Chapter 8
Ionizing & Non-Ionizing Radiation

Interest in this area of potential human hazard stems, in part, from the magnitude of harm or damage that an individual who is exposed can experience. It is widely known that the risks associated with exposures to ionizing radiation are significantly greater than comparable exposures to non-ionizing radiation. This fact notwithstanding, it is steadily becoming more widely accepted that non-ionizing radiation exposures also involve risks to which one must pay close attention. This chapter will focus on the fundamental characteristics of the various types of ionizing and non-ionizing radiation, as well as on the factors, parameters, and relationships whose application will permit accurate assessments of the hazard that might result from exposures to any of these physical agents.

RELEVANT DEFINITIONS

Electromagnetic Radiation

Electromagnetic Radiation refers to the entire spectrum of photonic radiation, from wavelengths of less than 10^{-5} Å (10^{-15} meters) to those greater than 10^{8} meters — a dynamic wavelength range of more than 22+ decimal orders of magnitude! It includes all of the segments that make up the two principal sub-categories of this overall spectrum, which are the "Ionizing" and the "Non-Ionizing" radiation sectors. Photons having wavelengths shorter than 0.4 μ (400 nm or 4,000 Å) fall under the category of Ionizing Radiation; those with longer wavelengths will all be in the Non-Ionizing group. In addition, the overall Non-Ionizing Radiation sector is further divided into the following three sub-sectors:

Optical Radiation Band *	0.1 μ to 2,000 μ, or 0.0001 to 2.0 mm
Radio Frequency/Microwave Band	2.0 mm to 10,000,000 mm, or 0.002 to 10,000 m
Sub-Radio Frequency Band	10,000 m to 10,000,000+ m, or 10 km to 10,000+ km

* *It must be noted that the entirety of the ultraviolet sector [0.1 μ to 0.4 μ wavelengths] is listed as a member of the Optical Radiation Band, and appears, therefore, to be a Non-Ionizing type of radiation. This is not true. UV radiation is indeed ionizing; it is just categorized incorrectly insofar as its group membership among all the sectors of* ***Electromagnetic Radiation****.*

Although the discussion thus far has focused on the wavelengths of these various bands, this subject also has been approached from the perspective of the frequencies involved. Not surprisingly, the dynamic range of the frequencies that characterize the entire **Electromagnetic Radiation** spectrum also covers 22+ decimal orders of magnitude — ranging from 30,000 exahertz or 3×10^{22} hertz [for the most energetic cosmic rays] to approximately 1 or 2 hertz [for the longest wavelength ELF photons]. The energy of any photon in this overall spectrum will be directly proportional to its wavelength — i.e., photons with the highest frequency will be the most energetic.

The most common **Electromagnetic Radiation** bands are shown in a tabular listing on the following page. This tabulation utilizes increasing wavelengths, or λs, as the basis for identifying each spectral band.

Electromagnetic Radiation Bands

Spectral Band	Photon Wavelength, λ, for each Band: Band Min. λ	Band Max. λ
IONIZING RADIATION		
Cosmic Rays	<0.00005 Å	0.005 Å
γ-Rays	0.005 Å	0.8 Å
X-Rays — hard	0.8 Å	5.0 Å
X-Rays — soft	5.0 Å 0.5 nm	80 Å 8.0 nm
NON-IONIZING RADIATION — Optical Radiation Bands		
Ultraviolet — UV-C	8.0 nm 0.008 μ	250 nm 0.25 μ
Ultraviolet — UV-B	250 nm 0.25 μ	320 nm 0.32 μ
Ultraviolet — UV-A	320 nm 0.32 μ	400 nm 0.4 μ
Visible Light	0.4 μ	0.75 μ
Infrared — Near or IR-A	0.75 μ	2.0 μ
Infrared — Mid or IR-B	2.0 μ	20 μ
Infrared — Far or IR-C	20 μ 0.02 mm	2,000 μ 2 mm
Radio Frequency/Microwave Bands		
Extremely High Frequency [EHF] *Microwave* Band	1 mm	10 mm
Super High Frequency [SHF] *Microwave* Band	10 mm	100 mm
Ultra High Frequency [UHF] *Microwave* Band	100 mm 0.1 m	1,000 mm 1 m
Very High Frequency [VHF] *Radio Frequency* Band	1 m	10 m
High Frequency [HF] *Radio Frequency* Band	10 m	100 m
Medium Frequency [MF] *Radio Frequency* Band	100 m 0.1 km	1,000 m 1 km
Low Frequency [LF] Band	1 km	10 km
Sub-Radio Frequency Bands		
Very Low Frequency [VLF] Band	10 km	100 km
Ultra Low Frequency [ULF] Band	100 km 0.1 Mm	1,000 km 1 Mm
Super Low Frequency [SLF] Band	1 Mm	10 Mm
Extremely Low Frequency [ELF] *Power Freq.* Band	10 Mm	>100 Mm

Ionizing Radiation

Ionizing Radiation is any photonic (or particulate) radiation — either produced naturally or by some man-made process — that is capable of producing or generating ions. Only the shortest wavelength [highest energy] segments of the overall electromagnetic spectrum are capable of interacting with other forms of matter to produce ions. Included in this grouping are most of the ultraviolet band [even though this band is catalogued in the Non-Ionizing sub-category of Optical Radiation], as well as every other band of photonic radiation having wavelengths shorter than those in the UV band.

Ionizations produced by this class of electromagnetic radiation can occur either "directly" or "indirectly." "Directly" ionizing radiation includes:

(1) electrically charged particles [i.e., electrons, positrons, protons, α-particles, etc.], &
(2) photons/particles of sufficiently great kinetic energy that they produce ionizations by colliding with atoms and/or molecules present in the matter.

In contrast, "indirectly" ionizing particles are always uncharged [i.e., neutrons, photons, etc.]. They produce ionizations indirectly, either by:

(1) liberating one or more "directly" ionizing particles from matter with which these particles have interacted or are penetrating, or
(2) initiating some sort of nuclear transition or transformation [i.e., radioactive decay, fission, etc.] as a result of their interaction with the matter through which these particles are passing.

Protection from the adverse effects of exposure to various types of **Ionizing Radiation** is an issue of considerable concern to the occupational safety and health professional. Certain types of this class of radiation can be very penetrating [i.e., γ-Rays, X-Rays, & neutrons]; that is to say these particles will typically require very substantial shielding in order to ensure the safety of workers who might otherwise become exposed. In contrast to these very penetrating forms of **Ionizing Radiation**, α- and β-particles are far less penetrating, and therefore require much less shielding.

Categories of Ionizing Radiation

Cosmic Radiation

Cosmic Radiation [cosmic rays] makes up the most energetic — therefore, potentially the most hazardous — form of Ionizing Radiation. **Cosmic Radiation** consists primarily of high speed, very high energy protons [protons with velocities approaching the speed of light] — many or even most with energies in the billions or even trillions of electron volts. These particles originate at various locations throughout space, eventually arriving on the earth after traveling great distances from their "birthplaces." Cataclysmic events, or in fact any event in the universe that liberates large amounts of energy [i.e., supernovae, quasars, etc.], will be sources of **Cosmic Radiation**. It is fortunate that the rate of arrival of cosmic rays on Earth is very low; thus the overall, generalized risk to humans of damage from cosmic rays is also relatively low.

Nuclear Radiation

Nuclear Radiation is, by definition, terrestrial radiation that originates in, and emanates from, the nuclei of atoms. From one perspective then, this category of radiation probably should not be classified as a subset of electromagnetic radiation, since the latter is made up of photons of pure energy, whereas **Nuclear Radiation** can be either energetic photons or particles possessing mass [i.e., electrons, neutrons, helium nuclei, etc.]. It is clear, however, that this class of "radiation" does belong in the overall category of Ionizing Radiation; thus it will be discussed here. In addition, according to Albert Einstein's Relativity Theory, energy and mass are equivalent — simplistically expressed as $\mathbf{E = mc^2}$ — this fact further solidifies the inclusion of **Nuclear Radiation** in this area.

Nuclear events such as radioactive decay, fission, etc. all serve as sources for **Nuclear Radiation**. Gamma rays, X-Rays, alpha particles, beta particles, protons, neutrons, etc., as stated on the previous page, can all be forms of **Nuclear Radiation**. Cosmic rays should also be included as a subset in this overall category, since they clearly originate from a wide variety of nuclear sources, reactions, and/or disintegrations; however, since they are extraterrestrial in origin, they are not thought of as **Nuclear Radiation**. Although of interest to the average occupational safety and health professional, control and monitoring of this class of ionizing radiation usually falls into the domain of the Health Physicist.

Gamma Radiation

Gamma Radiation — Gamma Rays [γ-Rays] — consists of very high energy photons that have originated, most probably, from one of the following four sources:

(1) nuclear fission [i.e., the explosion of a simple "atomic bomb," or the reactions that occur in a power generating nuclear reactor],
(2) nuclear fusion [i.e., the reactions that occur during the explosion of a fusion based "hydrogen bomb," or the energy producing mechanisms of a star, or the operation of one of the various experimental fusion reaction pilot plants, the goal of which is the production of a self-sustaining nuclear fusion-based source of power],
(3) the operation of various fundamental particle accelerators [i.e., electron linear accelerators, heavy ion linear accelerators, proton synchrotrons, etc.], or
(4) the decay of a radionuclide.

While there are clearly four well-defined source categories for **Gamma Radiation**, the one upon which we will focus will be the decay of a radioactive nucleus. Most of the radioactive decays that produce γ-Rays also produce other forms of ionizing radiation [β^--particles, principally]; however, the practical uses of these radionuclides rest mainly on their γ-Ray emissions. The most common application of this class of isotope is in the medical area. Included among the radionuclides that have applications in this area are: $^{125}_{53}\mathrm{I}$ & $^{131}_{53}\mathrm{I}$ [both used in thyroid therapy], and $^{60}_{27}\mathrm{Co}$ [often used as a source of high energy γ-Rays in radiation treatments for certain cancers].

Gamma rays are uncharged, highly energetic photons possessing usually 100+ times the energy, and less than 1% of the wavelength, of a typical X-Ray. They are very penetrating, typically requiring a substantial thickness of some shielding material [i.e., lead, steel reinforced concrete, etc.].

Alpha Radiation

Alpha Radiation — Alpha Rays [α-Rays, α-particles] — consists solely of the completely ionized nuclei of helium atoms, generally in a high energy condition. As such, α-Rays are particulate and not simply pure energy; thus they should not be considered to be electromagnetic radiation — see the discussion under the topic of Nuclear Radiation, beginning on the previous page.

These nuclei consist of two protons and two neutrons each, and as such, they are among the heaviest particles that one ever encounters in the nuclear radiation field. The mass of an α-particle is 4.00 atomic mass units, and its charge is +2 [twice the charge of the electron, but positive — the basic charge of an electron is -1.6×10^{-19} coulombs]. The radioactive decay of many of the heaviest isotopes in the periodic table frequently involves the emission of α-particles. Among the nuclides included in this grouping are: $^{238}_{92}U$, $^{226}_{88}Ra$, and $^{222}_{86}Rn$.

Considered as a member of the nuclear radiation family, the α-particle is the least penetrating. Typically, **Alpha Radiation** can be stopped by a sheet of paper; thus, shielding individuals from exposures to α-particles is relatively easy. The principal danger to humans arising from exposures to α-particles occurs when some alpha active radionuclide is ingested and becomes situated in some vital organ in the body where its lack of penetrating power is no longer a factor.

Beta Radiation

Beta Radiation constitutes a second major class of directly ionizing charged particles; and again because of this fact, this class or radiation should not be considered to be a subset of electromagnetic radiation.

There are two different β-particles — the more common negatively charged one, the β^- [the electron], and its positive cousin, the β^+ [the positron]. **Beta Radiation** most commonly arises from the radioactive decay of an unstable isotope. A radioisotope that decays by emitting β-particles is classified as being beta active. Among the most common beta active [all β^- active] radionuclides are: $^{3}_{1}H$ (tritium), $^{14}_{6}C$, and $^{90}_{38}Sr$.

Most **Beta Radiation** is of the β^- category; however, there are radionuclides whose decay involves the emission of β^+ particles. β^+ emissions inevitably end up falling into the Electron Capture [EC] type of radioactive decay simply because the emitted positron — as the antimatter counterpart of the normal electron, or β^- particle — annihilates immediately upon encountering its antiparticle, a normal electron. Radionuclides that are β^+ active include: $^{22}_{11}Na$ and $^{18}_{9}F$.

Although more penetrating than an α-particle, the β-particle is still not a very penetrating form of nuclear radiation. β-particles can generally be stopped by very thin layers of any material of high mass density [i.e., 0.2 mm of lead], or by relatively thicker layers of more common, but less dense materials [i.e., a 1-inch thickness of wood]. As is the case with α-particles, β-particles are most dangerous when an ingested beta active source becomes situated in some susceptible organ or other location within the body.

Neutron Radiation

Although there are no naturally occurring neutron sources, this particle still constitutes an important form of nuclear radiation; and again since the neutron is a massive particle, it should not simply be considered to be a form of electromagnetic radiation. As was the case with both α- and β-particles, neutrons can generate ions as they interact with matter; thus they definitely are a subset of the overall class of ionizing radiation. The most important source of **Neutron Radiation** is the nuclear reactor [commercial, research, and/or military]. The characteristic, self-sustaining chain reaction of an operating nuclear reactor, by definition, generates a steady supply of neutrons. Particle accelerators also can be a source of **Neutron Radiation**.

Protecting personnel from exposures arising from **Neutron Radiation** is one of the most difficult problems in the overall area of radiation protection. Neutrons can produce considerable damage in exposed individuals. Unlike their electrically charged counterparts [α- and β-particles], uncharged neutrons are not capable, either directly or indirectly, of producing ionizations. Additionally, neutrons do not behave like high energy photons [γ-Rays and/or X-Rays] as they interact with matter. These relatively massive uncharged particles simply pass through matter without producing anything until they collide with one of the nuclei that are resident there. These collisions accomplish two things simultaneously:

(1) they reduce the energy of the neutron, and
(2) they "blast" the target nucleus, usually damaging it in some very significant manner — i.e., they mutate this target nucleus into an isotope of the same element that has a higher atomic weight, one that will likely be radioactive. Alternatively, if neutrons are passing through some fissile material, they can initiate and/or maintain a fission chain reaction, etc.

Shielding against **Neutron Radiation** always involves processes that reduce the energy or the momentum of the penetrating neutron to a point where its collisions are no longer capable of producing damage. High energy neutrons are most effectively attenuated [i.e., reduced in energy or momentum] when they collide with an object having approximately their same mass. Such collisions reduce the neutron's energy in a very efficient manner. Because of this fact, one of the most effective shielding media for neutrons is water, which obviously contains large numbers of hydrogen nuclei, or protons which have virtually the same mass as the neutron.

X-Radiation

X-Radiation — X-Rays — consists of high energy photons that, by definition, are man-made. The most obvious source of **X-Radiation** is the X-Ray Machine, which produces these energetic photons as a result of the bombardment of certain heavy metals — i.e., tungsten, iron, etc. — with high energy electrons. X-Rays are produced in one or the other of the two separate and distinct processes described below:

(1) the acceleration (actually, negative acceleration or "deceleration") of a fast moving, high energy, negatively charged electron as it passes closely by the positively charged nucleus of one of the atoms of the metal matrix that is being bombarded [energetic X-Ray photons produced by this mechanism are known as "Bremsstrahlung X-Rays," and their energy ranges will vary according to the magnitude of the deceleration experienced by the bombarding electron]; and
(2) the de-excitation of an ionized atom — an atom that was ionized by a bombarding, high energy electron, which produced the ionization by "blasting" out one of the target atom's own inner shell electrons — the de-excitation occurs when one of the target atom's remaining outer shell electrons "falls" into (transitions into) the vacant inner shell position, thereby producing an X-Ray with an energy precisely equal to the energy difference between the beginning and ending states of the target atom [energetic X-Ray photons produced in this manner are known as "Characteristic X-Rays" because their energies are always precisely known].

The principal uses of **X-Radiation** are in the areas of medical and industrial radiological diagnostics. The majority of the overall public's exposure to ionizing radiation occurs as a result of exposure to X-Rays.

Like their γ-Ray counterparts, X-Rays are uncharged, energetic photons with substantial penetrating power, typically requiring a substantial thickness of some shielding material [i.e., lead, iron, steel reinforced concrete, etc.] to protect individuals who might otherwise be exposed.

