RADIATION SAFETY EXAM
STUDY GUIDE

FOR USERS OF
RADIOACTIVE MATERIAL

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Washington University Medical Center

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PREFACE

This manual is intended to provide the research and laboratory medicine staff of Washington University in St. Louis and Washington University Medical Center a convenient summary of the basic essentials of radioactivity and radiation safety practices necessary to pass the institutional radiation safety examination, a requirement of personnel prior to their working with radioactive materials without the direct supervision of their Authorized User or designated Lab Contact.

The Nuclear Regulatory Commission, the federal regulatory agency with authority over the use of radioactive materials at Washington University and the Medical Center, specifies that personnel must be instructed concerning the following:

- Radioactive decay and radiation
- Potential hazards or risks
- Radiation signs, symbols and labels
- Radioactive materials used
- Locations where radioactive materials are use or stored
- ALARA program
- Protective measures to keep personnel exposure low
- Emergency actions
- Specific radiation safety program requirements
- Existence and location of NRC license
- Existence and role of regulatory agencies
- Each worker's obligation to report unsafe conditions
- Worker's rights
- Who to contact if there are questions

Each of these topics is addressed in this manual.
1. NATURE OF RADIOACTIVITY AND RADIATION

Radioactivity is a spontaneous process characteristic of atoms with unstable nuclei in which the nucleus releases energy either as a particle with kinetic energy or as electromagnetic energy. Upon release of this energy the nucleus may be stable or it may still be unstable and subsequently transform again. The original isotope prior to radioactive decay is termed the "parent" with the isotope after the transformation called the "daughter". A given transformation, that is, one parent/daughter transition, is called a "decay" or a "disintegration".

1.1. Radioactive Decay

The rate of radioactive decay, also called the disintegration rate or decay rate, is used to indicate the "radioactivity" of a sample and is termed the “activity”. The traditional unit of activity is the curie (Ci) defined as the amount of radioactive material having a disintegration rate of $3.70 \times 10^{10}$ (37 billion) disintegrations per second (dps). It is common to express activities in curies (Ci), millicuries (1 thousand mCi = 1 Ci), microcuries (1 million $\mu$Ci = 1 Ci), nanocuries (1 billion nCi = 1 Ci), picocuries (1 trillion pCi = 1 Ci), etc. It is important to note that activity denotes the rate of disintegration; it provides no information regarding the kind of radiation emitted during the radioactive decay.

In most of the world, the curie has been replaced by new units based on the metric system. The unit of activity in the System International (SI) is the becquerel (Bq). The becquerel is defined as a disintegration rate of one per second, that is, 1 Bq = 1 dps. For example, a millicurie of activity ($3.7 \times 10^7$ dps = $37 \times 10^6$ dps) is equivalent to 37 megabecquerel (37 MBq) of activity. It is common to see activity levels in the literature expressed in both units, usually with one in parenthesis. However, the Nuclear Regulatory Commission (NRC) uses the traditional unit, the curie, to denote activity levels, so for radiation safety purposes we do as well.

1.2. Half-Life

The “half-life” is an important characteristic of any radionuclide. (Any specific nuclear combination of neutrons and protons comprise a nuclide; an unstable nuclide is termed a radionuclide.) The half-life corresponds to the time necessary for one-half of the radioactive atoms of a sample to decay. The fraction of atoms (or activity) remaining as a function of the number of elapsed half-lives is as follows:
In general, the fraction remaining is expressed by the relationship, where \( n \) is the number of half-lives that have passed:

\[
\text{fraction remaining} = \left(\frac{1}{2}\right)^n
\]

Thus, \( 1/2 \) (50\%) of the activity remains after 1 half-life, \( 1/4 \) (25\%) after 2 half-lives, \( 1/8 \) (12.5\%) after 3 half-lives, and so on.

