 3000 *Hz*.

Power lines use 50 or 60 *Hz* currents, which create fields at those frequencies, often called *power frequencies*.

**Field Strengths**

 Electric fields can be measured by inserting a *displacement sensor* – a pair of flat conductive plates – into the field and measuring the electric potential between the plates.

The electric field lines land on one plate and induce a voltage that drives a current through the meter to the other plate.

The electric field can be calculated by dividing the voltage between the two plates by the distance between the plates.

Instruments like this are widely used for measuring electric fields at frequencies ranging up to 100 *kHz*.

 Magnetic fields are often measured with *magnetometers*, which contain loops of conducting wire.

The lines of magnetic flux passing though the loop induce current flow.

The field can be calculated by measuring the amperes of induced current and dividing that by the circumference of the loop.

The common unit of magnetic field strength in the U.S. was the gauss (*G*), but is commonly replaced by an SI unit, the tesla (*T*): 1 *T* = 10,000 *G*.

Comment: Magnetic mines.

Iron/steel ships of WWI and WWII.

Degaussing cables.

**How Fields Interact with the Body**

The body is a good conductor of electricity, but it does not have well-known magnetic structures.

Electric charge imbalances are balanced as quickly as possible.

Imagine you were below a high-voltage electric transmission line and the line’s polarity was positive.

Your body would develop a corresponding negative charge because you are a conductor, the positive charge above would attract moveable negative charges toward it.

These charges would come from your body and from the infinite pool of charges you were standing on—the ground.

The electric field lines would originate at the power line and land on your body.

If the electric field were time varying, as the polarity reversed, the charge in your body would also subside and reverse.

The rush of negative charges into our body would be replaced by an exodus of negative charges and a rush of positive charges, so you would take on a positive charge as the line overhead became negatively charged.

The time-varying electric field would induce a time-varying electric current from the earth into your body at the same frequency as the alternating voltage in the overhead power line.

The electric field lines are perpendicular to the conducting surface they end at or leave.

The result of this perpendicularity phenomenon is that a person in an electric field created by a source above the person (e.g., a power line), distorts field lines in the nearby space so they land perpendicular to the head.

As a result, the electric field around the head becomes highly concentrated and intense.

At other regions of space, the electric field lines are spread further apart, lower the field intensity.

Note: If this person was holding an electric field meter at waist height, the surveyor’s body would largely shield it, and the reading would be falsely low.

Magnetic fields are easier to measure because the human body does not perturb the magnetic field as it perturbs the electric field.

We are filled with conductive brine, so a magnetic field that changes with time induces loop-shaped current flows in a direction perpendicular to the orientation of the time-varying magnetic field.

The strength of the induced current is proportional to the strength of the magnetic field and the radius of the loop in which the current is flowing.

**Biological Effects and Standards for Steady Electric Fields**

Steady (DC) fields are created with charges and currents that do not change polarity or strength with time.

Steady electric fields are not a significant are of concern today; in fact, no instrument is marketed that is intended for use in safety surveys for DC fields.

The adverse effects are:

 irritating sparks at electric field strengths of 5 *kV/m* or more

 painful sparks at electric field strengths of 15 *kV/*m

Note: The 2012 Threshold Limit Value (TLV) for DC electric fields form 0 *Hz* to 22 *Hz* is *25 kV/m* as a ceiling limit.

The field strengths in the TLV are the field levels present in air away from the surfaces of conductors (where spark discharges and contact currents pose significant hazards).

**Biological Effects and Exposure Standards for Static Magnetic Fields**

Magnetic effects are caused by charges in motion or changes in magnetic fields.

The static fields from permanent magnets do not change with time, so any interaction would need to occur where charges are in motion.

While an animal is in a static magnetic field, the effect of static magnetic fields can be seen on an electrocardiogram (ECG).

The entire output of the heart is pumped into the aorta at high speed.

This flow induces a magnetohydrodynamic (MHD) voltage that appears on the ECG at the same time as the T-wave of the heart.

The added MHD voltage makes the T-wave look bigger.

Note: Based on this effect, the current TLV is 2 tesla (*T*), which is an eight hour time-weighted average (TWA) criterion.

The peak exposure is set at 8 *T* and a maximum value of 20 *T* for exposure to the limbs.

 Humans exposed to 4-*T* fields may experience symptoms such as nausea, metallic taste in the mouth, dizziness, and when the heads is moved, flashes of light in the eyes (known as magnetic phosphenes caused by induced currents stimulating the retina).

 Special training to limit rapid movements in high field areas should be received by workers exposed to fields > 2 *T*.

 Rotating the earth’s magnetic field (usually about 0.5 *G* (10-5 *T*) disrupts the *circadian rhythm* of test animals and fluctuations in body function that are associated with time of day (e.g., hormone levels, body temperature).

This is related to the sense of time, which is perceived as jet lag.

This effect occurs if the animal is unawares of the day-night cycles around it due to a lack of light exposure to the eye (even 9-*T* fields did not break the sense of time of animals aware of light-dark cycles).

Note: People who work in strong magnetic fields should avoid unusual shift work that causes them to lose track of day-night cycles.

**Other Safety Concerns of Static Magnetic Fields**

It is necessary to consider two related issues:

** effects on medical electronic devices**

- Artificial cardiac pacemakers work by amplifying the electrical activity of the natural pacemaker tissues of the heart.

Artificial cardiac pacemakers can be fooled by ambient electric and magnetic fields, includes very strong AC fields.

When this happens, they could amplify the AC fields instead of boosting the activity of the natural pacemaker, and the heart, now trying to work at 60 *Hz*, would not circulate blood.

- Pacemakers have built-in protection circuits that sense malfunctions and cause the pacemaker to send impulses to the heart at a fixed rate.

The wearer tests these circuits by changing the setting of a switch in the artificial pacemaker so it fires at the fixed rate.

A permanent magnet held over the pacemaker is used to reset the switch.