Ultraviolet Radiation

Photons in the **Ultraviolet Radiation**, or UV, spectral band have the least energy that is still capable of producing ionizations. As stated earlier, all of the UV band has been classified as being a member of the *Optical Radiation Band*, which — by definition — is Non-

Ionizing. This is erroneous, since UV is indeed capable of producing ionizations in exposed matter. Photoionization detection, as a basic analytical tool, relies on the ability of certain wavelengths of UV radiation to generate ions in certain gaseous components.

"Black Light" is a form of **Ultraviolet Radiation**. In the industrial area, UV radiation is produced by plasma torches, arc welding equipment, and mercury discharge lamps. The most prominent source of UV is the Sun.

Ultraviolet Radiation has been further classified into three sub-categories by the *Commission Internationale d'Eclairage* (CIE). These CIE names are: UV-A, UV-B, and UV-C. The wavelengths associated with each of these "CIE Bands" are shown in the tabulation on Page 8-2.

The UV-A band is the least dangerous of these three, but it has been shown to produce cataracts in exposed eyes. UV-B and UV-C are the bands responsible for producing injuries such as photokeratitis [i.e., welder's flash, etc.], and erythema [i.e., sunburn, etc.]. A variety of protective measures are available to individuals who may become exposed to potentially harmful UV radiation. Included among these methods are glasses or skin ointments designed to block harmful UV-B and/or UV-C photons.

Categories of Non-Ionizing Radiation

Visible Light

Visible Light is that portion of the overall electromagnetic spectrum to which our eyes are sensitive. This narrow spectral segment is the central member of the *Optical Radiation Band*. The hazards associated with **Visible Light** depend upon a combination of the energy of the source and the duration of the exposure. Certain combinations of these factors can pose very significant hazards [i.e., night and color vision impairments]. In cases of extreme exposure, blindness can result. As an example, it would be very harmful to an individual's vision for that individual to stare, even for a very brief time period, at the sun without using some sort of eye protection. In the same vein, individuals who must work with visible light lasers must always wear protective glasses — i.e., glasses with appropriate optical density characteristics.

For reference, the retina, which is that part of the eye that is responsible for our visual capabilities, can receive the entire spectrum of visible light as well as the near infrared — which will be discussed under the next definition. It is the exposure to these bands that can result in vision problems for unprotected individuals.

Infrared Radiation

Infrared Radiation, or IR, is the longest wavelength sector of the overall *Optical Radiation Band*. The IR spectral band, like its UV relative, is usually thought of as being divided into three sub-segments, the near, the mid, and the far. These three sub-bands have also been designated by the *Commission Internationale d'Eclairage* (CIE), respectively, as IR-A, IR-B, and IR-C. The referenced non-CIE names, "near," "mid," and "far," refer to the relative position of the specific IR band with respect to visible light — i.e., the near IR band has wavelengths that are immediately adjacent to the longest visible light wavelengths, while the far IR photons, which have the greatest infrared wavelengths, are most distant from the visible band. In general, we experience **Infrared Radiation** as radiant heat.

As stated earlier in the discussion for visible light, the anterior portions of the eye [i.e., the lens, the vitreous humor, the cornea, etc.] are all largely opaque to the mid and the far IR; only the photons of the near IR can penetrate all the way to the retina. Near IR photons are, therefore, responsible for producing retinal burns. Mid and far IR band photons, for which the anterior portions of the eye are relatively opaque, will typically be absorbed in these tissues and are, therefore, responsible for injuries such as corneal burns.

Microwave Radiation

General agreement holds that **Microwave Radiation** involves the EHF, SHF, & UHF Bands, plus the shortest wavelength portions of the VHF Band — basically, the shortest wavelength half of the *Radio Frequency/Microwave Band* sub-group. All the members of this group have relatively short wavelengths — the maximum λ is in the range of 3 meters.

Virtually all the adverse physiological effects or injuries that accrue to individuals who have been exposed to harmful levels of **Microwave Radiation** can be understood from the perspective of the "radiation" rather than the "electric and/or magnetic field" characteristics of these physical agents [see the discussion of the differences between these two characteristic categories, as well as the associated concepts of the "Near Field" and the "Far Field," later on Pages 8-10 & 8-11, under the heading, Radiation Characteristics vs. Field Characteristics]. Physiological injuries to exposed individuals, to the extent that they occur at all, are simply the result of the absorption — within the body of the individual who has been exposed to the **Microwave Radiation** — of a sufficiently large amount of energy to produce significant heating in the exposed organs or body parts. The long-term health effects of exposures that do not produce any measurable heating [i.e., increases in the temperature of some organ or body part] are unknown at this time.

Some of the uses/applications that make up each of the previously identified **Microwave Radiation** bands are listed in the following tabulation:

Band	Wavelength	Frequency	Use or Application
EHF	1 to 10 mm	300 to 30 GHz	Satellite Navigational Aids & Communications, Police 35 GHz *K Band* Radar, Microwave Relay Stations, Radar: *K (partial), L & M Bands* (military fire control), High Frequency Radio, etc.
SHF	10 to 100 mm	30 to 3 GHz	Police 10 & 24 GHz *J & K Band* Radars, Satellite Communications, Radar: *F, G, H, I, J, & K (partial) Bands* (surveillance, & marine applications), etc.
UHF	0.1 to 1.0 m	3,000 to 300 MHz	UHF Television [Channels 14 to 84], certain CB Radios, Cellular Phones, Microwave Ovens, Radar: *B (partial), D, & E Bands* (acquisition & tracking, + air traffic control), Taxicab Communications, Spectroscopic Instruments, some Short-wave Radios, etc.
VHF	1.0 to 3.0 m	300 to 100 MHz	Higher Broadcast Frequency Standard Television [174 to 216 MHz: Channels 7 to 13], Radar *B Band*, Higher Frequency FM Radio [100+ MHz], walkie-talkies, certain CB Radios, Cellular Telephones, etc.

Radio Frequency Radiation

Radio Frequency Radiation makes up the balance of the *Radio Frequency/Microwave Band* sub-group. The specific segments involved are the longest wavelength half of the VHF Band, plus all of the HF, MF, & LF Bands. In general, all of the wavelengths involved in this sub-group are considered to be long to very long, with the shortest λ being 3+ meters and the longest, approximately 10 km, or just less than 6.25 miles.

The adverse physiological effects or injuries, if any, that result from exposures to **Radio Frequency Radiation** can be understood from the perspective of the "electric and/or magnetic field," rather than the "radiation" characteristics of these particular physical agents [again, see the discussion of the differences between these two characteristic categories, as well as the associated concepts of the "Near Field" and the "Far Field," later on Pages 8-10 & 8-11, under the heading, Radiation Characteristics vs. Field Characteristics]. Injuries to exposed individuals, to the extent that they have been documented at all, are also the result of the absorption by some specific organ or body part of a sufficiently large amount of energy to produce highly localized heating. As was the case with Microwave Radiation exposures, the long-term health effects of exposure events that do not produce any measurable heating are unknown at this time.

Some of the uses/applications that make up each of the previously identified **Radio Frequency Radiation** bands are listed in the following tabulation:

Band	Wavelength	Frequency	Use or Application
VHF	3.0 to 10.0 m	100 to 30 MHz	Lower Frequency Broadcast Standard Television [54 to 72, & 76 to 88 MHz: Channels 2 to 6], Lower Frequency FM Radio [88 to 100 MHz], Dielectric Heaters, Diathermy Machines, certain CB Radios, certain Cellular Telephones, etc.
HF	10 to 100 m	30 to 3 MHz	Plasma Processors, Dielectric Heaters, various types of Welding, some Short-wave Radios, Heat Sealers, etc.
MF	0.1 to 1.0 km	3,000 to 300 kHz	Plasma Processors, AM Radio, various types of Welding, some Short-wave Radios, etc.
LF	1 to 10 km	300 to 30 kHz	Cathode Ray Tubes or Video Display Terminals

Sub-Radio Frequency Radiation

This final portion of the overall electromagnetic spectrum is comprised of its longest wavelength members. **Sub-Radio Frequency Radiation** makes up its own "named" category, namely, the *Sub-Radio Frequency Band*, as the final sub-group of the overall category of Non-Ionizing Radiation.

At the time that this paragraph is being written, there is little agreement as to the adverse physiological effects that might result from exposures to **Sub-Radio Frequency Radiation**. Again, and to the extent that human hazards do exist for this class of physical agent, these hazards can be best understood from the perspective of the "electric and/or magnetic field," rather than the "radiation" characteristics of **Sub-Radio Frequency Radiation** [again, see the discussion of the differences between these two characteristic categories, as well as the associated concepts of the "Near Field" and the "Far Field," on this page and the next, under the heading, Radiation Characteristics vs. Field Characteristics].

Primary concern in this area seems generally to be related to the strength of either or both the electric and the magnetic fields that are produced by sources of this class of radiation. The American Conference of Government Industrial Hygienists [ACGIH] has published the following expressions that can be used to calculate the appropriate 8-hour TLV-TWA — each as a function of the frequency, **f**, of the **Sub-Radio Frequency Radiation** source being considered. The relationship for electric fields provides a field strength TLV expressed in volts/meter [V/m]; while the relationship for magnetic fields produces a magnetic flux density TLV in milliteslas [mT].

Electric Fields

$$\mathbf{E_{TLV}} = \frac{\mathbf{2.5 \times 10^6}}{\mathbf{f}}$$

Magnetic Fields

$$\mathbf{B_{TLV}} = \frac{\mathbf{60}}{\mathbf{f}}$$

Finally, one area where there does appear to be very considerable, well-founded concern about the hazards produced by **Sub-Radio Frequency Radiation** is in the area of the adverse impacts of the electric and magnetic fields produced by this class of source on the normal operation of cardiac pacemakers. An electric field of 2,500 volts/meter [2.5 kV/m] and/or a magnetic flux density of 1.0 gauss [1.0 G, which is equivalent to 0.1 milliteslas or 0.1 mT] each clearly has the potential for interrupting the normal operation of an exposed cardiac pacemaker, virtually all of which operate at roughly these same frequencies.

Some of the uses/applications that make up each of the previously identified **Sub-Radio Frequency Radiation** bands are listed in the following tabulation:

Band	Wavelength	Frequency	Use or Application
VLF	10 to 100 km	30 to 3 kHz	Cathode Ray Tubes or Video Display Terminals [video flyback frequencies], certain Cellular Telephones, Long-Range Navigational Aids [LORAN], etc.
ULF	0.1 to 1 Mm	3,000 to 300 Hz	Induction Heaters, etc.
SLF	1 to 10 Mm	300 to 30 Hz	Standard Electrical Power [60 Hz], Home Appliances, Underwater Submarine Communications, etc.
ELF	10 to 100 Mm	30 to 3 Hz	Underwater Submarine Communications, etc.

Radiation Characteristics vs. Field Characteristics

All of the previous discussions have been focused on the various categories and subcategories of the electromagnetic spectrum [excluding, in general, the category of particulate nuclear radiation]. It must be noted that every band of electromagnetic radiation — from the extremely high frequencies of Cosmic Rays [frequencies often greater than 3×10^{21} Hz or 3,000 EHz] to the very low end frequencies characteristic of normal electrical power in the United States [i.e., 60 Hz] — will consist of photons of **radiation** possessing both electric and magnetic **field** characteristics.

That is to say, we are dealing with **radiation** phenomena that possess **field** [electric and magnetic] characteristics. The reason for considering these two different aspects or factors is that measuring the "strength" or the "intensity" of any radiating source is a process in which only rarely will both the **radiation** and the **field** characteristics be easily quantifiable. The vast majority of measurements in this field will, of necessity, have to be made on only one or the other of these two characteristics. It is the frequency and/or the wavelength being considered that determines whether the measurements will be made on the **radiation** or the **field** characteristics of the source involved.

When the source frequencies are relatively high — i.e., **f** > 100 MHz [with **λ** < 3 meters] — it will almost always be easier to treat and measure such sources as simple **radiation** sources. For these monitoring applications [with the exception of situations that involve lasers], it will be safe to assume that the required "strength" and/or "intensity" characteristics will behave like and can be treated as if they were **radiation** phenomena — i.e., they vary according to the inverse square law.

In contrast, when the source frequencies fall into the lower ranges — i.e., **f** ≤ 100 MHz [with **λ** ≥ 3 meters] — then it will be the **field** characteristics that these sources produce [electric and/or magnetic] that will be relatively easy to measure. While it is certainly true that these longer wavelength "photons" do behave according to the inverse square law — since they are, in fact, radiation — their relatively long wavelengths make it very difficult to measure them as radiation phenomena.

These measurement problems relate directly to the concepts of the Near and the Far Field. The Near Field is that region that is close to the source — i.e., no more than a very few wavelengths distant from it. The Far Field is the entire region that exists beyond the Near Field.

Field measurements [i.e., separate electric and/or magnetic field measurements] are usually relatively easy, so long as the measurements are completed in the Near Field. It is in this region where specific, separate, and distinct measurements of either of these two **fields** can be made. The electric **fields** that exist in the Near Field are produced by the voltage characteristics of the source, while the magnetic **fields** in this region result from the source's electrical current. Electric field strengths will typically be expressed in one of the following three sets of units: (1) volts/meter — v/m; (2) $volts^2/meter^2$ — v^2/m^2; or (3) $milliwatts/cm^2$ — mW/cm^2. Magnetic field intensities will typically be expressed in one of the following four sets of units: (1) amperes/meter — A/m; (2) milliamperes/meter — mA/m; (3) $Amperes^2/meter^2$ — A^2/m^2; or (4) milliwatts/cm — mW/cm.

Radiation measurements, in contrast, are typically always made in the Far Field. As an example, let us consider a 75,000 volt X-Ray Machine — i.e., one that is producing X-Rays with an energy of 75 keV. For such a machine, the emitted X-Rays will have a frequency of 1.81×10^{19} Hz and a wavelength of 1.66×10^{-11} meters, or 0.166 Å [from Planck's Law]. Clearly for such a source, it would be virtually impossible to make any measurements in the Near Field — i.e., within a very few wavelengths distant from the source — since even a six wavelength distance would be only 1 Å away [a 1 Å distance is less than the diameter of a methane molecule!!]. Measurements made in the Far Field of the strength or intensity of a radiating source then will always be **radiation** measurements, usually in units such as millirem/hour — mRem/hr. As stated earlier, **radiation** behaves according to the inverse square law, a relationship that states that radiation intensity decreases as the square of the distance between the point of measurement and the source.

Sources of Ionizing Radiation

Radioactivity

Radioactivity is the process by which certain unstable atomic nuclei undergo a nuclear disintegration. In this disintegration, the unstable nucleus will typically emit one or more of: (1) the common sub-atomic particles [i.e., the α-Particle, the β-Particles, etc.], and/or (2) photons of electromagnetic energy, [i.e., γ-Rays, etc.].

Radioactive Decay

Radioactive Decay refers to the actual process — involving one or more separate and distinct steps — by which some specific radioactive element, or radionuclide, undergoes the transition from its initial condition, as an "unstable" nucleus, ultimately to a later generation "unstable" radioactive nucleus, or — eventually — a "stable" non-radioactive nucleus. In the process of this **Radioactive Decay**, the originally unstable nucleus will very frequently experience a change in its basic atomic number. Whenever this happens, its chemical identity will change — i.e., it will become an isotope of a different element. As an example, if an unstable nucleus were to emit an electron [i.e., a β^--particle], its atomic number would increase by one — i.e., an unstable isotope of calcium decays by emitting an electron, and in so doing becomes an isotope of scandium, thus:

$${}^{45}_{20}\mathrm{Ca} \rightarrow {}^{45}_{21}\mathrm{Sc} + {}^{0}_{-1}\mathrm{e}\text{, which could also be written as follows: } {}^{45}_{20}\mathrm{Ca} \rightarrow {}^{45}_{21}\mathrm{Sc} + \beta^-$$

A second example would be the **Radioactive Decay** of the only naturally occurring isotope of thorium, which involves the emission of an α-particle:

$${}^{232}_{90}\mathrm{Th} \rightarrow {}^{228}_{88}\mathrm{Ra} + {}^{4}_{2}\mathrm{He}\text{, which could also be written as follows: } {}^{232}_{90}\mathrm{Th} \rightarrow {}^{228}_{88}\mathrm{Ra} + {}^{4}_{2}\alpha$$

In this situation, the unstable thorium isotope was converted into an isotope of radium.