With a starting activity of 40 mCi, the activity left after 4 half-lives would be 2.5 mCi (40 mCi \( \times (1/2)^4 = 40/16 = 2.5 \) mCi). The following illustration shows a very easy way to determine the activity remaining for the same example.

\[
\begin{align*}
\text{40 mCi} & \rightarrow \text{20 mCi} \rightarrow \text{10 mCi} \rightarrow \text{5 mCi} \rightarrow \text{2.5 mCi} \\
\text{n (T}_{1/2}\text{'s}) & = 1 \rightarrow 2 \rightarrow 3 \rightarrow 4
\end{align*}
\]

The half-lives of several radionuclides commonly used at our institution are:

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Half-Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen-3 (tritium) ((^3)H)</td>
<td>12.3 years</td>
</tr>
<tr>
<td>Carbon-14 ((^{14})C)</td>
<td>5700 years</td>
</tr>
<tr>
<td>Phosphorus-32 ((^{32})P)</td>
<td>14.3 days</td>
</tr>
<tr>
<td>Sulfur-35 ((^{35})S)</td>
<td>88 days</td>
</tr>
<tr>
<td>Iodine-125 ((^{125})I)</td>
<td>60 days</td>
</tr>
</tbody>
</table>

1.3. Types of Radioactive Decay

Only a limited number of types of transformation have been observed in the decay of radionuclides. The four most common types of radioactive decay are (1) alpha decay, (2) beta decay, (3) electron capture and (4) isomeric transition. Prior to discussing
these types of radioactive decay it is helpful to introduce a unit of energy, the "electron volt". This unit is used to denote particle and photon energies in atomic physics and it represents the energy change experienced by an electron while undergoing a potential energy change of one volt. It is common to express certain energies in kiloelectron volts (keV = one thousand eV), megaelectron volts (MeV = one million eV), etc. For comparative purposes, the kinetic energy of an air molecule at typical room temperature is about 0.025 eV.

1.3.1. Alpha Decay

Alpha decay is generally limited to isotopes of the heavy elements (isotopes are different nuclear varieties of an element – same atomic number, Z, but different mass numbers, A). In alpha decay, a charged particle (alpha particle) consisting of two protons and two neutrons, is ejected from the nucleus with high kinetic energy – typically, about 4 MeV. The alpha particle, although its initial energy is great, is stopped by a few centimeters of air or by a few microns of tissue. After the emission of the alpha particle, the daughter atom may be in an excited level of that particular isotope. The resulting transition to the ground state is generally accompanied by the emission of a gamma-ray, a photon of electromagnetic energy that is emitted from the nucleus of the excited atom.

1.3.2. Beta Decay

Beta decay is the name of a transition that results in the emission of an electron from the nucleus. The emitted electron may be negatively charged, that is, an ordinary electron referred to as a beta particle (β-particle) or it may be positively charged, that is, a positron, depending on the particular radioactive isotope.

There are some radionuclides that exhibit "simple β-decay", and the daughter nucleus is at the "ground state" subsequent to the decay. Important examples of such radionuclides are tritium (hydrogen-3, ³H), carbon-14 (¹⁴C), phosphorus-32 (³²P) and sulfur-35 (³⁵S). In the case of simple beta decay, the only detectable radiation emitted during the decay process is the beta particle.

However, the more common situation is for the daughter to be an "excited isomeric state" of the nuclide with subsequent emission from the nucleus (usually promptly) of a photon of electromagnetic radiation, called a "gamma ray". Either the gamma rays or the β-particles can be detected to identify the presence of the radionuclide.
1.3.3. **Electron Capture**

An unstable nucleus of certain isotopes can convert a proton to a neutron by a process termed electron capture. An orbital electron is "captured" while passing through the nucleus of these unstable nuclei. The captured electron combines with a nuclear proton to yield a neutron. A rearrangement of the orbital electrons results to fill the vacancy left by the captured electron. This rearrangement of orbital electrons is generally accompanied by the emission of characteristic x-rays. In addition, if the decay leaves the daughter at an excited level, then γ-rays are likely to be emitted in the subsequent transition(s) to the ground state of the daughter nucleus. The presence of radionuclides that decay by electron capture, chromium-51 (\(^{51}\text{Cr}\)) and iodine-125 (\(^{125}\text{I}\)) are examples, can often be identified by either the x-rays or gamma-rays or both.