Thus, strong static fields could cause this switch setting to inadvertently change in places where no medical super vision is available.

Note: A pacemaker safety criterion of 0.5 *mT* (5 *G*) has been set.

** classic safety concerns**

Magnetic fields exert forces on objects that can be magnetized.

The degree to which material can be magnetized depends on its *permeability*.

- aluminum, stainless steel, plastics, and no organisms are not permeable.

- soft iron, steel, and various transition metal alloys are permeable.

Tools and some medical implants are made of permeable alloys so they can move in a strong magnetic field.

The force of such a field is proportional to the strength and gradient of the field.

Note: A steel wrench in a perfectly uniform, super-strong magnetic field would not move because there is not gradient, but it would move as it was taken from the strong field through a weak field.

Thus, limits are needed to prevent unintended motion of tools, and other objects like compressed gas cylinders or metal prosthetic implants in workers.

The simplest test devised to located hazardous locations is to tie a washer or other small permeable object to a string and tie off the other end to a belt loop and watch for places where the washer is pulled out by magnetic fields.

Note: The International Conference on Nuclear Energy and Radiation Physics (ICNERP) advises that mechanical hazards due to flying tools and movement of metallic medical implants become a potential hazard when fields are as low as 3 *mT* (30 *G*).

The ICNIRP also advise that magnetic media (e.g., magnetic stripes on the backs of credit cards, computer diskettes) can be erased by fields above 1 *mT* (10 *G*).

**Biological Effects and Exposure Standards for Time-Varying Subradiofrequency Fields**

Time-varying subradiofrequency fields, particularly ELF fields from power lines, have emerged as an area of concern because of widespread fear that they may lead to cancer.

A large body of research has accumulated, but much of it is contradictory.

The National Institute of Environmental Health Sciences (NIEHS) did classify ELF magnetic fields as a possible human carcinogen, largely based on an elevated risk of childhood leukemia.

 It is now generally (but not universally) accepted that power line fields can influence cell membranes.

This effect is observable as an increase in the rate at which calcium ions are moved from the inside of a cell through the cell membrane to the outside.

The possible effects of these interactions are potentially far-reaching, and include promotion of tumor growth; however, adverse effects have not been demonstrated in replicated experiments.

 It is also generally accepted that power line fields affect circadian rhythms much as static fields.

Circadian rhythm is controlled by the pineal gland, located in the center of the brain.

The pineal secretes the hormone melatonin at night.

Altered pineal function could reduce the ability of the immune system to eliminate infections and suppress tumors.

Health regulations fall into two broad categories:

** exposure criteria**

Specify the amount of exposure for an individual.

** emission criteria**

Describe how much can be released into or be present in the environment near a source.

Both types of regulations exist for non-ionizing radiation.

The one well-established mechanism of interaction is based on induced current flows through tissue, which can cause electrical stimulation of nerves and muscles, and tissue heating.

Many possible alternative mechanisms have been proposed, but none have been proven.

This uncertainty is important because some of the proposed mechanisms do not involve either of the classic monotonic (linear) dose-response models.

If a nonlinear dose response model is found, it is possible that a range of moderated field intensities could be hazardous, whereas stronger or weaker fields would not be hazardous.

Regulations generally have assumed that less is safer, so the possibility of “windowed” effects with respect to field strength is not considered.

The standards that do exist base on the known effects of currents induced in the body follow an increasing dose-response curve for effects and are a function of frequency.

Guidelines for magnetic fields and exposure limits can be created that are intended to place a basic restriction on induced currents the body.

Note: The ICNERP has issued general public and occupational exposure criteria (1 *Hz* to 100 *kHz*) based on induced current flow considerations.

ACGIH has also issued TLV exposure criteria for workers, based on avoiding induced currents that are stronger than those that already exist in the body due to the normal functioning of nerves and muscles.

A number of states have established emission criteria for power transmission lines by specifying maximum fields that can exist along the edges of the right-of-way.

The clamor for action has prompted researchers and regulators to develop a number of ideas.

Two are worth noting:

** prudent avoidance**

Relies on reducing magnetic or electric fields when possible by means that do not involve greater expense (similar to ALARA concept used for ionizing radiation).

** precautionary principle**

In the absence of established safety information or uncertainty about health effects, uncontrolled exposures should be limited to the extent practical in situations where new sources are being introduced.

Note: Applying these approaches in the absence of definitive scientific data may result in overly restrictive exposure limits.

**Measuring Subradiofrequency Fields**

 Electric fields are measured using variants of the displacement sensor described earlier.

The surveyor must stand away from the detector when measuring electric fields because the surveyor’s body will shield the detector and create a falsely low measurement.

Thus, these instruments come with long non-conductive handles.

These instruments are directional, and must be held so the electric field is perpendicular to the paddle.

The reading reaches a peak level when the sensor is aligned properly.

 Magnetic fields are measure with loops.

Loops are highly directional.

The current induced in a loop reaches a peak value when the plane of the loop coil is perpendicular to the flux lines of a magnetic field.

- When using a *single-loop detector*, it is necessary either to know how the field is oriented, or to measure the field with the detector pointed in one directions, then in another perpendicular direction, and finally in a third direction perpendicular to the other two.

The center of the detector must be the same for these three measurements.

- Another method of magnetic field measurement relies on the *Hall effect*.

An object with a current flowing through it in a magnetic field will develop a voltage that can be measured across it in a direction perpendicular the the magnetic field.

Personal dosimeters are now available that have three mutually orthogonal coils or Hall effect sensors, for isotropic response to magnetic fields.

Isotropic response means the response is about equal for all probe orientations in the field, and the sensor is largely non-directional.

Loops are often ganged together in mutually orthogonal array so of three loops so the detector does not operate in a directional manner.

**Controls and Shielding**

 Blocking or reducing electric fields is relatively easy using a grounded conductor.

If a sheet of conductive material was placed between the person and the overhead source, and that conductor was grounded, induced charges would flow between the conductor and the earth.