Radioactive Decay can occur in any of nine different modes. These nine are listed below, in each case with an example of a radioactive isotope that undergoes radioactive decomposition — in whole or in part — following the indicated decay mode:

Decay Mode	Example
Alpha Decay [α-decay]	${}^{235}_{92}\mathrm{U} \rightarrow {}^{231}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$
Beta Decay [β^--decay]	${}^{90}_{38}\mathrm{Sr} \rightarrow {}^{90}_{39}\mathrm{Y} + {}^{0}_{-1}\mathrm{e}$
Positron Decay [β^+-decay]	${}^{22}_{11}\mathrm{Na} \rightarrow {}^{22}_{10}\mathrm{Ne} + {}^{0}_{+1}\mathrm{e} + \gamma$ [simultaneous β^+ **&** γ-decay]
Gamma Decay [γ-decay]	${}^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + {}^{0}_{-1}\mathrm{e} + \gamma$ [simultaneous β^- **&** γ-decay]
Neutron Decay [*n*-decay]	${}^{252}_{98}\mathrm{Cf} \rightarrow {}^{107}_{42}\mathrm{Mo} + {}^{141}_{56}\mathrm{Ba} + 4{}^{1}_{0}\mathrm{n}$ [simultaneous *n*-decay **&** SF]
Electron Capture [EC]	${}^{125}_{53}\mathrm{I} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{125}_{52}\mathrm{Te} + \gamma$ [simultaneous EC **&** γ-decay]
Internal Conversion [IC]	${}^{125}_{52}\mathrm{Te} \rightarrow {}^{0}_{-1}\mathrm{e}$ [following the simultaneous EC **&** γ-decay reaction shown above; the electron is ejected — i.e., IC — from one of the technetium atom's innermost electron sub-shells]
Isomeric Transition [IT]	${}^{121m}_{50}\mathrm{Sn} \rightarrow {}^{121}_{50}\mathrm{Sn} + \gamma$ [simultaneous IT **&** γ-decay]
Spontaneous Fission [SF]	${}^{252}_{98}\mathrm{Cf} \rightarrow {}^{107}_{42}\mathrm{Mo} + {}^{141}_{56}\mathrm{Ba} + 4{}^{1}_{0}\mathrm{n}$ [simultaneous SF **&** *n*-decay]

Radioactive Decay Constant

The **Radioactive Decay Constant** is the isotope specific "time" coefficient that appears in the exponent term of Equation **#8-4** on Page 8-18. Equation **#8-4** is the widely used relationship that always serves as the basis for determining the quantity [atom count or mass] of any as yet undecayed radioactive isotope. This exponential relationship is used to evaluate remaining quantities at any time interval after a starting determination of an "initial" quantity. By definition, all radioactive isotopes decay over time, and the **Radioactive Decay Constant** is an empirically determined factor that effectively reflects the speed at which the decay process has occurred or is occurring.

Mean Life

The **Mean Life** of any radioactive isotope is simply the average "lifetime" of a single atom of that isotope. Quantitatively, it is the reciprocal of that nuclide's Radioactive Decay Constant — see Equation **#8-6**, on Page 8-19. **Mean Lives** can vary over extremely wide ranges of time; as an example of this wide variability, the following are the **Mean Lives** of two fairly common radioisotopes, namely, the most common naturally occurring isotope of uranium and a fairly common radioactive isotope of beryllium:

For an atom of ${}^{238}_{92}U$, the **Mean Life** [α-decay] is 6.44×10^{9} years

For an atom of ${}^{7}_{4}Be$, the **Mean Life** [EC decay] is 76.88 days

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Half-Life

The **Half-Life** of any radioactive species is the time interval required for the population of that material to be reduced, by radioactive decay, to one half of its initial level. The **Half-Lives** of different isotopes, like their Mean Lives, can vary over very wide ranges. As an example, for the two radioactive decay schemes described under the definition of Radioactive Decay on the previous page, namely, Page 8-12, the **Half-Lives** are as follows

For ${}^{45}_{20}Ca$, the **Half-Life** is 162.7 days

For ${}^{232}_{90}Th$, the **Half-Life** is 1.4×10^{10} years

As can be seen from these two **Half-Lives**, this parameter can assume values over a very wide range of times. Although the thorium isotope listed above certainly has a very long **Half-Life**, it is by no means the longest. On the short end of the scale, consider another thorium isotope, ${}^{218}_{90}Th$ which has a **Half-Life** of 0.11 microseconds.

Nuclear Fission

Nuclear Fission, as the process that will be described here, differs from the Spontaneous Fission mode that was listed on Page 8-12 under the description of Radioactive Decay as one of the nine radioactive decay modes. This class of **Nuclear Fission** is a nuclear reaction in which a fissile isotope — i.e., an isotope such as ${}^{235}_{92}U$ or ${}^{239}_{94}Pu$ — upon absorbing a free neutron undergoes a fracture which results in the conversion of the initial isotope into:

1. two daughter isotopes,
2. two or more additional neutrons,
3. several very energetic γ-rays, and
4. considerable additional energy, usually appearing in the form of heat.

Nuclear Fission reactions are the basic energy producing mechanisms used in every nuclear reactor, whether it is used to generate electric power, or to provide the motive force for a nuclear submarine. One of the most important characteristics of this type of reaction is that by regenerating one or more of the particles [i.e., neutrons] that initiated the process, the reaction can become self-sustaining. Considerable value can be derived from this process if the chain reactions involved can be controlled. In theory, control of these chain reactions occurs in such things as nuclear power stations. An example of an uncontrolled **Nuclear Fission** reaction would be the detonation of an atomic bomb.

An example of a hypothetically possible **Nuclear Fission** reaction might be:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{109}_{44}Ru + ^{123}_{48}Cd + 3\ ^{1}_{0}n + 3\ \gamma s + \text{considerable energy}$$

In this hypothetical fission reaction, the sum of the atomic masses of the two reactants to the left of the arrow is 236.052589 amu, whereas the sum of atomic masses of all the products to the right of this arrow is 234.856015 amu. Clearly there is a mass discrepancy of 1.196574 amu or 1.987×10^{-24} grams. It is this mass that was converted into the several γ-rays that were created and emitted, as well as the very considerable amount of energy that was liberated. It appears that Albert Einstein was correct: mass and energy are simply different forms of the same thing.

Since **Nuclear Fission** reactions are clearly sources for a considerable amount of ionizing radiation, they are of interest to occupational safety and health professionals.

Radiation Measurements

The Strength or Activity of a Radioactive Source

The most common measure of **Radiation Source Strength** or **Activity** is the number of radioactive disintegrations that occur in the mass of radioactive material per unit time. There are several basic units that are employed in this area; they are listed below, along with the number of disintegrations per minute that each represents:

Unit of Source Activity	Abbreviation	Disintegrations/min
1 Curie	Ci	2.22×10^{12}
1 Millicurie	mCi	2.22×10^{9}
1 Microcurie	µCi	2.22×10^{6}
1 Picocurie	pCi	2.22
1 Becquerel	Bq	60

Exposure

Exposure is a unit of measure of radiation that is currently falling into disuse. The basic definition of **Exposure** — usually designated as X — is that it is the sum number of all the ions, of either positive or negative charge — usually designated as ΣQ — that are produced in a mass of air — which has a total mass, Σm — by some form of ionizing radiation that, in the course of producing these ions, has been totally dissipated. Quantitatively, it is designated by the following formula:

$$X = \frac{\sum Q}{\sum m}$$

The unit of **Exposure** is the roentgen, or R. There is no *SI* unit for **Exposure**; thus as stated above this measure is now only rarely encountered. References to **Exposure** are now only likely to be found in older literature.

Dose

Dose, or more precisely **Absorbed Dose**, is the total energy imparted by some form of ionizing radiation to a known mass of matter that has been exposed to that radiation. Until the mid 1970s the most widely used unit of **Dose** was the rad, which has been defined to be equal to 100 ergs of energy absorbed into one gram of matter. Expressed as a mathematical relationship:

$$1.0 \text{ rad} = 100 \frac{\text{ergs}}{\text{gram}} = 100 \text{ ergs} \cdot \text{grams}^{-1}$$

At present, under the *SI System*, a new unit of **Dose** has come into use. This unit is the gray, which has been defined to be the deposition of 1.0 joule of energy into 1.0 kilogram of matter. Expressed as a mathematical relationship:

$$1.0 \text{ gray} = 1.0 \frac{\text{joule}}{\text{kilogram}} = 1.0 \text{ joule} \cdot \text{kilogram}^{-1}$$

The gray is steadily replacing the rad although the latter is still in fairly wide use. For reference, 1 gray = 100 rad [1 Gy = 100 rad], or 1 centigray = 1 rad [1 cGy = 1 rad]. For most applications, Doses will be measured in one of the following "sub-units": (1) millirad — mrads; (2) microrads — μrads; (3) milligrays — mGys; or (4) micrograys — μGys. These units are — as their prefixes indicate — either 10^{-3} or 10^{-6} multiples of the respective basic Dose unit.

Dose, as a measurable quantity, is always represented by the letter "D."

Dose Equivalent

The **Dose Equivalent** is the most important measured parameter insofar as the overall subject of radiation protection is concerned. It is basically the product of the Absorbed Dose and an appropriate Quality Factor, a coefficient that is dependent upon the type of ionizing particle involved — see Equation **#8-12** on Pages 8-22 & 8-23. This parameter is usually represented by the letter "H." There are two cases to consider, and they are as follows:

1. If the Dose or Absorbed Dose, D, has been given in units of rads [or mrads, or μrads], then the units of the Dose Equivalent, H, will be rem [or mrem, or μrem] as applicable.
2. If the Dose or Absorbed Dose, D, has been given in units of grays [or mGy, or μGy], then the units of the Dose Equivalent, H, will be sieverts [or mSv, or μSv] as applicable.

It is very important to note that since **1 Gray = 100 rads**, it follows that **1 sievert = 100 rem**.

Finally, if it is determined that a Dose Equivalent > 100 mSv, there is almost certainly a very serious situation with a great potential for human harm; thus, in practice, for Dose Equivalents above this level, the unit of the sievert is rarely, if ever, employed.

RELEVANT FORMULAE & RELATIONSHIPS

Basic Relationships for Electromagnetic Radiation

Equation #8-1:

For any photon that is a part of the overall electromagnetic spectrum, the relationship between that photon's wavelength, its frequency, and/or its wavenumber is given by the following expression, Equation **#8-1**, which is shown below in two equivalent forms:

$$\mathbf{c} = \lambda \nu$$

$$\mathbf{c} = \frac{\nu}{\mathbf{k}}$$

Where:

- **c** = the speed of light in a vacuum, which is 2.99792458×10^{8} meters/second [frequently approximated as 3.0×10^{8} meters/second];
- **λ** = the wavelength of the photon in question, in units of meters [actually meters/cycle];
- **ν** = the frequency associated with the photon in question, in units of reciprocal seconds — sec^{-1} — [actually cycles/second or Hertz]; &
- **k** = the wavenumber of the photon in question, in units of reciprocal meters — meters^{-1} — [actually cycles/meter].

Equation #8-2:

The relationship between the wavelength and the wavenumber of any electromagnetic photon is given by the following expression, Equation **#8-2**:

$$\lambda = \frac{1}{\mathbf{k}}$$

Where:

- **λ** = the wavelength of the photon in question, in units of meters [actually meters/cycle], as defined above for Equation **#8-1**; &
- **k** = the wavenumber of the photon in question, in units of reciprocal meters — meters^{-1} — [actually cycles/meter], also as defined above for Equation **#8-1**. Note: wavenumbers are very frequently expressed in units of reciprocal centimeters — cm^{-1} — and when expressed in these units, the photon is said to be at "xxx" wavenumbers [i.e., a 3,514 cm^{-1} photon is said to be at 3,514 wavenumbers].

Equation #8-3:

Equation **#8-3** expresses the relationship between the energy of any photon in the electromagnetic spectrum, and the wavelength of that photon. This relationship is **Planck's Law**, which was the first specific, successful, quantitative relationship ever to be applied in the area of quantum mechanics. This Law, as the first significant result of Planck's basic research in this area, formed one of the main foundation blocks upon which modern physics and/or quantum mechanics was built.

$$\mathbf{E = h\nu}$$

Where:

E = the energy of the electromagnetic photon in question, in some suitable energy unit — i.e., joules, electron volts, etc.;

h = Planck's Constant, which has a value of 6.626×10^{-34} joule·seconds, and/or 4.136×10^{-15} electron volt·seconds; &

ν = the frequency associated with the photon in question, in units of reciprocal seconds [actually cycles/second or Hertz] — as defined on the previous page for Equation **#8-1**.

Calculations Involving Radioactive Decay

Equation #8-4:

For any radioactive isotope, the following Equation, #**8-4**, identifies the current **Quantity** or amount of the isotope that would be present at any incremental time period after the initial or starting mass or number of atoms had been determined [i.e., the mass or number of atoms that has not yet undergone radioactive decay]. With any radioactive decay, the number of disintegrations or decays per unit time will be exponentially proportional to both the Radioactive Decay Constant for that nuclide, and the actual numeric count of the nuclei that are present [i.e., the **Quantity**].

$$N_t = N_0 e^{-kt}$$

Where:

N_t = the **Quantity** of any radioactive isotope present at any time, **t**; this **Quantity** is usually measured either in mass units [mg, µg, etc.] OR as a specific numeric count of the as yet undecayed nuclei remaining in the sample [i.e., 3.55×10^{19} atoms];

N_0 = the **Initial Quantity** of that same radioactive isotope — i.e., the **Quantity** that was present at the time, $t = t_0$ [i.e., 0 seconds, 0 minutes, 0 hours, 0 days, or whatever unit of time is appropriate to the units in which the Radioactive Decay Constant has been expressed]. This is the "Starting" or **Initial Quantity** of this isotope, and it is always expressed in the same units as N_t, which is described above;

k = the **Radioactive Decay Constant**, which measures number of nuclear decays per unit time; in reality, the "number of nuclear decays" is a simple integer, and as such, is effectively dimensionless; thus this parameter should be thought of as being measured in reciprocal units of time [i.e., $seconds^{-1}$, $minutes^{-1}$, $hours^{-1}$, $days^{-1}$, or even $years^{-1}$, etc.]; &

t = the **Time Interval** that has passed since the Initial Quantity of material was determined. This **Time Interval** must be expressed in an appropriate unit of time — i.e., the units of "**k**" and "**t**" must be mutually consistent; thus the units of "**k**" must be: seconds, minutes, hours, days, years, etc.

Equation #8-5:

The following Equation, #**8-5**, provides the relationship between the **Half-Life** of a radioactive isotope and its **Radioactive Decay Constant**. The **Half-Life** of any radioactive nuclide is the statistically determined time interval required for exactly half of the isotope to decay, effectively leaving the other half of the isotope in its original form.

$$T_{1/2} = \frac{0.693}{k}, \text{ or}$$

$$k = \frac{0.693}{T_{1/2}}$$

Where:

$T_{1/2}$ = the **Half-Life** of the radioactive isotope under consideration; this parameter must be expressed in the same units of time that are used as reciprocal time units for the Radioactive Decay Constant; &

k = the **Radioactive Decay Constant**, measured in reciprocal units of time [i.e., seconds^{-1}, minutes^{-1}, hours^{-1}, days^{-1}, or even years^{-1}, etc.], as defined on the previous page, namely Page 8-18, for Equation **#8-4**.

Equation #8-6:

The **Mean Life** of any radioactive isotope is the measure of the average 'lifetime" of a single atom of that isotope. It is simply the reciprocal of that nuclide's Radioactive Decay Constant. Equation **#8-6** provides the quantitative relationship that is involved in calculating this parameter.

$$\tau = \frac{1}{k} = \frac{T_{1/2}}{0.693} = 1.443T_{1/2}$$

Where:

τ = the **Mean Life** of some specific radionuclide, expressed in units of time [i.e., seconds, minutes, hours, days, or years, etc.]

k = the **Radioactive Decay Constant**, measured in consistent reciprocal units of time [i.e., seconds^{-1}, minutes^{-1}, hours^{-1}, days^{-1}, or even years^{-1}, etc.]; &

$T_{1/2}$ = the **Half-Life** of the radioactive isotope under consideration; this parameter must be expressed in the same units of time as the Mean Life, and as the reciprocal of the time units in which the Radioactive Decay Constant is expressed.