1.3.4. **Isomeric Transition**

The excited levels and the ground state level of a radionuclide differ only in nuclear energy content. The various energy levels are called nuclear "isomers" and the transitions between them are called isomeric transitions. These transitions normally occur promptly after formation of the excited level (promptly usually means de-excitation times of the order of nanoseconds) and generally result in γ-rays of energy equal to the difference of the energies of the two isomeric levels involved in the transition. Occasionally, there are instances in which the excited state of a daughter nucleus is relatively long-lived with the transition to the ground level, being delayed not by nanoseconds but by minutes or hours. The protracted excited level is termed a metastable level and is denoted by adding the letter m to the mass number. An example is technetium-99m (\(^{99m}\text{Tc}\)), which has a half-life of the metastable state of 6 hours.

2. **INTERACTION OF RADIATION WITH MATTER**

2.1.1. **X- and γ-Radiation (x- and γ-rays)**

X-rays and γ-rays are electromagnetic radiation. The terms x-ray and γ-ray distinguish the origin of the radiation; x-rays are emitted by electrons, whereas γ-rays are emitted by the nucleus of an atom involved in radioactive decay. X-rays and γ-rays of the same energy are identical in every respect except origin. Electromagnetic radiation, such as x- and γ-rays can interact with matter by more than ten different processes. In some interactions the electromagnetic radiation behaves like energy waves, and in others it behaves like particles, called photons. As electromagnetic radiation, x- and γ-rays travel with the speed of light and are characterized by their energy. For radiation safety
purposes, there are only three important interactions: photoelectric absorption, Compton scattering, and pair production. The following sections summarize these three important photon interactions with matter.

2.1.1.1. Photoelectric Absorption

In this process the incident photon is absorbed by a bound electron present in a constituent atom of the material with which the photon interacts, and the photon ceases to exist. The electron is ejected from its previously bound state and carries away most of the absorbed energy as kinetic energy.

The probability of photoelectric absorption is very much dependent upon the energy of the radiation and upon the atomic number of the absorbing material. In general, photoelectric absorption is the dominant absorption process at low radiation energies and it occurs, for a given energy, much more in materials of high atomic number than in materials with low atomic number. Thus, lead with the high atomic number of 82, is an excellent material for absorbing radiation by the photoelectric process.

2.1.1.2. Compton Scattering

In this interaction the incident photon undergoes a billiard-ball type collision with an electron of the interacting material. The photon is deflected, or “scattered”, by the collision and continues on with reduced energy. Compton interactions occur to about the same extent in unit masses of different materials, that is, a gram of wood is about as effective as a gram of lead if the attenuation process is Compton scattering. The probability of Compton scattering in any material steadily decreases as the energy of the radiation increases.

2.1.1.3. Pair Production

In this attenuation process, the incident photon materializes as a pair of particles (an electron and a positron) in the vicinity of a nucleus. The minimum or threshold energy for this interaction is 1.02 MeV (This corresponds to the rest mass energy equivalence of the 2 created particles). The probability of pair production increases above the threshold and it occurs more in matter with high atomic number constituents than matter of low atomic number. Pair production is an important way to stop or attenuate electromagnetic radiation only for high energy radiation, that is, for photon energies greater than several MeV.

In general, photoelectric absorption is the dominant interaction at low energies while pair production is the dominant interaction at very high energies. Compton scatter is the important mechanism for intermediate energies. The relative importance of each
process is shown below as a function of photon energy and absorbers of different atomic number.

2.1.1.4. Half-Value-Layer

It is frequently convenient to express the attenuation or "absorption" properties of a material in terms of its half-value-layer, HVL. The HVL is defined as the thickness of the material required to reduce the transmitted radiation to one-half of the incident value.