As a result, the field lines would begin at the source above the person, induce current flow in the sheet through the ground, and not reach down to the person.

The material can be solid, but in practice a mesh will do, as long as the opening of the mesh is much smaller than about one-quarter of a wavelength.

This means that screen or chicken wire can block a 60-*Hz* electric field.

Note: Operational shields must be grounded in accordance with electrical safety codes.

 Magnetic fields are much more difficult to shield.

Magnetic fields are controlled using permeable alloy that confines the magnetic flux lines into the materials and diverts them around the shielded area.

Magnetic shielding can be made using high nickel alloys called mu metal or soft iron.

Note: Magnetic field shielding alloys are less permeable at low field strengths than at high field strengths, so they work best at high field strengths.

**active shielding**

Another approach is to use non-permeable metals such as copper or aluminum to produce eddy currents that cancel out the original magnetic field.

*Active shielding*, or field cancellation using an electrical coil system and feedback controls to oppose an unwanted field is also possible.

Exposures of people to magnetic fields is routinely but unintentionally reduced by canceling fields, as in appliance cores with two closely spaced conductors.

If a current flows in one direction through a wire and the return current flows back in the opposite direction through the neighboring conductor, each conductor creates a magnetic field, but the orientations of the fields are opposite and they nearly cancel each other out.

The closer the two conductors are, the more cancellation occurs.

Note: Overhead power lines use widely spaced conductors to avoid arcing, so relatively little cancellation occurs compared with underground power lines.

Field cancellation technology is being increasingly used for AC fields.

Utilities can require transmission lines to obtain more cancellation.

Field cancellation may also prove useful in households here poorly wired appliances are leaking currents to the ground.

The current leaving a house through the ground often does not enter where the current entered the house, so it cannot cancel the magnetic fields created by the incoming current.

A house with leaking appliances can have two magnetic hot spots: one where the service enters the house and the other by the ground carrying the leaking current.

**Radiofrequency/Microwave Radiation and Fields**

This portion of the electromagnetic spectrum covers a huge range of frequencies from 3 *kHz* to 300*GHz*, or wavelengths from 100 *km* to 1 *mm*.

Some radiofrequency/microwave (RF/MW) scenarios involve fields and others involve radiation.

Radiation is likely to be found at frequencies above 300 *MHz* (wavelengths = 1 *m*), whereas fields are likely to be found at lower frequencies.

Note: The practical consequence of this is that two surveys (one for electric fields and the other for magnetic fields) are required at lower frequencies, but only one survey is needed at higher frequencies.

 very low frequency (VLF) (3-30 *kHz*) - portable telephones, induction heating

 low frequency (LF) (30-300 *kHz*) - marine and long range communications

 medium frequency (MF) (300 kHz-3 *MHz*) - AM radio, amateur radio

 high frequency (HF) (3-30 *MHz*) - TV, CB radio

 very high frequency (VHF) (30-300 *MHz*) - FM radio, TV fire/police communications

 ultrahigh frequency (UHF) (300 MHz-3 *GHz*) - microwave ovens, CB radio

 super high frequency (SHF) (3-30 *GHz*) - radar, police speed guns

 extremely high frequency (EHF) (30-300 *GHz*) - satellite communications

Note: Microwaves occupy the portion of the radiofrequency spectrum ranging from 300 *MHz* to 300 *GHz*.

**Industrial, Scientific, and Medical Bands and Frequency Nomenclature**

A *band* is a part of the entire electromagnetic spectrum.

Safety and health specialists often find equipment working in the industrial, scientific, and medical (ISM) bands, which anyone can freely use because no licensing is required.

Note: The most popular ISM band is the 2.45-*GHz* band used by microwave ovens.

Note: Electrical engineers often use the traditional band designations originally used for radars and military electronics in WWII.

Thus, you may hear or read about the Ka band police radar speed gun.

These designations were not user-friendly.

The modern designation system uses letters of the alphabet, in ascending order to describe increasing frequencies (see Table 11-D in text, p. 292).

**Interactions of Radiation and Matter**

The interactions of radiation and matter can be described in terms of how much energy in the radiation is lost to the mater it strikes.

** adsorption**

If all of the energy in the radiation is lost to the matter, it is absorbed.

** scatter**

If some energy, but not all, passes from a chunk of matter, then the radiation is scattered.

** transmission**

If none of the energy is lost, then the radiation was transmitted.

Electrical engineers call objects such as radio broadcast towers and radar sets as emitters rather than transmitters.

** reflection**

Finally, radiation does not pass from one medium to another when the electrical properties are too dissimilar.

When this occurs, the radiation is reflected back into the medium it came from.

Note: Reflection is the basis of radar; controlling reflections from mirrors and other shiny objects is a major concern in laser safety.

RF/MW that is absorbed or scattered can impart energy to living matter by induction of current flow, or by interactions between the electric field and charged portions of water or organic molecules such as proteins.

Electrically charged portions of molecules can be caused to vibrate and ions of metals dissolved in water can be caused to move in response to the electric fields.

In both cases, the energy finally appears as heat.

**Biological Effects and Exposure Standards for Radiofrequency Fields**

The status of biophysics research in the radiofrequencies is somewhat more certain than it is for the subradiofrequencies.

More research is needed to answer concerns about the safety of consumer radiofrequency devices such as cell phones, wireless Internet, and police radars.

The research to date has been sufficient to develop accepted safety standards.

Radiofrequency and microwave energy causes a wide variety of biological effects, especially if exposures are intense enough to cause significant heating.

**Dosimetry**

It is not enough in radiofrequency biophysics research to state that rats were exposed to 10 *mW/cm*2 of 2.45 *GHz* continuous wave radiation and certain effects were observed.

Researchers must address physics problems that determine how much of the power density in the rats’ ambient environment is absorbed into power deposited in the rats’ tissues.

The response of tissue to radiation and fields is determined by the electrical properties of the tissue.