Equation #s 8-7 & 8-8:

The **Activity** of any radioisotope is defined to be the number of radioactive disintegrations that occur per unit time. Equation **#s 8-7** & **8-8** are two simplified forms of the relationship that can be used to calculate the **Activity** of any radioactive nuclide.

Equation #8-7:

$$\mathbf{A_b = kN}$$

Equation #8-8:

$$\mathbf{A_c = \frac{kN}{3.70 \times 10^{10}} = \left[2.703 \times 10^{-11}\right] kN}$$

Where:

A_b = the **Activity** of the radionuclide, expressed in becquerels,

OR

A_c = the **Activity** of the radionuclide, expressed in curies;

k = the **Radioactive Decay Constant**, measured in reciprocal units of time [i.e., seconds^{-1}, minutes^{-1}, hours^{-1}, days^{-1}, or even years^{-1}, etc.]; &

N = the **Quantity** of the radioactive isotope that is present in the sample at the time when the evaluation of the **Activity** is to be made, measured as a specific numeric count of the as yet undecayed nuclei remaining in the sample [i.e., 3.55×10^{19} atoms];

Equation #s 8-9 & 8-10:

The following two Equations, **#s 8-9** & **8-10**, provide the two more general forms of the relationship for determining the **Activity** of any radioactive nuclide.

Equation #8-9:

$$\mathbf{A_t = kN_0 e^{-kt}}$$

Equation #8-10:

$$A_t = \left[\frac{0.693}{T_{1/2}}\right] N_0 \, e^{-(0.693)t/T_{1/2}}$$

Where:

A_t = the **Activity** of any radioactive nuclide at any time, **t**. The units of this calculated parameter will be becquerels;

k = the **Radioactive Decay Constant**, measured in reciprocal units of time [i.e., $seconds^{-1}$, $minutes^{-1}$, $hours^{-1}$, $days^{-1}$, or even $years^{-1}$, etc.];

N_0 = the **Initial Quantity** of that same radioactive isotope — i.e., the **Quantity** that was present at the time, $t = t_0$ [i.e., 0 seconds, 0 minutes, 0 hours, 0 days, or zero of whatever unit of time is appropriate to the dimensionality in which the Radioactive Decay Constant has been expressed] — this is the "Starting" or **Initial Quantity** of this isotope, measured as a specific numeric count of the as yet undecayed nuclei remaining in the sample [i.e., 3.55×10^{19} atoms];

$T_{1/2}$ = the **Half-Life** of the radioactive isotope under consideration; this parameter must be expressed in the same units of time that appear as reciprocal time units for the Radioactive Decay Constant; &

t = the **Time Interval** that has passed since the Initial Quantity of material was determined; this **Time Interval** must be expressed in an appropriate unit of time — i.e., the units of "**k**" and "**t**" must be consistent with each other.

Dose and/or Exposure Calculations

Equation #8-11:

The following Equation, #**8-11**, is applicable only to **Dose Exposure Rates** caused by high energy X-Rays and/or γ-Rays [as well as — hypothetically, at least, but certainly not practically — any other photons such as a Cosmic Ray, which have a still shorter wavelength]. Determinations of these **Dose Exposure Rates** are largely limited to medical applications. In order to be able to make these determinations, some very specific and unique source-based radiological data [i.e., the Radiation Constant of the source] must be known. In addition, the Radiation Source Activity, and the distance from the source to the point at which **Dose Exposure Rate** is to be measured, must also be known.

$$\mathbf{E = \frac{\Gamma A}{d^2}}$$

Where:

E = the **Dose Exposure Rate** that has resulted from an individual's exposure to some specific X- or γ-radiation source, for which the specific Radiation Constant, **Γ**, is known; this dose rate is commonly expressed in units such as Rads/hour;

Γ = the **Radiation Constant** for the X- or γ-Ray active nuclide being considered, expressed in units of $[\text{Rads} \cdot \text{centimeters}]^2$ per $\text{millicurie} \cdot \text{hour}$, or

$$\left[\frac{\text{Rad} \cdot \text{cm}^2}{\text{mCi} \cdot \text{hr}}\right];$$

A = the **Radiation Source Activity**, measured usually in millicuries [mCi's]; &

d = the **Distance** between the "Target" and the radiation source, measured in centimeters [cm].

Equation #8-12:

This Equation, #**8-12**, provides for the conversion of an **Absorbed Radiation Dose**, expressed either in Rads or in Grays, to a more useful form — useful from the perspective of measuring the magnitude of the overall impact of the dose on the individual who has been exposed. This alternative, and more useful, form of Radiation Dose is called the **Dose Equivalent** and is expressed either in **rems** or in **sieverts**, both of which measure the "Relative Hazard" caused by the energy transfer that results from an individual's exposure to various different types or categories of radiation. The **rem** and/or the **sievert**, therefore, is dependent upon two specific factors: (1) the specific type of radiation that produced the exposure, and (2) the amount or physical dose of the radiation that was involved in the exposure.

To make these determinations, a "Quality Factor" is used to adjust the measurement that was made in units of **rads** or **grays** — both of which are independent of the radiation source — into an equivalent in **rems** and/or **sieverts**.

This Quality Factor [QF] is a simple multiplier that adjusts for the effective ***Linear Energy Transfer*** (***LET***) that is produced on a target by each type or category of radiation. The higher the ***LET***, the greater will be the damage that can be caused by the type of radiation being considered; thus, this alternative **Dose Equivalent** measures the overall biological effect, or impact, of an otherwise "simple" measured Radiation Dose.

The "range" of β- and/or α-rays is, as stated earlier, very limited — i.e., the "range" is the distance that any form of radiation is capable of traveling through solid material, such as metal, wood, human tissue, etc. before it is stopped. Because of this, Quality Factors as they apply to alpha and beta particles are only considered from the perspective of internal **Dose Equivalent** problems. Quality factors for neutrons, X-, and γ-rays apply both to internal and external **Dose Equivalent** situations.

$$\mathbf{H_{Rem} = D_{Rad}[QF]} \quad \& \quad \mathbf{H_{Sieverts} = D_{Grays}[QF]}$$

Where: $\mathbf{H_{Rem}}$ or $\mathbf{H_{Sievert}}$ = the adjusted **Dose Equivalent** in the more useful "effect related" form, measured in either rems or *sieverts [SI Units]*;

$\mathbf{D_{Rad}}$ or $\mathbf{D_{Gray}}$ = the **Absorbed Radiation Dose**, which is independent of the type of radiation, and is measured in either rads or *grays [SI Units]*; &

QF = the **Quality Factor**, which is a properly dimensioned coefficient — either in units of rems/rad or sieverts/gray, as applicable — that is, itself, a function of the type of radiation being considered [see the following Tabulation].

Tabulation of Quality Factors [QFs] by Radiation Type

Types of Radiation	Quality Factors — QFs	Internal/External
X-Rays <u>or</u> γ-Rays	1.0	Both
β-Rays [positrons <u>or</u> electrons]	1.0	Internal Only
Thermal Neutrons	5.0	Both
Slow Neutrons	4.0 - 22.0	Both
Fast Neutrons	3.0 - 5.0	Both
Heavy, Charged Particles [Alphas, etc.]	20.0	Internal Only

Calculations Involving the Reduction of Radiation Intensity Levels

Equation #8-13:

This Equation, #**8-13**, identifies the effect that shielding materials have in reducing the intensity level of a beam of ionizing radiation. The **Radiation Emission Rate** produced by such a beam can be reduced either by interposing shielding materials between the radiation source and the receptor, or by increasing the source-to-receptor distance. Obviously, the **Radiation Emission Rate** could be decreased still further by using both approaches simultaneously.

The approach represented by Equation **#8-13** deals solely with the use of shielding materials [i.e., it does not consider the effect of increasing source-to-receptor distances]. This approach involves the use of the Half-Value Layer [HVL] concept. A **Half-Value Layer** represents the thickness of any shielding material that would reduce, by one half, the intensity level of incident X- or γ-radiation. This expression is provided in two forms:

$$\mathbf{ER_{goal}} = \frac{\mathbf{ER_{source}}}{2^{x/\mathrm{HVL}}} \quad \text{or}$$

$$\mathbf{x} = \frac{\log\left[\frac{\mathbf{ER_{source}}}{\mathbf{ER_{goal}}}\right][\mathbf{HVL}]}{\log 2} = 3.32\log\left[\frac{\mathbf{ER_{source}}}{\mathbf{ER_{goal}}}\right][\mathbf{HVL}]$$

Where:

$\mathbf{ER_{goal}}$ = the target **Radiation Emission Rate**, measured in units of radiation dose per unit time [i.e., Rads/hour];

$\mathbf{ER_{source}}$ = the observed **Radiation Emission Rate** to be reduced by interposing Shielding Materials, in the same units as $\mathbf{ER_{goal}}$;

x = the **Thickness** of shielding material required to reduce the measured **Radiation Emission Rate** to the level desired, usually measured in units of centimeters or inches [cm or in]; &

HVL = the **Half-Value Thickness** of the Shielding Material being evaluated (i.e., the **Thickness** of this material that will halve the Intensity Level of incident X- or γ-radiation), measured in the same units as "**x**," above.

Equation #8-14:

The following Equation, **#8-14**, is the relationship that describes the effect of increasing the distance between a point source of X- or γ-radiation and a receptor, as an alternative method for decreasing the incident radiation intensity on the receptor. The relationship involved is basically geometric, and is most commonly identified or referred to as **The Inverse Squares Law**.

$$\frac{ER_a}{ER_b} = \frac{S_b^2}{S_a^2} \quad \text{or}$$

$$ER_a S_a^2 = ER_b S_b^2$$

Where:

ER_a = the **Radiation Emission Rate**, or **Radiation Intensity**, in units of radiation dose per unit time [i.e., Sieverts/hour], measured at a distance, "**a**" units from the radiation source;

ER_b = the **Radiation Emission Rate**, or **Radiation Intensity**, in the same units as, ER_a, above, measured at a different distance, "**b**" units from the radiation source;

S_a = the "**a**" **Distance**, or the distance between the radiation source and the first position of the Receptor; this distance is measured in some appropriate unit of length [i.e., meters, feet, etc.]; &

S_b = the "**b**" **Distance**, or the distance between the radiation source and the second — usually more distant — position of the Receptor; this distance is also measured in some appropriate unit of length, and most importantly in the same units of length as S_a, above [i.e., meters, feet, etc.].

Calculations Involving Optical Densities

Equation #8-15:

The following Equation, #**8-15**, describes the relationship between the absorption of monochromatic visible light [i.e., laser light], and the length of the path this beam of light must follow through some absorbing medium. This formula relies on the fact that each incremental thickness of this absorbing medium will absorb the same fraction of the incident radiation as will each other identical incremental thickness of this same medium.

The logarithm of the ratio of the **Incident Beam Intensity** to the **Transmitted Beam Intensity** is used to calculate the **Optical Density** of the medium. This relationship, then, is routinely used to determine the intensity diminishing capabilities [i.e., the **Optical Density**] of the protective goggles that must be worn by individuals who must operate equipment that makes use of high intensity monochromatic light sources, such as lasers.

$$OD = \log\left[\frac{I_{incident}}{I_{transmitted}}\right]$$

Where:

- **OD** = the measured **Optical Density** of the material being evaluated, this parameter is dimensionless;
- $I_{incident}$ = the **Incident Laser Beam Intensity**, measured in units of power/unit area [i.e., W/cm^2]; &
- $I_{transmitted}$ = the **Transmitted Laser Beam Intensity**, measured in the same units as $I_{incident}$, above.

Relationships Involving Microwaves

Equation #8-16:

The following Equation, #**8-16**, provides the necessary relationship for determining the **Distance to the *Far Field*** for any radiating circular microwave antenna. The ***Far Field*** is that region that is sufficiently distant [i.e., more than 2 or 3 wavelengths away] from the radiating antenna, that there is no longer any interaction between the electrical and the magnetic fields being produced by this source. In the ***Near Field*** the interactions between the two electromagnetic fields being produced by any source require a different approach to the measurement of the effects, etc. The ***Near Field*** is every portion of the radiation field that is not included in the ***Far Field*** — i.e., it is that area that is closer to the source antenna than is the ***Far Field***.

$$\mathbf{r_{FF}} = \frac{\mathbf{A}}{\mathbf{2\lambda}} = \frac{\boldsymbol{\pi}\mathbf{D^2}}{\mathbf{8\lambda}}$$

Where:

$\mathbf{r_{FF}}$ = the **Distance to the *Far Field*** from the microwave radiating antenna [all distances equal to or greater than $\mathbf{r_{FF}}$ are considered to be in the ***Far Field***; all distances less than this value will be in the ***Near Field***], these distances are usually measured in centimeters [cm];

A = the **Area** of the radiating circular antenna, measured in square centimeters [cm^2] — for reference, this area can be calculated according to the following relationship,

$$\text{Circular Area} = \frac{\pi\mathbf{D}^2}{4};$$

D = the circular microwave antenna **Diameter**, measured in centimeters [cm]; &

λ = the **Wavelength** of microwave energy being radiated by the circular antenna, also measured in centimeters [cm].

Equation #8-17:

The following Equation, #**8-17**, provides the relationship for determining the ***Near Field*** **Microwave Power Density** levels that are produced by a circular microwave antenna, radiating at a known **Average Power Output**.

$$W_{NF} = \frac{4P}{A} = \frac{16P}{\pi D^2}$$

Where:

- W_{NF} = the ***Near Field*** **Microwave Power Density**, measured in milliwatts/cm^2 [mW/cm^2];
- **P** = the **Average Power Output** of the microwave radiating antenna, measured in milliwatts [mW];
- **A** = the **Area** of the radiating circular antenna, measured in square centimeters [cm^2] — for reference, this area can be calculated according to the following relationship,

  $$\text{Circular Area} = \frac{\pi D^2}{4}\ ; \ \&$$

- **D** = the circular microwave antenna **Diameter**, measured in centimeters [cm].

Equations #s 8-18 & 8-19:

The following two Equations, **#s 8-18** & **8-19**, provide the basic approximate relationships that are used for calculating either microwave **Power Density Levels** in the ***Far Field*** [Equation #**8-18**], OR, alternatively, for determining the actual ***Far Field*** **Distance** from a radiating circular microwave antenna at which one would expect to find some specific **Power Density Level** [Equation #**8-19**].

Unlike the Equation at the top of this page [i.e., Equation #**8-17**], these two formulae have been empirically derived; however, they may both be regarded as sources of reasonably accurate values for the **Power Density Levels** at points in the ***Far Field*** [Equation #**8-18**], or for various ***Far Field*** **Distances** [Equation #**8-19**].

Equation #8-18:

$$W_{FF} = \frac{AP}{\lambda^2 r^2} = \frac{\pi D^2 P}{4\lambda^2 r^2}$$

Equation #8-19:

$$r = \frac{1}{\lambda}\sqrt{\frac{AP}{W_{FF}}} = \frac{D}{2\lambda}\sqrt{\frac{\pi P}{W_{FF}}}$$

Where:

W_{FF} = the **Power Density Level** at a point in the ***Far Field*** that is "**r**" centimeters distant from the circular microwave antenna, with this Power Density Level measured in milliwatts/cm^2 [mW/cm^2];

r = the ***Far Field*** **Distance** [from the point where the **Power Density Level** is being evaluated] to the radiating circular microwave antenna, also measured in centimeters [cm];

D = the circular microwave antenna's **Diameter**, measured in centimeters [cm].

A = the **Area** of the radiating circular antenna, measured in square centimeters [cm^2] — for reference, this area can be calculated according to the following relationship,

$$\text{Circular Area} = \frac{\pi \mathbf{D}^2}{4};$$

λ = the **Wavelength** of microwave energy being radiated by the circular antenna, also measured in centimeters [cm]; &

P = the **Average Power Output** of the microwave radiating antenna, measured in milliwatts [mW].

IONIZING AND NON-IONIZING RADIATION PROBLEM SET

Problem #8.1:

The mid-infrared wavelength at which the carbon-hydrogen bond absorbs energy [i.e., the "carbon-hydrogen stretch"] is at approximately 3.35 μ [i.e., 35 microns]. What is the frequency of a photon having this wavelength?

Applicable Definitions:	Electromagnetic Radiation	Page 8-1
	Infrared Radiation	Pages 8-7 & 8-8
Applicable Formula:	Equation **#8-1**	Page 8-16
Solution to this Problem:	Page 8-60	

Problem Workspace

Problem #8.2:

What is the energy, in electron volts, of one of these "carbon-hydrogen stretch" photons? Remember, the wavelength of these photons is 3.35 μ.