The transmitted fraction \( f \) through \( n \) half-value-layers is given by the expression

\[
f = \left( \frac{1}{2} \right)^n
\]

Thus, 1/2 (50%) of the incident radiation is transmitted through one HVL, 1/4 (25%) through 2 HVL, 1/8 (12.5%) through 3 HVL, and so on.
The following illustration shows a very easy way to determine the amount of activity remaining after transmission through a given number of HVL’s. Assume a starting activity of 10 mCi. The activity left after transmission through 3 HVL’s would be 1.25 mCi.

\[
\begin{align*}
10 \text{ mCi} & \rightarrow 5 \text{ mCi} \rightarrow 2.5 \text{ mCi} \rightarrow 1.25 \text{ mCi} \\
\frac{1}{2} & \quad \frac{1}{2} \quad \frac{1}{2}
\end{align*}
\]

\[n \text{ (HVLs)} = 1 \quad 2 \quad 3\]

2.1.2. Particle Interactions

As a charged particle passes among the atoms of an absorbing material it may (1) dislodge electrons from atoms to form positive and negative ions (ionization), (2) excite electrons to higher energy levels in atoms, (3) set up vibrations of molecules in the path, (4) break molecular bonds, or (5) produce electromagnetic radiation subsequent to a sudden change in its course (bremsstrahlung). It is the ionization process that is responsible for the radiobiological effects of radiation and it also makes possible the detection of radiation with various types of equipment.

The energy that a particle loses to its surroundings for each unit of path length is called the linear energy transfer (LET). Think about running a race: for every mile you run, you lose a little more energy. The average energy per mile that you lost would be your “linear energy transfer”.

The distance that a charged particle travels from the point of its origin to the place where it no longer acts as a destructive particle is called its range. Think again of our race: at the finish line, you are completely spent…you can’t go one step farther and have reached your “range”.

You need to understand the process of bremsstrahlung. When electrons are diverted or stopped by their interactions with matter, some of their energy can go into creating x-rays. For electrons of a given energy, \(E\) (MeV), the fraction of their energy, \(f\), that is lost by the emission of x-rays (called bremsstrahlung), is given by the expression:

\[
f = \frac{ZE}{1400}
\]

where \(Z\) = the absorber atomic number. This means that the higher the absorber’s atomic number (\(Z\)), the greater the energy lost by the electron which then appears as bremsstrahlung (x-rays). Thus, it is preferable to shield a pure beta emitter of high energy, for example, \(^{32}\text{P}\), with low atomic number (low “Z”) plastic rather than high atomic number lead in order to minimize the production of the penetrating x-rays referred to as bremsstrahlung.
3. RADIATION EXPOSURE AND DOSE

It is important to know the "radiation level" to which workers are exposed. Every radiation worker must not only consider his or her own radiation level, but be cautious to minimize the radiation level affecting others in the area.

There are three different technical concepts used to discuss radiation levels:

- the ambient radiation field in an area, or "radiation exposure";
- the energy deposited by radiation in a material, the "absorbed dose"; and
- the biological relevance of the energy deposited by radiation – specifically in living tissue – called the "dose equivalent".

The terms "dose" and "exposure" are commonly, or casually, used as if they are interchangeable, and it is hard to avoid doing so. However, when we specifically use the three terms “radiation exposure”, “absorbed dose”, and “dose equivalent”, they have very specific and conceptually different meanings:

Radiation exposure – This term applies to x- and γ-radiation fields only. This concept is based on the ability of photon (electromagnetic) radiation to ionize air. Specifically, the amount of electrical charge liberated in a unit volume of air is used to define the level of radiation exposure. The traditional unit of radiation exposure is the roentgen, R, which is approximately 2.08x10^9 ion pairs per cm^3 of dry air at standard temperature and pressure (or equivalently, 2.58 x10^-4 coulomb per kilogram of air).

Absorbed dose – This term applies to all forms of ionizing radiation, that is, both photon (electromagnetic) and particulate (α, β, neutron, etc.) radiation. The absorbed dose denotes the amount of energy imparted to any kind of matter by ionizing radiation, per unit mass of the irradiated material at the point of interest. The traditional unit of absorbed dose is the rad. The rad is defined as the energy absorption of 100 ergs per gram of material (or equivalently, 0.01 joule per kilogram of material).