The discipline that address this concern is *RF/MW dosimetry*, which looks at the:

** size of the organism** compared with the wavelength of the radiation

An organism acts as an antenna.

An object absorbs the most radiation if it about 40 percent of the wavelength and not well-grounded, or when it is about 20 percent of the wavelength and well-grounded.

Note: The resonant frequency for a rat is much higher than for a human.

Example: Consider a 6-foot (1.83 *m*) tall human.

If ungrounded, this person will act as an antenna intercepting radiation that has a wavelength of 4.6 *m*.

$$x  0.40=1.83 m$$

$$x= \frac{1.83 m}{0.40}$$

$$x=4.58 m$$

$$299,792,458 m/s ÷4.58 m=65,456,869 s (\~65 MHz)$$

What frequency would be intercepted best if the person was well-grounded?

9.15 *m* wavelengths (32,764,203 *s* = 33 *MHz*).

** polarization of the radiation**

How the electric field is aligned relative to the earth’s surface compared with the orientation of the exposed organism; and

Radiofrequency radiation is absorbed most when the electric field is parallel to the long axis of the organism and is absorbed least when the magnetic field is parallel to the long axis of the organism.

Note: Rats typically best absorb horizontally polarized radiation, whereas upright humans best absorb vertically polarized radiation.

** interaction of exposed tissues**

The dose rate is the rate at which energy is transferred to tissue, is called the *specific absorption rate (SAR)* expressed in watts of power deposited per kilogram of tissue (*W/kg*).

The term for the quantity of energy transferred to tissue is *specific absorption (SA)*, expressed in joules of energy per kilogram (*J/kg*) of tissue.

Note: Energy is equal to power times time.

Power is expressed in watts, and 1 *W* times 1 second equals 1 *J* of energy.

Note: Current regulations assume that peak absorption, or resonance for humans, occurs at frequencies of 30 to 300 *MHz*.

Dosimetry can be done by:

** measurement dosimetry**

Measurement dosimetry involves measuring temperature changes in tissues that result from exposure to RF/MW fields.

Measurement dosimetry was hampered by using common thermocouples, which include a pair of conducting wires trailing from the object being tested.

The wires interacted with the electric fields, so only one temperature measurement could be made even in a human-sized object.

Fiber-optic devices are now available so that several concurrent temperature measurements can be made in one animal.

** mathematical dosimetry**

Mathematical dosimetry is also progressing as newer mathematical models make more efficient use of computer memory and offer adequate capacity to do complex, tedious calculations.

Newer models are based on MRI images of human internal organs and structures and can estimate the SAR for specific organs and small parts of the body.

Note: The most common dosimetric standard in the U.S. is 0.4 *W/kg* as a whole-body average.

This objective is based on heat avoidance behavior of animals at a SAR of 4 *W/kg*, divided by a safety factor of 10.

**Target Organs**

A variety of effects are known to occur at SARs above 4 *W/kg*, but the target organs are the eyes and testes, based on limits of circulation and heat dissipation at these two organ systems.

It is assumed that the thermal equilibrium time for these target organs could be as brief as six minutes, so the standards specify exposure limits that apply for six minute time intervals.

When the frequency rises above 3 *GHz*, the time interval drops to 10 seconds.

Note: The only proven adverse effects for humans, regardless of SAR, are eye cataracts, facial burns, and electric shocks and burns.

Other effects have been demonstrated in animals, such as teratogenic effects and neurochemical and eye effects.

**Standard-Stetting Rationale**

The radiofrequency portion of the electromagnetic spectrum can be divided into three major parts:

** sub-resonant region** (<3 *MHz*)

Region in which current flow considerations are most important.

The goal of the standard is to prevent burns caused by radiofrequency electric current and excessive ankle heating caused by the surge of electricity to and from the ground through the feet.

** resonant region** (*3 MHz* to 6 *GHz*)

Region where current flow and SAR are both important considerations.

In this region, bodies act as good antennas.

Controlling SAR becomes the main concern and remains a serious concern at higher frequencies until skin absorption becomes dominant.

Note: Standards are most stringent between 30 *MHz* and 300 *--* the human resonant frequency zone.

** super-resonant region**

Region where skin absorption predominates -- at frequencies above 15 *GHz*, most radiation is absorbed in the first centimeter of tissue.

The properties of microwaves become similar to those of infrared (IR) radiation, and thermal damage to the skin becomes a major concern.

**Averaging Time and Pulsed Fields**

Industrial hygienists are used to thinking in terms of eight hour averaging times for exposures to chemicals.

However, radiofrequency heating occurs much more rapidly, and exposure limits must be devised to be protective for acute damage to the target organs.

In the case of whole body exposure, thermal equilibrium of the target organs (eyes and testes), occurs rapidly and is assumed to be about six minutes for limbs, organs, and partial body structures.

Thus, time averaging calculations can be made much as they are for chemicals, but the exposures must not exceed the C95.1 limit over a six-minute averaging interval rather than an eight-hour shift.

Note: The idea of limiting above-average exposure so the six minute time-weighted average is below the standard has limitations in the case of exposure to very short term but intense pulses of energy common in some radar and laboratory settings.

As with chemical exposures, a simple TWA allows for extremely intense exposures if they are brief enough.

**Regulatory Considerations**

The standard paperback volume of 29 CFR 1910 includes the original 1970 radiofrequency/microwave exposure standard (29 CFR 1910.97).

This standard, based on ANSI C95.1-1966, is obsolete.

The original regulation was struck down in 1981, but a legal decision allows OSHA to apply state-of-the-art standards developed by others when OSHA has no standard of its own.

IEEE adopted a revision of C95.1 in 2005, and the American National Standard Institute (ANSI) adopted the revision.

Hence, OSHA can enforce ANSI/IEEE C95.1-2005, so the student should become acquainted with this standard.

**Measuring Radiofrequency Radiation and Fields**

Recall that fields rather than radiation are presumed to exist at frequencies below 300 *MHz*.