Applicable Definitions:	Electromagnetic Radiation	Page 8-1
	Infrared Radiation	Pages 8-7 & 8-8
Applicable Formula:	Equation **#8-3**	Page 8-17
Solution to this Problem:	Page 8-60	

Problem Workspace

Problem #8.3:

What is the wavenumber of the mid-infrared photon that is readily absorbed by a carbon-hydrogen bond [i.e., a photon with a wavelength of 3.35 μ — see Problem **#8.1**, on the previous page, namely, Page 8-30]?

Applicable Definitions:	Electromagnetic Radiation	Page 8-1
	Infrared Radiation	Pages 8-7 & 8-8
Applicable Formulae:	Equation **#8-2**	Page 8-16
OR	Equation **#8-1**	Page 8-16
Solution to this Problem:	Page 8-60	

Problem Workspace

Problem #8.4:

One of the two γ-ray photons that are emitted during the decay of ${}^{60}_{27}Co$ has a frequency, ν, of 2.84×10^{14} MHz. What is the wavelength, in microns, of this photon?

Applicable Definitions:	Electromagnetic Radiation	Page 8-1
	Gamma Radiation	Page 8-4
	Radioactive Decay	Page 8-12
Applicable Formula:	Equation **#8-1**	Page 8-16
Solution to this Problem:	Page 8-61	

Problem Workspace

Problem #8.5:

What is the wavenumber, in cm^{-1}, of the γ-ray photon identified in Problem **#8.4**, on the previous page, namely Page 8-31? Remember, this photon has a frequency of 2.84×10^{14} MHz.

Applicable Definitions:	Electromagnetic Radiation	Page 8-1
	Gamma Radiation	Page 8-4
Applicable Formulae:	Equation **#8-2**	Page 8-16
OR	Equation **#8-1**	Page 8-16
Solution to this Problem:	Page 8-61	

Problem Workspace

Problem #8.6:

What is the energy, in electron volts, of the γ-ray photon emitted during the decay of $^{60}_{27}Co$, as described in Problem **#8.5** above on this page? Remember, the frequency, ν, of this photon is 2.84×10^{14} MHz.

Applicable Definitions:	Electromagnetic Radiation	Page 8-1
	Gamma Radiation	Page 8-4
	Radioactive Decay	Page 8-12
Applicable Formula:	Equation **#8-3**	Page 8-17
Solution to this Problem:	Page 8-62	

Problem Workspace

Problem #8.7:

An atom is observed, in order:

(1) to absorb an ultraviolet [UV-B] photon having a wavelength, $\lambda_{UV\text{-}B}$, of 274 nm, and then subsequently

(2) to emit a visible light photon having a wavelength, λ_{Vis}, of 0.46 μ.

What was the net energy absorbed by this atom during this process? If the ionization energy of this atom is known to be 1.2 ev, did this process ionize this atom?

Applicable Definitions:	Electromagnetic Radiation	Page 8-1
	Ultraviolet Radiation	Pages 8-6 & 8-7
	Visible Light	Page 8-7
Applicable Formulae:	Equation **#8-1**	Page 8-16
	Equation **#8-3**	Page 8-17
Solution to this Problem:	Pages 8-62 & 8-63	

Problem Workspace

Problem #8.8:

The radioactive isotope, $^{131}_{53}I$, is frequently used in the treatment of thyroid cancer. It has a Radioactive Decay Constant of 0.0862 days^{-1}. A local hospital received its order of 2.0 μg of this isotope on January 1st. How much of this isotope will remain on January 20th of the same year? How much will remain on the one year anniversary [not a leap anniversary] of the receipt of the 2.0 μg of the $^{131}_{53}I$ isotope?

Applicable Definitions:	Radioactivity	Page 8-12
	Radioactive Decay	Page 8-12
	Radioactive Decay Constant	Page 8-13
Applicable Formula:	Equation **#8-4**	Page 8-18
Solution to this Problem:	Page 8-63	

Problem Workspace

Problem #8.9:

What is the Half-Life of $^{131}_{53}I$? What is the Mean Life of an $^{131}_{53}I$ atom? Remember, $^{131}_{53}I$ has a Radioactive Decay Constant of 0.0862 $days^{-1}$ — see Problem **#8.8**, on the previous page, namely Page 8-34.

Applicable Definitions:	Radioactivity	Page 8-12
	Radioactive Decay	Page 8-12
	Half-Life	Page 8-13
	Mean Life	Page 8-13
	Radioactive Decay Constant	Page 8-13
Applicable Formulae:	Equation **#8-5**	Page 8-19
	Equation **#8-6**	Page 8-19
Solution to this Problem:	Page 8-64	

Problem Workspace

Problem #8.10:

What would be the measured Activity of the $^{131}_{53}I$ isotope mentioned in Problem **#8.8**, on Page 8-34, if measurement were made: (1) on January 1st — i.e., the day when it was received at the Hospital; (2) on January 20th of that same year; and (3) on January 1st of the following year [not a leap year]. Remember, the Radioactive Decay Constant of $^{131}_{53}I$ is 0.0862 days^{-1}, and its mass on January 1st, the day it was received at the Hospital, was 2.0 μg. If it is of any use to you, the atomic weight of the $^{131}_{53}I$ isotope is 130.9061 amu.

Applicable Definitions:	Amount of Any Substance	Page 1-3
	Radioactivity	Page 8-12
	Radioactive Decay	Page 8-12
	Radioactive Decay Constant	Page 8-13
	Activity of a Radioactive Source	Page 8-14
Applicable Formulae:	Equation **#1-10**	Page 1-20
	Equation **#1-11**	Page 1-20
	Equation **#8-7**	Page 8-20
	Equation **#8-9**	Page 8-22
Solution to this Problem:	Pages 8-64 & 8-65	

Problem Workspace

Workspace Continued on the Next Page

Continuation of Problem Workspace for Problem **#8.10**

Problem #8.11:

The smallest amount of $^{245}_{99}\text{Es}$ that can be detected or utilized in any type of experimentation, is 1.5×10^{-10} ng. The Radioactive Decay Constant for $^{245}_{99}\text{Es}$ is 0.502 minutes^{-1}. If 8.8×10^{-6} ng of this material was successfully accumulated by a research scientist, how much time will this scientist have available to her as she performs experiments with her supply of this isotope of einsteinium — i.e., how much time will pass before this quantity has decayed to the "barely detectable" level?

Applicable Definitions:	Radioactivity	Page 8-12
	Radioactive Decay	Page 8-12
	Radioactive Decay Constant	Page 8-13
Applicable Formula:	Equation **#8-4**	Page 8-18
Solution to this Problem:	Page 8-66	

Problem Workspace

Problem #8.12:

The heaviest hydrogen isotope, tritium, ${}^{3}_{1}H$, is radioactive. Its Half-Life is 12.26 years. What is its Radioactive Decay Constant?

Applicable Definitions:	Radioactivity	Page 8-12
	Radioactive Decay	Page 8-12
	Radioactive Decay Constant	Page 8-13
	Half-Life	Page 8-13
Applicable Formula:	Equation **#8-5**	Page 8-19
Solution to this Problem:	Page 8-66	

Problem Workspace

Problem #8.13:

What are the Half-Lives of the two isotopes, ${}^{131}_{53}\mathrm{I}$ and ${}^{245}_{99}\mathrm{Es}$, that were identified, respectively, in Problem **#s 8.8** & **8.11**, on Pages 8-34 & 8-38? The Radioactive Decay Constants for these two isotopes are as follows: for ${}^{131}_{53}\mathrm{I}$, k = 0.0862 days^{-1}, and for ${}^{245}_{99}\mathrm{Es}$, k = 0.502 minutes^{-1}.

Applicable Definitions:	Radioactivity	Page 8-12
	Radioactive Decay	Page 8-12
	Radioactive Decay Constant	Page 8-13
	Half-Life	Page 8-13
Applicable Formula:	Equation **#8-5**	Page 8-19
Solution to this Problem:	Page 8-67	

Problem Workspace

Problem #8.14:

$^{241}_{95}Am$ is one of the most commonly used and readily available radioactive isotopes. As an example, it is widely used as the ionization source in most commercial smoke detectors. Its Half-Life is 432.2 years. A functional smoke detector must have at least 1.75 μg of this isotope in order to operate properly. If there are 4.0×10^{15} Americium atoms in each microgram of this isotope, what is the minimum number of disintegrations per second that are required to operate a smoke detector?

Applicable Definitions:	Radioactivity	Page 8-12
	Radioactive Decay	Page 8-12
	Radioactive Decay Constant	Page 8-13
	Half-Life	Page 8-13
Applicable Formula:	Equation **#8-10**	Page 8-21
Solution to this Problem:	Page 8-67	

Problem Workspace

Problem #8.15:

If each commercial smoke detector is manufactured with 1.80 μg of $^{241}_{95}Am$, how long will it be before the minimum required level of radioactive disintegrations per second has been reached — i.e., how long will it take for this isotope's radioactive decay to reduce the mass of $^{241}_{95}Am$ to 1.75 μg? Is it your opinion that the manufacturer has successfully produced a product with guaranteed obsolescence?

Applicable Definitions:	Radioactivity	Page 8-12
	Radioactive Decay	Page 8-12
	Radioactive Decay Constant	Page 8-13
	Half-Life	Page 8-13
Applicable Formulae:	Equation **#8-4**	Page 8-18
	Equation **#8-5**	Page 8-19
Solution to this Problem:	Page 8-68	

Problem Workspace

Problem #8.16:

What is the Dose Exposure Rate, in mrads/day, that would be produced on a target that is at a distance of 1.0 meter from a 550 mCi $^{24}_{11}Na$ source? The Radiation Constant for the $^{24}_{11}Na$ isotope is 18.81 $\frac{rad \cdot cm^2}{mCi \cdot hr}$.

Applicable Definitions:	Radioactivity	Page 8-12
	Radioactive Decay	Page 8-12
	Dose	Page 8-15
Applicable Formula:	Equation **#8-11**	Page 8-22
Solution to this Problem:	Page 8-69	

Problem Workspace

Problem #8.17:

A Dose Exposure Rate of 48.0 mrads/hour was determined for a 440 µCi source of $^{226}_{88}\text{Ra}$ at a distance of 300 mm. What is the Radiation Constant for this isotope, expressed in units of $\frac{\text{rad}\cdot\text{cm}^2}{\text{mCi}\cdot\text{hr}}$?

Applicable Definitions:	Radioactivity	Page 8-12
	Radioactive Decay	Page 8-12
	Dose	Page 8-15
Applicable Formula:	Equation **#8-11**	Page 8-22
Solution to this Problem:	Page 8-69	

Problem Workspace

Problem #8.18:

$^{60}_{27}Co$ decays, in part, by emitting relatively high energy γ-rays. It is widely used as a radiation source in the treatment of certain cancerous tumors. The Radiation Technician who operates the **C**obalt **R**adiation **S**ource **T**umor **T**reatment **A**pparatus [the CRSTTA] at a major hospital accumulates a steady 0.09 mrad, as an absorbed dose, for each hour he is in the room with the CRSTTA when its aperture is closed [i.e., when no patient treatment is occurring]. This Technician's absorbed dose increases to 0.44 mrad/hr whenever the CRSTTA's aperture is opened and a patient is being treated — during this treatment period, the Technician occupies a shielded cell in which his radiation exposure is reduced. On a typical day, this facility will have 2.2 hours of open aperture treatment time, and 5.8 hours of closed aperture operations (i.e., set-up, dosimeter development, etc.). What would this Technician's Dose Equivalent be, expressed in rems/day?

Applicable Definitions:	Gamma Radiation	Page 8-4
	Radioactivity	Page 8-12
	Radioactive Decay	Page 8-12
	Dose	Page 8-15
	Dose Equivalent	Page 8-15
Applicable Formula:	Equation **#8-12**	Pages 8-22 & 8-23
Solution to this Problem:	Page 8-69	

Problem Workspace

Problem #8.19:

Among the numerous facilities that it makes available to its staff of Research Scientists — a large research facility has a pool type nuclear reactor, equipped with an externally accessible graphite "Thermal Column." The Technicians who work 8 hours each day, 5 days each week, around this nuclear reactor accumulate a background absorbed radiation dose at a rate of 0.12 mrads/hour [from thermal, or low energy, neutrons], when the Thermal Column's access port is closed. Whenever the access port to this Thermal Column is opened — in order to work on one of the experiments in it, etc. — each Technician's absorbed dose rate from neutron exposure increases to 0.83 mrads/hour. If this access port is opened only 2 hours each week, and remains closed for the balance of the time, what will be the Dose Equivalent, expressed in an appropriate "sieverts/week" type unit [i.e., mSv/week, μSv/week, etc.], for each of the Technicians who work in this area?

Applicable Definitions:	Neutron Radiation	Pages 8-5 & 8-6
	Absorbed Dose	Page 8-15
	Dose Equivalent	Page 8-15
Applicable Formula:	Equation **#8-12**	Pages 8-22 & 8-23
Solution to this Problem:	Page 8-70	

Problem Workspace

Problem #8.20:

The facility described in Problem **#8.18**, on Page 8-45, was equipped with a new improved shielded cell from which the Radiation Technician could operate the CRSTTA when its aperture was open to provide treatment to a cancer patient. As a result of his operating this facility from his new improved cell, his radiation dose was reduced. The previous cell had been made from concrete, and was 18 inches thick. The improved cell shielding was fabricated from lead, and was 8 inches thick.

(1) If the Half-Value Thickness for concrete is 2.45 inches;
(2) If the radiation emission rate for the ${}^{60}_{27}Co$ Source in the CRSTTA is 40 rads/hour;
(3) If the Technician-to-Source geometry is unchanged [except for the improvements in the cell shielding]; and
(4) If the observed Radiation Emission Rate for this facility has been reduced by a factor of 775 when the Technician operates the CRSTTA from the new cell;

what then would you calculate the Half-Value Thickness of lead to be when used to shield the γ-rays from a ${}^{60}_{27}Co$ source?

Applicable Definitions:	Radioactivity	Page 8-12
	Radioactive Decay	Page 8-12
	Dose	Page 8-15
Applicable Formula:	Equation **#8-13**	Page 8-24
Solution to this Problem:	Page 8-71	

Problem Workspace

Workspace Continued on the Next Page

Continuation of Problem Workspace for Problem **#8.20**

Problem #8.21:

A patient who has been injected with a quantity of ${}^{131}_{53}I$ for treatment of his thyroid cancer will, himself, become a radiation source for the γ-radiation emanating from this isotope as it accumulates in his cancerous thyroid gland. A doctor examining this patient from a distance of 15 cm would experience γ-radiation at an intensity of 2 mSv/hour. If this doctor were able to complete his examination at a distance of 25 cm, what would be the Dose Equivalent of radiation he would be experiencing at this increased distance?

Applicable Definitions:	Radioactivity	Page 8-12
	Radioactive Decay	Page 8-12
	Dose Equivalent	Page 8-15
Applicable Formula:	Equation **#8-14**	Page 8-25
Solution to this Problem:	Page 8-72	

Problem Workspace

Problem #8.22:

There is a commercially available therapeutic medical injectant incorporating a low level $^{226}_{88}Ra$ source [an α-emitter]. This material has been compounded so as to accumulate preferentially in a patient's liver. The adjusted radiation dose arising from this product is 40 μrem/hour, when this exposure is measured at a distance of 2.5 mm from the liver. An alternative form of this injectant is now also being marketed. This alternative has as its source, the radioisotope, $^{45}_{19}K$ [a β^--emitter]. This alternative injectant has been compounded so as to have the same low level of $^{45}_{19}K$ as is the case for the original form containing the $^{226}_{88}Ra$ source. What will be the effect on the adjusted radiation dose that would be experienced at the same 2.5 mm distance from a liver that contains this new injectant? At what distance from such a liver would the adjusted radiation dose be at the same 40 μrem/hour level as was the case for a point 2.5 mm from a liver containing the product with the radium isotope?