Dose equivalent – This term applies to all forms of ionizing radiation. The “dose equivalent” denotes the potential biological effect of the ionizing radiation. It is defined as the product of the absorbed dose and certain “modifying factors”. The modifying factors are intended to “adjust” the absorbed dose for the relative effectiveness with which different types of radiation produce more or less damage in biological tissue for the same amount energy deposited. The traditional unit of this "product", that is, the unit of dose equivalent, is the rem. Although several modifying factors have been proposed, only the "quality factor" (QF) has been extensively used. The quality factor is a subjective measure of the "relative hazard or biological effect" of a given type of radiation and is strongly related to the linear energy transfer (LET) of the radiation.
The quality factors for common types of radiation are:

- x-ray, γ-ray, or β-particle, QF=1;
- thermal neutron, QF=5; and
- α-particle or fast neutron, QF=20.

An estimate of biological effect, that is, the dose equivalent in rem, is computed by multiplying the absorbed dose in rad by the appropriate QF. Example: An individual receives a fast neutron absorbed dose of 2 rad. The computed dose equivalent is 40 rem.

Dose equivalent is used to indicate the radiation dose due to internal radioactive contamination as well as external exposure. The dose pattern from organ to organ that results from internal radioactivity is normally very uneven. A computational method of handling non-uniform organ and tissue doses is the effective dose equivalent (EDE). A computed EDE, obtained by adjusting (weighting) designated organ doses according to their relative sensitivity to harm by radiation, is a single quantity that indicates the potential harm or risk of the non-uniform dose pattern. Specifically, the EDE is the computed value of a uniform whole body dose that theoretically imparts the same numerical risk as the actual non-uniform dose situation.

The Nuclear Regulatory Commission employs several dose equivalent variations, including the following:

- **Deep dose equivalent** – the dose due to external radiation computed for a tissue depth of 1 cm.
- **Eye dose equivalent** – the dose to the lens of the eye due to external radiation computed for a tissue depth of 0.3 cm.
- **Shallow dose equivalent** – the dose due to external radiation computed for a tissue depth of 0.007 cm (representative skin thickness).
- **Committed organ dose equivalent** – the dose due to internal radioactivity to a specific organ during the 50-year period following the intake.
- **Committed effective dose equivalent** – the computed effective dose due to internal radioactivity during the 50-year period following the intake.
- **Total effective dose equivalent** – the sum of the deep dose due to external radiation and the committed effective dose equivalent.

Many scientific units have been redefined in order to achieve a world-wide consistency of usage. The new units are based on the metric system and are referred to as SI units (Systeme International d’Unites). Two radiation units that are affected are those for
absorbed dose and dose equivalent. The SI units and their relationship to the traditional units of absorbed dose and dose equivalent are as follows:

<table>
<thead>
<tr>
<th>Quantity</th>
<th>SI Unit Name</th>
<th>Symbol</th>
<th>Relationship To Traditional Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorbed Dose</td>
<td>gray</td>
<td>Gy</td>
<td>100 rad per gray</td>
</tr>
<tr>
<td>Dose Equivalent</td>
<td>sievert</td>
<td>Sv</td>
<td>100 rem per sievert</td>
</tr>
</tbody>
</table>

Thus, a milligray (mGy) = 100 millirad and a microsievert (μSv) = 0.1 millirem, as examples. The Nuclear Regulatory Commission, the federal agency that has authority over most radioactive materials in the United States, has not yet (2015) adopted SI units, and so our radiation safety program also continues to use the traditional units.