For this reason, two surveys (one for electric fields and the other for magnetic fields) are needed.

Only one survey is needed for frequencies above 300 *MHz*.

Magnetic fields are measured using single loop (directional) or triple-loop (isotropic response) magnetometers.

Electric fields at frequencies above 100 kHz are measured using small dipole antennas.

Single dipole antennas are directional, whereas ganging three sensors together so they are mutually orthogonal provides an isotropic response.

Note: Microwave oven survey instruments have two dipole/diode sensors that are perpendicular to each other.

The lack of the third sensor make them directional, and they must be held so the probe handle is perpendicular to the surface being measured.

Radiofrequency field and radiation measurements should be made where the worker would normally be, but without the person present, so reflections and induced fields do not create falsely high results.

The sensor is held just above floor level and raised up through the body position at 8-*in* (20-*cm*) vertical intervals and the result recorded for each point.

At this time, measurements must be made at the locations of the eyes and testes.

Exposures above the standard and their locations must also be recorded.

Excursions up to 20 times the standard are allowed at the extremities (e.g., hands and feet), and excursions up to eight times the standards are allowed elsewhere (except the locations of the eyes and testes).

Note: Contact- and induced-current meters are now available.

Contact-current meters have electrodes that are pressed against an object that may be electrically charged due to ambient FR fields.

Induced-current meters look like bathroom scales and are meant for people to stand on.

The induced current flows through the instrument that registers the current before going to ground.

**Microwave Ovens**

Microwave ovens use the 2.45-*GHz* ISM band.

This caused concern when microwave ovens first appeared because the radiation leaking from the oven was amplitude-modulated by the rotor and could be picked up by cardiac pacemakers of that era.

Since that time, pacemaker manufacturers have added capacitors and protective circuits to block out extraneous fields, and most pacemakers are now tested against electrical fields equivalent to 10 *mW/cm*2 (the ANSI C95.1 exposure standard when microwaves first came out).

The present emission standard for microwave ovens (21 CFR 1930.10) allows new ovens to leak no more than 1 *mW/cm*2 when measured at 5 *cm*.

**RF/MW Controls**

** shielding**

FR/MW shielding is relatively simple and can be installed using relatively inexpensive materials; lead is not needed.

The most effective form of shielding is applied at the source as an enclosure.

- absorbing foams

- metal screens or sheets

The key concept is that the mesh openings be no more than one-quarter of a wavelength in dimension.

Metal screens and sheets must be electrically bonded to each other and the whole assembly grounded (e.g., Faraday cage).

** waveguides and coaxial cables**

Waveguides and coaxial cables are used to transfer power and act as enclosures.

Waveguides are open metallic conduits with flanged ends that allow waveguides to be attached to each other, sources, or receivers.

Coaxial cables can be bent and fail, leading to leakage.

** distance**

Distance is very effective in far fields, due to the inverse square law, and can also be used in near fields (e.g., barricades, long-handled tools).

** time limitation**

Time limitations are possible, based on a six-minute averaging time, but often are not practical.

** signage**

The sign found in the OSHA non-ionizing radiation standard, became obsolete in 1992.

The symbol shown in Figure 11-15 (p. 306) should be used instead.

**Optical Radiation and Lasers**

**CIE (International Commission on Illumination) Bands**

Optical radiation includes infrared, visible, and ultraviolet radiation.

It is customary to describe optical radiation by wavelength rather than by frequency.

The band designations for infrared and ultraviolet radiation begin at the border of each band starting with visible radiation (wavelength of 400 *nm* to 750 *nm*) and extend each way from the visible band.

**CIE Band Wavelength Non-CIE nomenclature Primary Visual Hazard**

IR-C 3 *μm*-1 *mm* far IR corneal burns

IR-B 1.4 *μm*-3 *μm* intermediate IR corneal burns

IR-A 760 *nm*-1400 *nm* near IR retinal burns (lens cataracts)

optical 300 *nm*-750 *nm* visible light retinal burns (night & color impairment)

UV-A 315 *nm*-400 *nm* near UV (black light) lens cataracts

UV-B 280 *nm*-315 *nm* middle UV corneal injuries, lens cataracts

UV-C 100 *nm*-280 y far UV corneal injuries

**Biological Effects and Exposure Standards for Optical Radiation**

Biological effects of optical radiation result from thermal and photochemical mechanisms.

** thermal effects**

Thermal effects are dominant in the IR portion of the spectrum.

More important at the red end of the visible spectrum.

** photochemical effects**

Photochemical effects dominate in the UV portion.

Dominant at the blue end of the visible spectrum.

The target organs are the eyes and skin.

Visible and IR-A radiation is particularly hazardous to the eye because it is transmitted through the cornea, is focused by the lens, and strikes the retina.

The potential for retinal damage is great because the radiation can be highly concentrated by focusing.

**The Eye**

** iris**

The iris can absorb energy and be heated by radiation.

** lens**

The lens transmits visible and IR-A radiation, but other bands of IR and UV are absorbed by the lens or at the cornea.

** macula**

- fovea

The fovea (the small region that is rich in cones and essentially rod-free) located in the center of the macula directly opposite the center of the iris, makes color vision particularly vulnerable to overexposures to visible and IR-A radiation.

- retinal epithelium

The rods lie on a bed of highly pigmented tissue (retinal pigmented epithelium – RPE).

Although the rods, themselves, are essentially transparent and do not absorb light, the underlying pigmented tissue can absorb light, become hot, and damage the rods.

** choroid**

The blood circulating through the choroid below the retina is an important defense mechanism.

This capillary net is a vast liquid cooling system that extracts heat from the retina.

This defense can be overwhelmed by an extremely brief but intense pulse of light into the retina, providing energy above the rate at which the heat can be extracted by blood flow.

Pulsed lasers are particularly hazardous.

They can deposit energy so rapidly that the water in the retinal tissue flashes to a boil and “explodes,” causing local tissue damage.