Applicable Definitions:	Radioactivity	Page 8-12
	Radioactive Decay	Page 8-12
	Dose Equivalent	Page 8-15
Applicable Formulae:	Equation **#8-12** Table of "QFs"	Page 8-23
	Equation **#8-14**	Page 8-25
Solution to this Problem:	Pages 8-72 & 8-73	

Problem Workspace

Problem #8.23:

The Operator of a laser-based industrial metal trimmer [IR & visible light lasers] wears goggles that reduce the incident beam intensity at his eyes from 475 mW/cm^2 [at which level, he would not even be able to see the area he was trimming] to a more workable and safe level of 0.45 mW/cm^2, as the transmitted intensity. What is the effective Optical Density of the protective goggles he is wearing?

Applicable Definitions:	Visible Light	Page 8-7
	Infrared Radiation	Pages 8-7 & 8-8
Applicable Formula:	Equation **#8-15**	Page 8-26
Solution to this Problem:	Page 8-73	

Problem Workspace

Problem #8.24:

If the industrial metal trimmer identified in Problem **#8.23**, on the previous page, namely Page 8-51, were to be retrofitted with a new improved laser source that had 6.62 times the laser beam intensity of the original unit, and if it is hoped to reduce still further the transmitted beam intensity experienced by the Operator to a new lower level of 0.19 mW/cm^2 maximum, by how much must the Optical Density of the goggles be increased to satisfy these new requirements?

Applicable Definitions:	Visible Light	Page 8-7
	Infrared Radiation	Pages 8-7 & 8-8
Applicable Formula:	Equation **#8-15**	Page 8-26
Solution to this Problem:	Page 8-73	

Problem Workspace

Problem #8.25:

The UHF Microwave Systems that are used for transmitting a very large fraction of all the public telecommunications in the United States employ a circular antenna with a diameter of 40.5 inches. If these antennas transmit their information using UHF Microwaves that have a wavelength of 46 cm, what will be the distance from these antennas to the Far Field?

Applicable Definitions:	Microwave Radiation	Page 8-8
	Radiation vs. Field Characteristics	Pages 8-10 & 8-11
Applicable Formula:	Equation **#8-16**	Page 8-27
Solution to this Problem:	Page 8-74	

Problem Workspace

Problem #8.26:

If the average power output of the highly focused, very directional UHF Antennas described in Problem **#8.25**, on the previous page, namely Page 8-53, is 0.05 kilowatts, what will be the approximate Power Density produced by this antenna at a point 12 inches directly in front of it? If the established 6-minute TLV-STEL for this frequency [$\nu \sim 600$ MHz] is 6.0 mW/cm^2, for what maximum time period can a Service Technician work, if his assigned task requires that he stand 12 inches away from and directly in front of this transmitting antenna? You may assume that his exposure must not exceed the established 6-minute TLV-STEL.

Applicable Definitions:	Time Weighted Averages	Page 3-2
	Microwave Radiation	Page 8-8
	Radiation vs. Field Characteristics	Pages 8-10 & 8-11
Applicable Formulae:	Equation **#3-1**	Page 3-9
	Equation **#8-17**	Page 8-28
Solution to this Problem:	Page 8-75	

Problem Workspace

Problem #8.27:

In order never to exceed the established TLV-STEL provided in Problem **#8.26**, on the previous page, namely Page 8-54, what is the closest distance (directly in front of one of these transmitting UHF Antennas) that a Service Technician may safely work for periods of time longer than 6 minutes? Would this position be in the Near or the Far Field for this UHF antenna?

Applicable Definitions:	Microwave Radiation	Page 8-8
	Radiation vs. Field Characteristics	Pages 8-10 & 8-11
Applicable Formula:	Equation **#8-19**	Pages 8-28 & 8-29
Solution to this Problem:	Page 8-76	

Problem Workspace

Problem #8.28:

If these "line-of-sight" UHF Microwave Antenna Systems can successfully transmit voice or digital data over a distance 85 miles, what is the minimum Power Density Level at which the system's receiving antenna can still be expected to operate successfully?

Applicable Definitions:	Microwave Radiation	Page 8-8
	Radiation vs. Field Characteristics	Pages 8-10 & 8-11
Applicable Formula:	Equation **#8-18**	Page 8-28
Solution to this Problem:	Page 8-77	

Problem Workspace

Problem #8.29:

Highway Patrol Officers frequently use a J-Band Radar system to measure the speed of vehicles on the highway. These J-Band Speed Radar Guns operate at a microwave frequency of 10.525 GHz, and they radiate from a 4.02-inch diameter antenna. How far is it to the Far Field for such a Radar Gun?

Applicable Definitions:	Microwave Radiation	Page 8-8
	Radiation vs. Field Characteristics	Pages 8-10 & 8-11
Applicable Formulae:	Equation **#8-1**	Page 8-16
	Equation **#8-16**	Page 8-27
Solution to this Problem:	Page 8-77	

Problem Workspace

Workspace Continued on the Next Page

Continuation of Problem Workspace for Problem **#8.29**

Problem #8.30:

The J-Band Speed Radar Gun described in Problem **#8.29**, on Pages 8-57 & 8-58, has an output power of 45 mW. What is the minimum distance in front of this Gun's antenna that a Highway Patrolman must be in order to ensure that his exposure will never exceed the 6-minute TLV-STEL, which has been established at 10.0 mW/cm^2 for this frequency of microwave radar?

Applicable Definitions:	Microwave Radiation	Page 8-8
	Radiation vs. Field Characteristics	Pages 8-10 & 8-11
Applicable Formulae:	Equation **#8-1**	Page 8-16
	Equation **#8-18**	Page 8-28
Solution to this Problem:	Page 8-78	

Problem Workspace

Workspace Continued on the Next Page

Continuation of Problem Workspace for Problem **#8.30**

SOLUTIONS TO THE IONIZING AND NON-IONIZING RADIATION PROBLEM SET

Problem #8.1:

To solve this problem, we must use Equation **#8-1**, from Page 8-16; however, we must first convert the wavelength [given in microns] into its equivalent in meters:

$$\lambda = (3.35 \text{ microns})(10^{-6} \text{ meters/micron}) = 3.35 \times 10^{-6} \text{ meters}$$

$$c = \lambda\nu \qquad \text{[Eqn. \#8-1]}$$

$$\nu_{C-H\,Stretch} = \frac{c}{\lambda} = \frac{3.0 \times 10^{8}}{3.35 \times 10^{-6}} = 8.96 \times 10^{13} \text{ Hertz} = 8{,}960 \text{ GHz}$$

$$\therefore \quad \nu_{C-H\,Stretch} = 8{,}960 \text{ GHz}$$

Problem #8.2:

To solve this problem, we must again use Equation **#8-3**, from Page 8-17. To apply this relationship, we must use the form of the frequency as it was initially calculated in the previous problem, namely $\nu = 8.96 \times 10^{13}$ Hertz:

$$E = h\nu \qquad \text{[Eqn. \#8-3]}$$

$$E = (4.136 \times 10^{-15})(8.96 \times 10^{13}) = 0.37 \text{ electron volts}$$

$$\therefore \quad E_{\text{carbon-hydrogen stretch photon}} = 0.37 \text{ ev}$$

Problem #8.3:

We can use either Equation **#8-1** or **#8-2** to solve this problem. The most direct and simple approach is to use Equation **#8-2**, so that is the way it will be done:

$$\lambda = \frac{1}{k} \qquad \text{[Eqn. \#8-2]}$$

Rearranging to solve for the wavenumber, k, we get:

$$k = \frac{1}{\lambda} = \frac{1}{3.35 \times 10^{-6}} = 298{,}507 \text{ meters}^{-1}$$

$$\therefore \quad k_{\text{carbon-hydrogen stretch photon}} = 2.99 \times 10^{5} \text{ meters}^{-1}$$

$$\text{or} \quad k_{\text{carbon-hydrogen stretch photon}} = 2.99 \times 10^{5} \text{ cycles/meter}$$

$$\text{or} \quad k_{\text{carbon-hydrogen stretch photon}} = 2{,}990 \text{ cm}^{-1} = 2{,}990 \text{ wavenumbers}$$

Problem #8.4:

To solve this problem, we must use Equation **#8-1**, from Page 8-16, but first we must convert the frequency of this gamma photon, which has been provided in the problem statement in units of megahertz, into plain Hertz, as is required for this equation to apply:

$$\left(2.84\times10^{14}\ \text{MHz}\right)\left(10^{6}\ {}^{\text{Hz}}\!/_{\text{MHz}}\right) = 2.86\times10^{20}\ \text{Hz, and}$$

$$c = \lambda\nu \qquad \text{[Eqn. \textbf{\#8-1}]}$$

Solving for the wavelength, λ, we get:

$$\lambda = \frac{c}{\nu} = \frac{3.0\times10^{8}}{2.86\times10^{20}} = 1.05\times10^{-12}\ \text{meters}$$

Now converting this wavelength, λ, in meters, to its equivalent in microns, we get:

$$\left(1.05\times10^{-12}\ \text{meters}\right)\left(10^{6}\ {}^{\text{microns}}\!/_{\text{meter}}\right) = 1.05\times10^{-6}\ \text{microns} = 1.05\times10^{-6}\ \mu$$

$$\therefore\ \lambda_{\gamma\text{-ray photon}} = 1.05\times10^{-6}\ \mu$$

Problem #8.5:

Again, we will use the second form of Equation **#8-1** to solve this problem. First we will have to convert the frequency, ν, given in MHz to its equivalent in Hertz:

$$\left(2.84\times10^{14}\ \text{MHz}\right)\left(10^{6}\ {}^{\text{Hz}}\!/_{\text{MHz}}\right) = 2.86\times10^{20}\ \text{Hz, and}$$

$$c = \frac{\nu}{k} \qquad \text{[Eqn. \textbf{\#8-1}]}$$

Rearranging to solve for the wavenumber, k, we get:

$$k = \frac{\nu}{c} = \frac{2.86\times10^{20}}{3.0\times10^{8}} = 9.53\times10^{11}\ \text{meters}^{-1}$$

Now converting this wavenumber, k, in meters^{-1} to its equivalent in cm^{-1}, we get:

$$\left(9.53\times10^{11}\ \text{meters}^{-1}\right)\left(10^{-2}\ {}^{\text{cm}^{-1}}\!/_{\text{meter}^{-1}}\right) = 9.53\times10^{9}\ \text{cm}^{-1} = 9.53\times10^{9}\ \text{wavenumbers}$$

$$\therefore\ k_{\gamma\text{-ray photon}} = 9.53\times10^{9}\ \text{wavenumbers}$$

Problem #8.6:

To solve this problem, we must use Equation **#8-3**, from Page 8-17. First, we must convert the frequency, ν, from its listed value in MHz to its equivalent value in Hertz:

$$\left(2.84\times10^{14}\ \text{MHz}\right)\left(10^{6}\ \text{Hertz}/_{\text{MHz}}\right) = 2.84\times10^{20}\ \text{Hertz}$$

$$E = h\nu \qquad \text{[Eqn. \#8-3]}$$

$$E = \left(4.136\times10^{-15}\right)\left(2.84\times10^{20}\right) = 1{,}174{,}624\ \text{electron volts}$$

$$\therefore\ E_{\gamma\text{-ray photon}} = 1.17\ \text{Mev}$$

Problem #8.7:

To solve this problem, we must calculate the energy that was delivered to the atom by the UV-B photon. As a result of its having absorbed this UV-B photon, the atom will clearly have entered an excited or metastable state. In this state, it "decayed" by emitting the photon of visible light. Clearly, however, since the emitted photon [visible light] is less energetic than the absorbed one [UV-B], there will be a net energy gain by the atom. This gain will simply be the difference between the energy levels of these two photons. The first step then will involve the use of Equation **#8-1**, from Page 8-16. We will use this relationship to calculate the frequency of each of the two photons involved in this situation. We must start by converting the two wavelengths, one of which has been listed in nanometers, and the other in microns to their corresponding values in meters:

$$\lambda_{\text{UV-B Photon}} = \left(274\ \text{nm}\right)\left(10^{-9}\ \text{meters}/_{\text{nm}}\right) = 2.74\times10^{-7}\ \text{meters,}$$

$$\lambda_{\text{Visible Light Photon}} = \left(0.46\ \mu\right)\left(10^{-6}\ \text{meters}/_{\mu}\right) = 4.6\times10^{-7}\ \text{meters, \&}$$

$$c = \lambda\nu \qquad \text{[Eqn. \#8-1]}$$

Rewriting to solve for the wavelength, λ, we get:

$$\lambda = \frac{c}{\nu}$$

$$\nu_{\text{UV-B Photon}} = \frac{c}{\lambda_{\text{UV-B Photon}}} = \frac{3.0\times10^{8}}{2.74\times10^{-7}} = 1.09\times10^{15}\ \text{meters}^{-1}$$

$$\nu_{\text{Visible Light Photon}} = \frac{c}{\lambda_{\text{Visible Light Photon}}} = \frac{3.0\times10^{8}}{4.6\times10^{-7}} = 6.52\times10^{-14}\ \text{meters}^{-1}$$

Now we can apply the second required relationship, namely, Equation **#8-3**, shown on Page 8-17, to obtain the required answer:

$$E = h\nu \qquad \text{[Eqn. \#8-3]}$$

$$E_{\text{UV-B Photon}} = \left(4.136\times10^{-15}\right)\left(1.09\times10^{15}\right) = 4.51\ \text{electron volts}$$

$$E_{\text{Visible Light Photon}} = \left(4.136\times10^{-15}\right)\left(6.52\times10^{14}\right) = 2.70\ \text{electron volts}$$

Now, finally we can simply determine the energy absorbed by the atom by determining the difference between the energy levels of these two photons:

$$\text{Energy absorbed by the atom} = 4.51 - 2.70 = 1.81\ \text{ev}$$

Since the ionization energy for this atom is listed as 1.2 ev, and since the net energy absorbed by it was 1.81 ev, it is obvious that one of the results of this overall process was the ionization of the atom.

∴	The atom absorbed a total of 1.81 ev and was ionized in the process.

Problem #8.8:

To solve this problem, we must use Equation **#8-4**, from Page 8-18, and actually apply this relationship twice, once for each of the two subsequent times identified in the problem statement:

$$N_t = N_0 e^{-kt} \qquad \text{[Eqn. \textbf{\#8-4}]}$$

Consider first the quantity of ${}^{131}_{53}I$ that remained on January 20th of the same year. Clearly, this date involves a time interval after receiving this isotope of 19 days, thus, t = 19 days:

$$N_{t=19\text{ days}} = (2.0)e^{-(0.0862)(19)} = (2.0)e^{-1.6378} = (2.0)(0.1944) = 0.3888\ \mu g$$

Consider next the quantity of ${}^{131}_{53}I$ that remained on the one year anniversary of the arrival at the hospital of this isotope. For this case, t = 365 days:

$$N_{t=365\text{ days}} = (2.0)e^{-(0.0862)(365)} = (2.0)e^{-31.463} = (2.0)\left(2.167\times10^{-14}\right) = 4.33\times10^{-14}\ \mu g$$

Since the atomic weight of the ${}^{131}_{53}I$ isotope is ~ 130.91 amu, and since one mole of this isotope would weigh 130.91 grams and would contain 6.022×10^{23} atoms of ${}^{131}_{53}I$, we can calculate that the number of atoms remaining in 4.33×10^{-14} μg to be:

$$\text{Number of Atoms} = \left[\frac{4.33\times10^{-14}}{130.91}\right]\left[6.022\times10^{23}\right] = 1.99\times10^{10}\text{ atoms of } {}^{131}_{53}I$$

∴	On January 20th, there will be only ~ 0.39 μg of this ${}^{131}_{53}I$ isotope remaining [19.4% of the material that was received on January 1st]. One year later, there will only be an almost certainly undetectable 4.33×10^{-14} μg — 1.99×10^{10} atoms — remaining.

Problem #8.9:

To solve this problem we must use, first, Equation **#8-5**, from Page 8-19, to determine the Half-Life of this isotope. Next we will use Equation **#8-6**, also from Page 8-19, to determine the Mean Life of an $^{131}_{53}I$ atom. Let us start with the Half-Life determination:

$$T_{1/2} = \frac{0.693}{k} \qquad \text{[Eqn. \#8-5]}$$

$$T_{1/2} = \frac{0.693}{0.0682} = 10.16 \text{ days}$$

Next, let us determine the Mean Life of an $^{131}_{53}I$ atom:

$$\tau = \frac{1}{k} \qquad \text{[Eqn. \#8-6]}$$

$$\tau = \frac{1}{0.0682} = 14.66 \text{ days}$$

∴ The Half-Life of the $^{131}_{53}I$ isotope = 10.16 days; &
the Mean Life of an $^{131}_{53}I$ atom = 14.66 days.

Problem #8.10:

To solve this problem, we will have to employ a large number of relationships. To start with, we will have to determine the actual number of $^{131}_{53}I$ atoms that are present in each of the three time-based scenarios. This atom count is required for the application of either Equation **#8-7**, from Page 8-20, and/or Equation **#8-9**, from Page 8-20.

To make these required determinations, we must have specific designations for the three times of interest; thus we shall assign: t_0 = 0 days — for the situation on January 1st, the date when the isotope was delivered to the hospital; t_{19} = 19 days — for the situation on January 20th of that same year; and t_{365} = 365 days — for the situation one year after the delivery of the isotope to the hospital. We must start this process, for each of the times required, by determining the number of moles of the isotope present at that time. This is done by using Equation **#1-10**, from Page 1-20:

$$n = \frac{m}{MW} \qquad \text{[Eqn. \#1-10]}$$

For the situation on January 1st, when the isotope was delivered to the hospital:

$$n = \frac{2.0 \times 10^{-6}}{130.9061} = 1.53 \times 10^{-8} \text{ moles of } ^{131}_{53}I$$

Next, we must apply Equation **#1-11**, from Page 1-20, to determine the atom count on January 1st, when the isotope was delivered to the hospital:

$$n = \frac{N}{6.022 \times 10^{23}} \qquad \text{[Eqn. \#1-11]}$$

Transposing this relationship in order to solve for the atom count, Q, we get:

$$N_{t=0} = \left(6.022 \times 10^{23}\right)(n) = \left(6.022 \times 10^{23}\right)\left(1.53 \times 10^{-8}\right) = 9.20 \times 10^{15} \text{ atoms}$$

Now, we can address the determination of the required Activity on this date, this time using Equation **#8-7**, from Page 8-20:

$$A_b = kN \qquad \text{[Eqn. \textbf{\#8-7}]}$$

Now, using this relationship, we can determine the Activity level required:

$$A_{b/t=0} = kN_{t=0} = (0.0862)(9.20 \times 10^{15}) = 7.93 \times 10^{14} \text{ becquerels}$$

$$\text{or, expressed in curies, } A_{c/t=0} = \frac{7.93 \times 10^{14}}{3.70 \times 10^{10}} = 21,435 \text{ curies — a } \underline{\underline{\text{very}}}\ \underline{\underline{\text{hot}}}\ \underline{\underline{\text{source}}}!!$$

Next, we can use Equation **#8-9**, from Page 8-20, to determine the Activities of this source at the other two times of interest:

$$A_t = kN_0 e^{-kt} \qquad \text{[Eqn. \textbf{\#8-9}]}$$

First, for t = 19 days, we have:

$$A_{t=19 \text{ days}} = (0.0862)(9.20 \times 10^{15})e^{-(0.0862)(19)} = (7.93 \times 10^{14})e^{-1.6378}$$

$$A_{t=19 \text{ days}} = (7.93 \times 10^{14})(0.1944) = 1.54 \times 10^{14} \text{ becquerels}$$

or again expressing this Activity in curies, we have:

$$A_{t=19 \text{ days}} = \frac{1.54 \times 10^{14}}{3.70 \times 10^{10}} = 4,167 \text{ curies — still a } \underline{\underline{\text{very}}}\ \underline{\underline{\text{hot}}}\ \underline{\underline{\text{source}}}!!$$

Finally, for t = 365 days, we have:

$$A_{t=365 \text{ days}} = (0.0862)(9.20 \times 10^{15})e^{-(0.0862)(365)} = (7.93 \times 10^{14})e^{-31.463}$$

$$A_{t=365 \text{ days}} = (7.93 \times 10^{14})(2.167 \times 10^{-14}) = 17.2 \text{ becquerels}$$

∴ The three source Activity levels required for the solution of this problem are:

$$A_{t=0 \text{ days}} = 7.93 \times 10^{14} \text{ becquerels} = 21,435 \text{ curies}$$

$$A_{t=19 \text{ days}} = 1.54 \times 10^{14} \text{ becquerels} = 4,167 \text{ curies}$$

$$A_{t=365 \text{ days}} = 17.2 \text{ becquerels}$$

Problem #8.11:

To solve this problem, we must again use Equation **#8-4**, from Page 8-18:

$$N_t = N_0 e^{-kt} \qquad \text{[Eqn. \textbf{\#8-4}]}$$

Since we know both the "starting" and the "ending" masses of the isotope of einsteinium that is to be used for an experiment, we know all of the factors, except for the time, that are required for the solution of this problem:

$$1.5 \times 10^{-10} = \left(8.8 \times 10^{-6}\right) e^{-(0.502)t}$$

$$e^{-(0.502)t} = \frac{1.5 \times 10^{-10}}{8.8 \times 10^{-6}} = 1.705 \times 10^{-5}$$

Next, we take the natural logarithm of both sides of this equation:

$$ln\left[e^{-(0.502)t}\right] = ln\left[1.705 \times 10^{-5}\right], \;\&$$

$$-(0.502)t = -10.980$$

$$t = \frac{-10.980}{-0.502} = 21.87 \text{ minutes}$$

∴ This Scientist must complete her experiment, exhausting her supply of ${}^{245}_{99}Es$, in the next 21.87 minutes. That is to say, this amount of ${}^{245}_{99}Es$ will have decayed to the "barely detectable" level in 21.87 minutes, or 21 minutes and 52.3 seconds.

Problem #8.12:

To solve this problem, we must use Equation **#8-5** from Page 8-19:

$$T_{1/2} = \frac{0.693}{k} \qquad \text{[Eqn. \textbf{\#8-5}]}$$

$$k = \frac{0.693}{12.26} = 0.0565 \text{ years}^{-1}$$

∴ The Radioactive Decay Constant for ${}^{3}_{1}H = k_{tritium} = 0.0565 \text{ years}^{-1}$

Problem #8.13:

The solution to this problem also requires the use of Equation **#8-5** from Page 8-19:

$$T_{1/2} = \frac{0.693}{k} \quad \text{[Eqn. \#8-5]}$$

First, for the iodine isotope, $^{131}_{53}I$, which has a Radioactive Decay Constant = 0.0862 days^{-1}:

$$T_{1/2} = \frac{0.693}{0.0862} = 8.039 \text{ days}$$

Next, for the einsteinium isotope, $^{245}_{99}Es$, for which the Radioactive Decay Constant = 0.502 minutes^{-1}:

$$T_{1/2} = \frac{0.693}{0.502} = 1.381 \text{ minutes}$$

∴ The requested Half-Lives are as follows:
For the iodine isotope, $^{131}_{53}I$, $T_{1/2}$ ~ 8.04 days
For the einsteinium isotope, $^{245}_{99}Es$, $T_{1/2}$ ~ 1.38 minutes

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Problem #8.14:

The solution to this problem will require the use of Equation **#8-10**, from Page 8-21:

$$A_t = \left[\frac{0.693}{T_{1/2}}\right] N_0 e^{-(0.693)t/T_{1/2}} \quad \text{[Eqn. \#8-10]}$$

Before directly addressing the solution to this problem by using the foregoing Equation, we must first convert the Half-Life of americium from the form in which it has been given in the problem statement [that being in units of "years"] to units of "seconds," since the problem is to determine the number of disintegrations per second or becquerels:

$$T_{1/2} = (432.2 \text{ years})\left(365 \,{}^{\text{days}}\!/_{\text{year}}\right)\left(24 \,{}^{\text{hours}}\!/_{\text{day}}\right)\left(3,600 \,{}^{\text{seconds}}\!/_{\text{hour}}\right) = 1.363 \times 10^{10} \text{ seconds}$$

We are interested in the specific number of disintegrations that are occurring in each second, namely in the Activity in becquerels, at that instant in time when the actual mass of americium present is exactly 1.75 μg; thus as we substitute numbers and values into Equation **#8-10**, we shall use a time, t = 0 seconds, and the number of americium atoms that 1.75 μg of this isotope represents:

$$A_t = \left[\frac{(0.693)(1.75)\left(4.0 \times 10^{15}\right)}{1.363 \times 10^{10}}\right] e^{-\left[\frac{(0.693)(0)}{1.363 \times 10^{10}}\right]}$$

& since the exponent of e = $-\left[\frac{(0.693)(0)}{1.363 \times 10^{10}}\right]$ = 0, and since $e^0 = 1$, we have:

$$A_t = \frac{(0.693)(1.75)\left(4.0 \times 10^{15}\right)(1)}{1.363 \times 10^{10}} = \frac{4.851 \times 10^{15}}{1.363 \times 10^{10}} = 3.559 \times 10^{5} \text{ becquerels}$$

∴ A Smoke Detector will operate properly if there is a minimum of 355,900 $^{241}_{95}Am$ atoms disintegrating, or decaying, each second.

Problem #8.15:

To solve this problem, we must first use Equation **#8-5**, from Page 8-19, to determine the Radioactive Decay Constant of this americium isotope, and then use Equation **#8-4**, from Page 8-18, to develop the answer that has been requested in the problem statement:

$$k = \frac{0.693}{T_{1/2}} \qquad \text{[Eqn. \textbf{\#8-5}]}$$

$$k = \frac{0.693}{432.2} = 1.60 \times 10^{-3} \text{ years}^{-1}$$

Knowing this value, we can apply Equation **#8-4**, from Page 8-18, to obtain the solution:

$$N_t = N_0 e^{-kt} \qquad \text{[Eqn. \textbf{\#8-4}]}$$

$$1.75 \times 10^{-6} = \left(1.80 \times 10^{-6}\right) e^{-\left(1.60 \times 10^{-3}\right)t}$$

$$\frac{1.75 \times 10^{-6}}{1.80 \times 10^{-6}} = e^{-\left(1.60 \times 10^{-3}\right)t} = 0.972$$

Now, taking the natural logarithm of both sides of this equation, we get:

$$ln[0.972] = ln\left[e^{-\left(1.60 \times 10^{-3}\right)t}\right], \&$$

$$-0.282 = -\left(1.60 \times 10^{-3}\right)t, \&$$

$$t = \frac{-0.282}{-\left(1.60 \times 10^{-3}\right)} = 17.607 \text{ years}$$

∴ It will take ~17.6 years for the amount of the ${}^{241}_{95}Am$ provided in a new Smoke Detector to decay to the extent that there will be fewer than the minimum required 355,900 disintegrations/second occurring — i.e., the Activity will have fallen below 355,900 becquerels. It is unlikely that we can consider that the manufacturer has "built in" product obsolescence as a result of this "lifetime," since this time period [17.6 years] is simply too long. I cannot imagine that the average Smoke Detector owner would note that he will have to purchase a new unit 17+ years after the date of his current purchase; rather, after 17+ years, that person's Smoke Detector would simply cease to function properly without any obvious clue that it had done so!

Problem #8.16:

To solve this problem, we must employ Equation **#8-11**, from Page 8-22:

$$E = \frac{\Gamma A}{d^2} \qquad \text{[Eqn. #8-11]}$$

For this relationship to apply, we must have the distance between the target and the source expressed in units of centimeters; therefore, we must recognize that 1.0 meters = 100 cm:

$$E = \frac{(18.81)(550)}{(100)^2} = \frac{10,345.5}{10,000} = 1.035 \text{ rads/hour}$$

∴ The requested Dose Exposure Rate ~ 1.04 rads/hour.

Problem #8.17:

The solution to this problem also employs Equation **#8-11**, from Page 8-22:

$$E = \frac{\Gamma A}{d^2} \qquad \text{[Eqn. #8-11]}$$

$$48.0 = \frac{(440)\Gamma}{(30)^2}$$

$$\Gamma = \frac{(48.0)(30)^2}{440} = \frac{43,200}{440} = 98.18$$

∴ The Radiation Constant for $^{226}_{88}Ra$ is 98.2 $\frac{\text{Rad}\cdot\text{cm}^2}{\text{mCi}\cdot\text{hr}}$.

Problem #8.18:

To solve this problem, we must use Equation **#8-12**, on Pages 8-22 & 8-23:

$$D_{Rem} = D_{Rad}[QF] \qquad \text{[Eqn. #8-12]}$$

From the Tabulation of Quality Factors by Radiation Type, on Page 8-23, we can see that the Quality Factor is QF = 1.0, for γ-rays. Let us first consider the situation for this Technician when he is operating the CRSTTA with its aperture closed:

$$D_{Rem/Closed\ Aperture} = (0.09)(1.0) = 0.09 \text{ mrems/hour}$$

Next, let us deal with the open aperture situation:

$$D_{Rem/Open\ Aperture} = (0.44)(1.0) = 0.44 \text{ mrems/hour}$$

Now, since we know that this Technician experiences 2.2 hours/day of open aperture operations and the balance of the day, or 5.8 hours, of closed aperture operations, and since further we know the time rate of Equivalent Dose exposure, we can calculate directly the total Dose Equivalent this Technician will experience:

$$[\text{Dose Equivalent}]_{total} = (2.2)(0.44) + (5.8)(0.09) = 0.968 + 0.522 = 1.49 \text{ mrems}$$

∴ This Technician will experience a daily Dose Equivalent Exposure of 1.49 mrems.

Problem #8.19:

To solve this problem we must first understand the relationship between the units in which each Technician's Absorbed Dose numbers have been provided, and the units in which the required Dose Equivalent values have been requested in the problem statement. Specifically, remember that, for Absorbed Dose values: 1.0 Gy = 100 rad, and for Dose Equivalent values: 1.0 Sv = 100 rem. In the problem statement we have been given the Absorbed Dose data for each Technician in units of mrads/hour; therefore, it is easy and direct then to convert these data into their corresponding Dose Equivalent values in mrems/hour, using Equation **#8-12**, from Pages 8-22 & 8-23.

Note, too, that we are dealing in an "external" radiation situation — in contrast to an "internal" one, wherein the radiation source is located in some part of a person's body. We know that Quality Factors for all energy states of neutrons are valid for both internal and external radiation source situations; therefore, we can simply proceed using a QF = 5.0 to develop the solution to this problem.

As stated on the previous page, for thermal neutrons, the Quality Factor = QF = 5.0. We can assume that these Technicians are employed for a 5-day work week, with each workday consisting of 8 hours, thus a 40-hour work week. Let us consider, first, the situation that exists when the Thermal Column's access port is closed:

$$H_{Rem} = D_{Rad}[QF] \qquad \text{[Eqn. \textbf{\#8-12}]}$$

$$H_{rem\text{-}closed} = (0.12)(5.0) = 0.60 \text{ mrem/hr}$$

Let us consider next the situation when this access port is open:

$$H_{rem\text{-}open} = (0.83)(5.0) = 4.15 \text{ mrem/hr}$$

Next, we can combine these items of specific hourly Dose Equivalent information to the stated weekly time intervals for the two scenarios under which these Technicians routinely work. Consider first the closed port situation, which involves 38 hours per week:

$$H_{closed} = (0.60 \text{ mrem/hour})(38 \text{ hours}) = 22.80 \text{ mrem}$$

Next, we consider the situation that exists when the access port is open:

$$H_{open} = (4.15 \text{ mrem/hour})(2 \text{ hours}) = 8.30 \text{ mrem}$$

For the next step, we need only combine these two data items to determine the Dose Equivalent, in units of mrem, that each Technician experiences each week:

$$H_{weekly\ total} = 22.80 + 8.30 = 31.10 \text{ mrem}$$

And, since we know that 100 mrem = 1 mSv, we can obtain the answer in the form asked for in the problem statement:

$$(31.10 \text{ mrem})\left(10^{-2} \text{ mSv/mrem}\right) = 0.311 \text{ mSv} = 311 \ \mu\text{Sv}$$

∴ These Technicians experience a Dose Equivalent of 311 μSv/week for thermal neutrons.

Problem #8.20:

To solve this problem, we must use Equation **#8-13**, from Page 8-24:

$$ER_{goal} = \frac{ER_{source}}{2^{x/HVL}} \qquad \text{[Eqn. #8-13]}$$

We must consider two cases, namely: (1) a shielded cell fabricated from concrete; and (2) a shielded cell made of lead. We shall assume "effective relative" target Radiation Emission Rates for these two situations as follows:

775 for the concrete shielded cell, and

1.0 for the lead shielded cell.