Alternatively, large quantities of light can be hazardous when deposited over larger areas of the retina (e.g., if looking at the sun).

Visible radiation can cause retinal injuries or burns because it is transmitted and focused.

Another defense is afforded by *aversion reflex actions*, such as blinking or looking away from bright light.

Excessively bright light prompts these responses in about 0.25 *s*.

Note: One reason lasers are hazardous is because they can deposit damaging amounts of energy into the eye well before the aversion reflex ends the exposure.

**The Skin**

The outermost layer of the skin (epidermis) contains a single sheet of cells at its base, consisting of keratinocytes and melanocytes.

The keratinocytes divide and are pushed outward by newer cells being created by the basal cells.

As they move outward, they flatten, develop pigment granules, and finally die.

This pigment absorbs UV and prevents the generation of excessive levels of vitamin D and UV injuries to the dermal and subcutaneous tissues below.

IR and visible light skin injuries are confined to thermal burns.

UV also causes skin effects through photochemical mechanisms.

Sunbathers now use sunscreen lotions to allow UV-A to reach the skin and stimulate melanin production by the melanocytes, but absorb UV-B before it can reach the skin.

UV-B and UV-C produce two undesirable effects:

- skin toughening

Repeated exposure to UV, particularly UV-B, caused the skin to thicken and harden.

- skin cancer

Outdoor exposures do not include UV-C because it is absorbed by oxygen in the atmosphere to produce ozone.

Research shows that UV-A can also cause skin cancer.

The most common skin effect is erythema (reddening), commonly called sunburn.

UV penetrates to het living cells of the dermis and caused damage, which is repaired.

Blood supply to the skin is increased as part of the repair process, causing the reddening.

Note: The exposure standards that address UV and far IR exposure to the skin are about the same as the standards addressing eye exposures.

The standards for visible and near IR skin exposure are much more lenient than those for eye exposure because of the possibility of retinal damage caused by focusing.

**Standards**

Optical radiation and laser safety standards use radians rather than degrees as a measure of angle.

The length of an arc (segment of a circle) created by a given angle is equal to the radius of the circle times the size of the angle in radians.

Therefore, the size of a source that is emitting radiation, or a surface that is reflecting radiation, is equal to the distance between the source and the viewer times the angle in radians.

The customary symbol for the angle is alpha (*α*).

Another angular measure is also used to describe portions of the surface of a sphere, the steradian.

Radians and degrees cover familiar two-dimensional circles and arcs, but the steradian unit applies to three-dimensional situations.

The size of an illuminated or radiating area is equal to the square of the distance between the area and the observe times the solid angle, in steradians:

*size* = *d*2   *α* (in steradians)

Note: The principal standards used for non-laser optical radiation are found in the back of the TLV booklets issued annually by the ACGIH.

ACGIH groups visible radiation with IR radiation and addresses UV separately.

These TLVs are fundamentally identical in concept to the more familiar noise standard in that they use spectral effectiveness factors to account for the difference in damage caused by energy of different wavelengths and they trade exposure intensity off against permissible exposure time.

** visible/IR radiation standards**

Has two basic elements:

- visible standards (visible + IR)

Must account for both photochemical injuries at the blue end and thermal injuries at the red end and IR.

The thermal injury standard covers wavelengths from 400 *nm* to 1400 *nm*.

Note: Stronger exposures to more hazardous wavelengths from bigger sources warrant shorter permissible exposures.

Note: The TLV does not extend to wavelengths > 1.4 *μm*, since the concern about retinal focusing does not exist above 1.4 *μm*.

- IR standards (no visible)

Two formulas are given for situations where IR is not accompanied by visible radiation (e.g., heat lamps).

One formula addresses corneal hazards form 770 *nm* to 3 *μm* by limiting exposure times.

The other addresses retinal hazards from 770 *nm* to 1400 *nm*.

** UV standards**

The TLV for UV uses similar logic and relies on a combined eye and skin hazard weighting curve, so only one set of measurements is needed.

The combined curve shows maximum potency at 270 *nm*.

**Controls for Non-Laser Sources**

** optical density**

*Optical density* (OD) is the log10 of the ratio of the intensity of the radiation leaving the filter divided by the intensity of the radiation entering the filter (i.e., the attenuation provided by the filter).

Example: If a filter absorbs all but 1 percent, or 1/100, of the radiation entering it, then the filter factor is 100.

The OD is the log10 of 100, or 2.

Example: If a 1-*kW* laser beam strikes a filter and only 1 *mW* is transmitted through the filter, then the filter factor is 1,000,000.

The OD is the log10 of 1,000,000, or 6.

** shade factor**

A variation of optical density, shade number, has been used in ANSI A49.1 to describe welders’ eye protection for several decades.

The *shade number* is 1 plus the product of 7/3 (2.33) multiplied by the optical density of the filter.

Baffles and sight barriers are common engineering controls for optical radiation, particularly for welding areas (e.g., absorbing plastic panels allow observes to see welders without being exposed to hazards from arcs).

A wide variety of personal protective equipment is now available for non-laser optical radiation hazards:

- the shade numbers for welding eyewear are excepted rom ANSI A-49.1-2005.

OSHA is still using ANSI A.49.1-1988.

- common glass does not offer complete protection against UV-A, although it is very effective against UV-B and UV-C.

Tinted eyewear is often effective against UV-A.

- the use of photochemically darkened lenses should be avoided because the lenses can darken fairly rapidly in response to sunlight, but become paler slowly.

One can enter a building or drive into a tunnel and experience impairment of vision, particularly immediately after entry.

- special lenses are available for non-laser light and IR sources, such as glassblowing and steel making.

- OSHA standard (29 CFR 1910.133) requires eye and face protectors to be distinctly marked to facilitate identification

Also requires that protective eyewear for users with prescriptions either have the prescription built in or be worn over prescription lenses.

**Laser**

*Laser* is an acronym for light amplification by stimulated emission of radiation.