Consider first the concrete shielded cell:

$$ER_{goal_{concrete}} = \frac{ER_{source}}{2^{\left[\frac{x_{concrete}}{HVL_{concrete}}\right]}}$$, and substituting in the appropriate "effective relative" values:

$$775 = \frac{ER_{source}}{2^{\left[\frac{18}{2.45}\right]}} = \frac{ER_{source}}{2^{7.35}} = \frac{ER_{source}}{162.80}$$

Next, rearranging this equation to solve for the observed Radiation Emission Rate of the source, we get:

$$ER_{source} = (775)(162.80) = 126{,}168.42 \text{ mrads/hour} \sim 126.2 \text{ rads/hr}$$

Next we must consider the lead shielded cell:

$$ER_{goal_{lead}} = \frac{ER_{source}}{2^{\left[\frac{x_{lead}}{HVL_{lead}}\right]}}$$, and now substituting in the lead "effective relative" values:

$$1.0 = \frac{126{,}168.42}{2^{\left[\frac{8}{HVL_{lead}}\right]}}$$, and rearranging:

$$2^{\left[\frac{8}{HVL_{lead}}\right]} = 126{,}158.42 \text{ mrads/hour} \sim 126.2 \text{ rads/hr}$$

Next, we must take the common logarithm of both sides of this equation:

$$(log[2])\left(\frac{8}{HVL_{lead}}\right) = log[126{,}168.42]$$

$$(0.301)\left(\frac{8}{HVL_{lead}}\right) = 5.101$$, and rearranging:

$$\frac{8}{HVL_{lead}} = \frac{5.101}{0.301} = 16.945$$

Finally, now, solving for the Half-Value Thickness of lead, we get:

$$HVL_{lead} = \frac{8}{16.945} = 0.472 \text{ inches}$$

∴ Thus, we see that the Half-Value Thickness of lead is ~ 0.47 inches ~ 1.20 cm.

Problem #8.21:

The solution to this problem requires the use of Equation **#8-14**, from Page 8-25:

$$\frac{ER_a}{ER_b} = \frac{S_b^2}{S_a^2} \qquad \text{[Eqn. \textbf{\#8-14}]}$$

$$\frac{ER_a}{2.0} = \frac{(15)^2}{(25)^2} = \frac{225}{625} = 0.36$$

$$ER_a = (0.36)(2.0) = 0.72 \text{ mSv/hr}$$

∴ The Doctor would experience a radiation intensity of 0.72 mSv/hour at the greater distance from the Patient.

Problem #8.22:

The solution to this problem will require, initially, the use of the Quality Factor Table, from Page 8-23; this tabulation is associated with Equation **#8-12**, which has been described on Pages 8-22 & 8-23. Note, in this problem, we are dealing with: (1) an "internal" radiation situation, and (2) both α- and/or β-radiation sources — for each of which, the listed Quality Factors apply only to "internal" radiation situations. In order, the Quality Factors for each of these classes of radiation are, respectively: $QF_\alpha = 20.0$, and $QF_\beta = 1.0$.

Knowing these data points, we must next use Equation **#8-14**, from Page 8-25. We will first determine what the impact on the adjusted radiation Dose Equivalent, expressed in µrem, would be as a result of the change in the character of the radiation source (i.e., the source changing from being an alpha emitter to being a beta emitter):

$$\frac{QF_{\text{Beta Source}}}{QF_{\text{Alpha Source}}} = \frac{1.0}{20.0} = 0.05$$

Thus we see that by simply changing the type of radiation being emitted [by changing the radioactive source], we will diminish the experienced radiation Dose Equivalent by a factor of 20, thus:

$$(40_{\mu\text{rem/hour}})(0.05) = 2.0 \ \mu\text{rem/hour}$$

Next, we must apply Equation **#8-14**, from Page 8-25, to determine the distance at which the Dose Equivalent of the new beta source would equal 40 µrem/hour:

$$\frac{ER_a}{ER_b} = \frac{S_b^2}{S_a^2} \qquad \text{[Eqn. \textbf{\#8-14}]}$$

Substituting in, we get:

$$\frac{2}{40} = \frac{S_b^2}{(2.5)^2}$$

Solving now for S_b, we get:

$$S_b^2 = \frac{(2.5)^2(2)}{40} = \frac{12.5}{40} = 0.313\text{, and}$$

$$S_b = \sqrt{0.313} = 0.559 \text{ mm}$$

∴ The adjusted hourly radiation Dose Equivalent produced by the injectant containing the $^{45}_{19}K$ source vs. the value for the injectant containing the $^{226}_{88}Ra$ source would be 2.0 μrem vs. 40.0 μrem. A Dose Equivalent value of 40.0 μrem/hour could be measured for the injectant containing the $^{45}_{19}K$ source at a distance of approximately 0.56 mm from the liver in which this injectant has accumulated.

Problem #8.23:

To solve this problem, we must use Equation **#8-15**, from Page 8-26:

$$OD = log\left[\frac{I_{incident}}{I_{transmitted}}\right] \quad \text{[Eqn. \#8-15]}$$

$$OD = log\left[\frac{475}{.45}\right] = log[1,055.56]$$

$$OD = log\left[\frac{475}{.45}\right] = log[1,055.56] = 3.023$$

∴ The Optical Density of the Operator's Goggles = OD = 3.02.

Problem #8.24:

This problem also requires the use of Equation **#8-15**, from Page 8-26:

$$OD = log\left[\frac{I_{incident}}{I_{transmitted}}\right] \quad \text{[Eqn. \#8-15]}$$

$$OD = log\left[\frac{(475)(6.62)}{0.19}\right] = log\left[\frac{3,144.5}{0.19}\right] = log[16,550.0] = 4.219$$

We have been asked, in the statement of the problem, not simply for the new Optical Density, but rather what increase in Optical Density would be required under the conditions that prevail for the new; thus we shall proceed as follows:

$\Delta OD = \frac{OD_{new}}{OD_{former}}$, and substituting the two known Optical Densities:

$$\Delta OD = \frac{4.219}{3.023} = 1.395 = 139.5\%$$

∴ The Optical Density of the goggles will have to be increased by approximately 140%, to a new Optical Density value of 4.22.

Problem #8.25:

This problem requires the use of Equation **#8-16**, from Page 8-27:

$$r_{FF} = \frac{\pi D^2}{8\lambda} \qquad \text{[Eqn. \#8-16]}$$

Remembering that since the antenna diameter term, "D," for this expression must be in units of "centimeters," rather than "inches," we must convert the dimension provided in the problem statement from inches into centimeters:

$$D = (40.5 \text{ inches})(2.54 \text{ cm/inch}) = 102.87 \text{ cm, and now substituting in:}$$

$$r_{FF} = \frac{\pi(102.87)^2}{(8)(46)} = \frac{33,245.08}{368} = 90.34 \text{ cm}$$

∴ The Far Field is ~ 90.3 cm ~ 35.6 inches out in front of this UHF antenna.

Problem #8.26:

The first part of this problem can be solved by the application of Equation **#8-17**, from Page 8-28. From the previous problem, we see that the distance to the Far Field is just under 3 feet; therefore, we are dealing with a situation in the Near Field, which means that this relationship is the valid way to obtain the solution to this problem. We must now convert all the units provided in the problem statement into the units required for use in this equation:

$$P = (0.05 \text{ kilowatts})(10^6 \text{ milliwatts/kilowatt}) = 5\times10^4 \text{ mW}$$

$$D = (40.5 \text{ inches})(2.54 \text{ cm/inch}) = 102.87 \text{ cm, and now substituting in:}$$

$$W_{NF} = \frac{16P}{\pi D^2} \qquad \text{[Eqn. \textbf{\#8-17}]}$$

$$W_{NF} = \frac{(16)(5\times10^4)}{\pi(102.87)^2} = \frac{8\times10^5}{\pi(10,582.24)} = \frac{8\times10^5}{33,245.08} = 24.06 \text{ mW/cm}^2$$

We must next determine the time interval during which the Service Technician can safely work in a position in the Near Field in front of this radiating antenna. To obtain this answer, we shall use Equation **#3-1**, from Page 3-9:

$$TWA = \frac{\sum_{i=1}^{n} T_i C_i}{\sum_{i=1}^{n} T_i} = \frac{T_1C_1 + T_2C_2 + \ldots + T_nC_n}{T_1 + T_2 + \ldots + T_n} \qquad \text{[Eqn. \textbf{\#3-1}]}$$

We shall assume that this Service Technician will spend "t" minutes [out of every 6-minute time intervals] working at a point in the Near Field in front of this antenna, and the remainder of the time during this 6-minute period, namely, "(6 – t)" minutes, this Technician will be well away from this antenna — in a position where the microwave Power Density = 0.0 mW/cm^2. We shall further assume that the 6-minute TWA exposure that this Service Technician experienced was at the TLV-STEL level of 6.0 mW/cm^2:

$$6 = \frac{24.06t + 0.0(6-t)}{t + (6-t)} = \frac{24.06}{6}t = 4.011t \text{ , and solving for "t," we get:}$$

$$t = \frac{6}{4.011} = 1.496 \text{ minutes} \sim 1.50 \text{ minutes}$$

∴ The Power Density in the Near Field directly in front of this UHF antenna will be ~ 24 mW/cm^2.

As to the second part of this problem, this Service Technician will only be able to work for very brief periods — each being 1.5 minutes [1 minute, 30 seconds] or less out of every 6 minutes — at the designated point in the Near Field, directly in front of this antenna, whenever it is transmitting. In essence, he will only be able to complete productive work for ~ 25% of the time; he must spend the remaining ~ 4.5 minutes out of every 6 away from this antenna — i.e., ~ 75% of his time. If he exceeds this duty cycle, he will exceed the TLV-STEL, which is 6.0 mW/cm^2.

Problem #8.27:

We do not know for certain that the answer to this problem will be a distance that will be great enough to put it in the Far Field for this antenna — i.e., a distance that is greater than 90.3 cm = 35.6 inches. For the moment, however, we will assume that the location is, in fact, in the Far Field. Based on this assumption, this problem will require the use of Equation **#8-19**, from Pages 8-28 & 8-29. Recall the following data and factors that apply to this antenna:

$D = 40.5 \text{ inches} = 102.87 \text{ cm}$

$\lambda = 46 \text{ cm}$

$P = 5 \times 10^4 \text{ mW}$

$W_{FF} = 6.0 \text{ mW/cm}^2$ — a power level equal to the TLV-STEL for this frequency; therefore, an electrical field power density that ensures that an exposed Technician will never exceed the established TLV-STEL.

$$r = \frac{D}{2\lambda}\sqrt{\frac{\pi P}{W_{FF}}} \qquad \text{[Eqn. \textbf{\#8-19}]}$$

Now plugging these values into this equation, we get:

$$r = \frac{102.87}{(2)(46)}\sqrt{\frac{\pi(5 \times 10^4)}{6.0}} = \frac{102.87}{92}\sqrt{\frac{157,079.63}{6}}$$

$$r = 1.118\sqrt{26,179.94} = (1.118)(161.8) = 180.92 \text{ cm} = 71.23 \text{ inches}$$

Although we did not know if the maximum required electrical field Power Density Level of 6.0 mW/cm^2 would be in the Far Field at the start of this problem, we can now see that it truly is a Far Field location [recall that the Far Field starts 90.3 cm from the antenna]. Had the calculated value for this problem been less than this distance, we would have been compelled to use the Near Field Power Density Level relationship, namely, Equation **#8-17**, from Page 8-28, to obtain the solution to this problem.

∴ Although it is difficult to determine how it would actually be done at the calculated distance, the closest that a Service Technician could safely work in front of this UHF antenna [and be certain never to exceed the 6-minute TLV-STEL of 6.0 mW/cm^2] would be at a distance of ~ 180.9 cm or ~ 71.2 inches. He would have to have VERY long arms!!

Problem #8.28:

This problem will also require the use of Equation **#8-18**, from Page 8-28. Clearly, this point is in the Far Field. In fact, we will have to convert this very large distance into the units required for this Equation; thus:

$$(85 \text{ miles})(5,280 \text{ feet/mile})(12 \text{ inches/foot})(2.54 \text{ cm/inch}) = 1.368 \times 10^{7} \text{ cm}$$

$$W_{FF} = \frac{\pi D^2 P}{4\lambda^2 r^2} \qquad \text{[Eqn. \textbf{\#8-18}]}$$

Now substituting in the appropriate values, we get:

$$W_{FF} = \frac{\pi(102.87)^2\left(5\times10^4\right)}{(4)(46)^2\left(1.368\times10^7\right)^2} = \frac{\pi(10,582.24)\left(5\times10^4\right)}{(4)(2,116)\left(1.871\times10^{14}\right)}$$

$$W_{FF} = \frac{1.662\times10^9}{1.584\times10^{18}} = 1.05\times10^{-9} \text{ mW/cm}^2$$

∴ The minimum Power Density required for this UHF receiving antenna to be able to operate successfully appears to be 1.05×10^{-9} mW/cm^2 = 1.05×10^{-6} μW/cm^2.

Problem #8.29:

This problem must be solved by first applying Equation **#8-1**, from Page 8-16, to determine the wavelength of this J-Band microwave radar [often referred to in police circles as "X-Band" Speed Radar; since during World War II, this particular frequency was in a band that was identified as the "X-Band"]. When we have this wavelength information, we can then utilize Equation **#8-16**, from Page 8-27, to develop the result that was requested in the problem statement:

$$\lambda = \frac{c}{\nu} \qquad \text{[Eqn. \textbf{\#8-1}]}$$

Remembering that the frequency term, n, must be in Hertz rather than gigahertz, we can substitute in the values provided:

$$\lambda = \frac{3\times10^8}{10.525\times10^9} = 2.85\times10^{-2} \text{ meters} = 2.85 \text{ cm}$$

Now since we now know the wavelength of this J-Band Speed Radar, we can now determine the distance to the Far Field, using Equation **#8-16**, from Page 8-27:

$$r_{FF} = \frac{\pi D^2}{8\lambda} \qquad \text{[Eqn. \textbf{\#8-16}]}$$

To apply this relationship, we must have the diameter of the radar antenna in units of centimeters:

$$(4.02 \text{ in})(2.54 \text{ cm/in}) = 10.21 \text{ cm}$$

Now we can substitute numerical values and determine the distance to the Far Field for this Speed Radar unit:

$$r_{FF} = \frac{\pi(10.21)^2}{(8)(2.85)} = \frac{327.49}{22.80} = 14.36 \text{ cm}$$

∴ It is ~ 14.36 cm or ~ 5.66 inches to the Far Field for this J-Band Speed Radar Gun.

Problem #8.30:

This problem will require the use of Equation **#8-1**, from Page 8-16, to calculate the wavelength of this J-Band Radar. When this value is known, we use Equation **#8-18**, from Page 8-28, to obtain the solution requested in the problem statement:

$$\lambda = \frac{c}{\nu} \qquad \text{[Eqn. #8-1]}$$

Remembering that the frequency term, n, must be in Hertz rather than gigahertz, we can substitute in the values provided:

$$\lambda = \frac{3\times 10^8}{10.525\times 10^9} = 2.85\times 10^{-2}\text{ meters} = 2.85\text{ cm}$$

Since we now know the wavelength of this J-Band Speed Radar, we can determine the distance at which the required maximum Power Density level occurs; for this step, as stated above, we will use Equation **#8-18**, from Page 8-28:

$$W_{FF} = \frac{\pi D^2 P}{4\lambda^2 r^2} \qquad \text{[Eqn. #8-18]}$$

Again, remembering that the diameter of this J-Band radar is 4.02 inches = 10.21 cm, we can substitute in the numeric values that we have. Note, this relationship is most commonly used to calculate the Power Density in the Far Field; however, the distance term, "r," is a factor in the denominator. Thus we will use this relationship — rearranged — to calculate the distance required in the problem statement:

$$10.0 = \frac{\pi(10.21)^2(45)}{(4)(2.85)^2 r^2}$$

$$r^2 = \frac{\pi(10.21)^2(45)}{(4)(2.85)^2(10.0)} = \frac{14{,}739.47}{324.9} = 45.37$$, & taking the square root of both sides:

$$r = \sqrt{45.37} = 6.74\text{ cm}$$

∴ The distance — in front of this J-Band Speed Radar Gun's antenna — at which the Power Density Level will be ≤ 10 mW/cm^2 will be ~ 6.74 cm, which is ~ 2.65 inches. For any distance greater than this, there will never be any danger of an individual exceeding the established TLV-STEL of 10 mW/cm^2; however, at distances less than this, exposures — especially relatively long duration exposures — may well exceed this Standard.