Lasers work by pumping the electrons in a suitable material (lasing medium) with strong energy and directing some of that energy out in the form of a beam of radiation.

The lasing medium is placed in a cavity with mirrors on each end and energized (pumped) so that it emits electrons.

The electrons are reflected off of mirrors on each end of the cavity, surging back-and-forth, gaining strength.

When electrons have gained enough energy (achieved a specific wavelength), they pass through the selective mirror at one end of the cavity, emerging as a beam with parallel sides.

Laser radiation has unique properties:

** monochromatic**

It has only one color of light and is made of one or a few wavelengths of radiation.

** coherent**

The waves are in phase (all wave crests line up) and have maximum intensity.

** bright**

It can have very high irradiance and be focused to deposit intense energy on small surfaces.

The parallel-sides and coherent nature of the product radiation means that the beam does not spread as rapidly as radiation from other sources.

Thus, a laser beam keeps its strength over long distances

Note: Visible and IR-A laser beams can be focused to create extremely intense exposures on the retina that deliver up to 300,000 times as much power or energy per unit area on the retina as on the outside of the eye.

This is why laser safety standards are much stricter in this band than at other bands and why laser standards are stricter than standards for non-coherent sources in this band.

Lasers can be operated in two major modes: pulsed and continuous wave (CW).

Exposure standards and laser outputs for pulsed and relatively brief exposures are expressed in joules per square centimeter (*J/cm*2) of illuminated area.

Exposure standards and outputs for continuous wave lasers are expressed in watts per square centimeter (*W/cm*2) of illuminated area.

**Biological Damage Mechanisms of Lasers**

Laser beams produce biological damage by the two mechanisms mentioned earlier: thermal burns and photochemical injuries.

Visible and IR-A lasers also produce retinal damage by a third mechanism unique to lasers.

The highly focused beam generates a steam bubble near the retina that pops, sending shock waves into the retinal tissue that produce *thermoacoustic tissue damage*.

Briefer pulses are more hazardous than longer pulses of equal energy content because the heat does not dissipate as much during a shorter pulse.

The bursting bubble produced in the eye when exposed to such pulses can damage blood vessels and blood is toxic to nerve tissue.

So the degree of lasting impairment caused by thermoacoustic injury is a matter of luck determined by what part of the retina was struck and whether blood reached nerve tissue.

Note: Both coherent visible light and IR-A radiation with wavelengths of 400 *nm* to 1400 *nm* can be focused into an ultra-small spot at the back of the retina.

The brightness of the radiation striking the retina may be 300,000 times stronger than that entering the eye.

**Standards**

The dominant standard for laser safety in the U.S. is the Laser Institute of America’s LIA/ANSI Z136.1-2007 (addresses facility and program elements as well as laser safety features).

Regulations for commercial laser products are promulgated by the Center for Devices and Radiological Health (CDRH) of the Food and Drug Administration (addresses product safety features).

Both standards were early uses of the hazard control class type of regulation.

*Control class regulations* require assigning a classification that reflects the severity of the hazards.

For lasers, the principal parameters that describe the anticipated hazard severity are wavelength and output power.

Other measures of anticipated severity are pulse duration and the size of extended sources (multiple sources)

Precautions can be relaxed when the beam is thoroughly enclosed or reduced in power before it can enter a place where people could be exposed.

This gives laser equipment suppliers a strong incentive to apply effective engineering controls.

Precautions become more stringent in a series of defined steps (classes) as the output of the laser increases from Class 1 (intrinsically safe) to Class 4 (very dangerous).

**Class 1** extremely weak intrinsically safe no precautions needed

**Class 2** low-power could be hazardous if viewed for prolonged periods limited precautions

**Class 3** moderate-power hazardous if viewed for brief periods more precautions

**Class 4** high-power harmful to skin and eyes, diffuse reflections hazardous rigorous precautions

Note: The use of hazard control classes reduces the need for measurements to determine personnel exposures and puts reliance on being able to estimate exposures by calculations.

**Controls**

Engineering and administrative controls and personal protective equipment are used for lasers and optical radiation.

** engineering controls**

- enclosure

Placing the laser and associated beam pathway(s) within protective housings and/or interlocked rooms.

- routing

Laser beams can be routed over or below walkways using mirrors.

- fail-safe interlocks

Placed on access panels of enclosures

- remote interlock connections

An extension of fail-safe interlocks, allowing additional interlocks to trigger a shutdown of electric power to a laser or drop a shutter or filter into the beam.

Note: Can make up safety chains for laser systems and include emergency panic button shutoffs.

Viewing portals, viewing screens, and optical instruments must be connected to interlocks.

It is convenient to add room status lights to the laser interlock system and to install a loudspeaker and buzzer near the room status lights so visitors can talk to the room occupants during laser operations.

- key-in-lock control

Useful for lasers located in places where unauthorized people could have access.

Only authorized personnel have keys to activate the energy source, making it very unlikely that the laser could be inadvertently operated by unauthorized people.

Of course, the authorized personnel must remember to remove their key.

Note: Engineering controls are effective when a laser system has already been set up, but not while it is being set up or while maintenance is being conducted.

Thus, special caution, including heavy reliance on administrative controls and special warning sighs, is needed during setup and maintenance.

37.2 percent of laser accidents occurred during alignment.

Specular (mirror-like) reflections are more hazardous than diffuse reflections because virtually all of the beam’s power is retained.

Safety precautions always include eliminating all unnecessary specular reflectors.

** administrative controls**

Administrative controls involve excluding people by barriers, signs, flashing beacons, and the diligence of personnel authorized to be in the nominal hazard zone.

Medical surveillance and training programs are required by CDRH for users of Class 3b and 4 lasers.

The laser safety program must include the following:

- a laser safety officer (laser safety committee);

- education of authorized personnel;

- application of the controls specified in the standards;

- accident reporting and investigations, and action plans to prevent recurrence; and

- medical surveillance.

Note: As with all personal protective equipment, it is necessary to select laser eyewear of appropriate optical density for the wavelengths of radiation encountered and the severity of exposure.

Color-coding is recommended for multi-laser environments

Protective eyewear usually includes glass or plastic lenses (in general, glass is heavier but provides better protection)

**Non-Beam Hazards of Lasers**

The two greatest hazards of lasers are electricity and fire.

** electricity**

Electrocution from high-voltage power supplies and capacitor banks is a real hazard and can kill.

Most laser exposures only result in some loss of vision at worst.

** fire**

- ignition source

The National fire Protection Association (NFPA) standard for laser fire protection advises that a continuous wave laser radiation creating an irradiance above 2 *W/cm*2 is an ignition hazard.

The beam could ignite flammable substances such as paper and solvents.

Dye lasers are particular fire hazards because most use solutions of dye in an alcohol, dimethyl sulfoxide (DMSO) or some other flammable or combustible solvent.

- pyrolysis products

Objects that could be struck by laser beams must be selected to avoid toxic pyrolysis products (e.g., some polyurethanes and epoxides produce hydrogen cyanide when they burn).

- PAHs

Laser beams can pyrolyze organic materials producing carcinogenic polycyclic aromatic hydrocarbons (PAHs).

Pyrolysis products must be controlled both in the air and as deposits on surfaces.

** lacerations**

Flash lamps can explode if dropped, struck, or improperly handled, posing a laceration hazard.

** biological**

Viable organisms can be found in the plumes created when lasers are used to cut tissue (e.g., medical procedures)

** toxicity/mutagenicity**

Many laser dyes were brought to the market with essentially no toxicology screening and often come from chemical families that include mutagens or highly toxic materials

Note: The original dye recipes used DMSO solvent, which carries other materials through the skin, including mutagenic or toxic dyes.

** corrosiveness**

Some lasers use gases that are toxic and/or corrosive.

Care is needed in selecting corrosion-resistant materials and consideration must be given to venting of these gases during cavity refilling.

** other radiation**

Other forms of radiation, such a flash lamp radiation, electromagnetic fields form power supplies, and x-rays from high-voltage devices can also be hazardous.

** hazardous materials**

Hazardous materials can be found in optical components (e.g., heavy metals in detectors, heat sinks).

**Other Regulatory Concerns with Lasers**

The OSHA construction standard specifies that those who could be exposed to direct or reflected light above 5 *mW* must be provided with laser eye protection and that only mechanical or electronic devices may be used to guide the alignment of a laser.

The standard also sets the following exposure criteria:

direct staring limit 1 *μW/cm*2

incidental observing limit 1 *μW/cm*2

diffused reflected light 2.5 *μW/cm*2

**Measuring Optical Radiation**

Two types of detectors are widely used:

** thermal**

Thermal detectors are best for IR measurements

Thermal detectors are fundamentally no different from globe thermometers used in heat stress studies.

They consist of a sensor embedded in an object that is dark-colored to absorb IR radiation, warm up, and produce a measureable response in the detector.

A variant is the pyroelectric detector, which measures the rate of temperature change in crystals.

** quantum**

Quantum detectors are best for UV, visible, and IR-A (up to 1100 *nm*) measurements.

Emit electrons in response to being struck by radiation.

**Lighting**

Insufficient light causes accidents and reduces work performance.

Most lighting concerns are quantitative, but some qualitative concerns may also arise (e.g., contrast, reflections, color).

The Illumination Engineering Society (IES) advises that 20 footcandles of illuminance are needed for tasks requiring sustained seeing.

OHSA regulations (IES/ANSI RP-7-1991) specifies the following illuminance levels for safety in normal conditions (i.e., where light will not ruin a process or pose a safety hazard):

 **Illuminance Level (footcandles)**

**Degree of Hazard Low Activity Level High Activity Level**

 slight hazard 0.5 2

 high hazard 1 5

The dominant standards for industrial lighting in the U.S. are IES/ANSI RP-1-1982 and RP-7-1991 (or RP-7-2001), which address office and industrial lighting, respectively.

Note: *Iluminance* is similar to irradiance and power density, but the levels of light of various wavelengths are weighed in terms of their impact on the functioning of the cone cells of the retina, which are involved in color and detailed vision.

The units of illuminance are the lux and the footcandle; 1 lux = 10 footcandles.

 ** quantitative concerns**

Important aspects of any seeing task are:

- object size

The bigger the object, the easier it is to see.

- contrast

A gradation of contrast is sought between the task and its immediate and more remote visual surroundings.

- time

The amount of time to do the seeing job.

- luminance

 ** qualitative concerns**

Common qualitative concerns include glare, contrast, and color.

- reflected glare

Specular reflection off of a screen or other shiny surface

- direct glare

Relatively bright objects in an otherwise dark area

**General Considerations**

 Non-laser lighting adheres to the inverse square law.

This means that lights must be placed close to areas being lit if the lighting is needed go perform a task.

Sometimes, this cannot be done by area lighting alone.

 Energy conservation and safety needs can be reconciled by using motion detectors to activate area lighting when a person enters an area.

 Cleaning and painting of the building and its lighting can make a tremendous difference.

 Light, matte-textured surfaces are preferred to avoid specular reflections.

 Color can be a problem if unusual fluorescent tubes or colored incandescent bulbs are installed.

- white light contains radiation associated with every color we can see, while colored lights radiate selected wavelengths more intensely.

- colored lighting is useful for some jobs.

 Colored lighting without some benefit can create difficulties.

Colors may be harder to perceive when non-white lighting is used.

Note: Concern has been expressed about the safety of fluorescent tubes since they contain a minute amount of mercury.

Disposing of fluorescent tubes is associated with other industrial hygiene concerns.

**Lighting Measurements**

Lighting measurements are usually made 30 *in* above the floor to measure the illumination striking surfaces that are to be seen.

Special measurements can be made on surfaces of interest (e.g., desktops, working surfaces).

The instruments used are typically inexpensive photoelectric devices (e.g., light meters).