4. BIOLOGICAL EFFECTS OF LOW LEVEL RADIATION

Radioactive material emits ionizing radiation whose interaction with human tissues may result in biological damage. The biological damage to tissues is primarily due to secondary charged particles that result when the tissues are exposed to the ionizing radiation. The energetic secondary particles yield highly reactive free radicals that interact with molecules in the tissues, breaking chemical bonds and causing other chemical changes. Some of the resulting damage is repairable, some is not. Biological effects of low-level radiation (Note: low-level radiation means acute whole body doses of 10 rem or less or substantially larger doses if received over an extended length of time) can be classified into the three categories below:

Somatic – Effects occurring in the exposed person. The manifestation of low dose effects is delayed. The period of time between exposure and demonstration of the delayed effect is referred to as the latent period.

Genetic – Abnormalities occurring in the future children of exposed persons and in subsequent generations.

Developmental or teratogenic – Effects observed in children who were exposed during the fetal or embryonic stages of development.

At the low levels observed from occupational exposure it is impossible to demonstrate a relationship between dose and effect. The changes induced by radiation often require many years or decades before being evident and, thus, a very long follow-up period is necessary to define risks. Studies of human populations exposed to low-level radiation are the appropriate basis for defining risk, but it is rare that they have the needed statistical power.
We can, instead, look for effects from higher-level radiation doses and try to extrapolate down into the low-level dose range. However, the number of situations from which the relationship between high radiation dose and response can be estimated is limited, the best being those of the A-bomb survivors in Nagasaki and Hiroshima. There is considerable uncertainty and controversy regarding the best estimates of the radiation risk of low level doses.

4.1. Summary of Current Radiation Risk Estimates

As used in this section, "risk" is the probability or chance of severe harm or death from radiation exposure.

4.1.1. Somatic Effects

The somatic effects of interest are cataract and cancer induction.

**Cataract Induction** – The lens of the eye differs from other organs in that dead and injured cells are not removed. Single doses of a few hundred rem can result in opacities that interfere with vision within a year. When the dose is fractionated over a period of a few years, larger doses are required and the cataract appears several years later. The 2006 BEIR VII Report (a report prepared by a special committee of the National Research Council) concludes that cataract induction is not a concern at the doses currently permitted for radiation workers, which are limited to 15 rem per year by the NRC (see section 6.1, below)

**Cancer Induction** – The 2006 BEIR VII Report concludes that cancer arising in a variety of organs and tissues is the only somatic effect possible at low levels of radiation exposure.

Various organs and tissues differ greatly in their susceptibility to cancer induction by radiation at high doses. For example, red bone marrow, the lungs and the gastrointestinal (GI) tract exhibit relatively high susceptibility to induced harm by radiation while skin, muscle, and bone surfaces are relatively insensitive to radiation harm. The following is known regarding radiation-induced cancer:

- The manifestations are delayed after exposure to radiation with latent periods of a few years for leukemia development and, perhaps, as many as 20 years or more for solid tumor formation.

- The resulting forms of cancer are indistinguishable from similar cancers spontaneously occurring in people.
NRC regulatory guidance states that a cautious, conservative estimate of the risk of fatal cancer due to ionizing radiation is approximately 4 chances in 10,000 per rem of whole body dose (or effective dose equivalent) when averaged over a representative population of radiation workers (or 1 chance per 2,500 rem). This information is presented in NRC Regulatory Guide 8.29 (1996) and is based on the 1990 BEIR V Report.

The more recent 2006 BEIR VII Report states that a more conservative estimate is approximately 1 chance in 1,000 per rem of whole body dose (or effective dose equivalent) when averaged over a representative population of radiation workers. Although this may be considered a more recent scientific evaluation, NRC guidance has not been updated. Thus for radiation safety purposes we use 4 chances in 10,000 rem as the basis for risk estimates in our program.

For perspective, the following are thought to result in comparable fatal risk (one in a million chance of death):

- 1 millirem of whole body dose or effective dose equivalent
- smoking 1.4 cigarettes
- eating 40 tablespoons of peanut butter
- driving a car 40 miles
- spending two days in New York City

Another comparison is to look at estimates of the average number of days of life expectancy lost from occupational exposure to radiation and to compare this number with days lost, on the average, for various types of industry. The following results suggest that the health risks from occupational radiation exposure are smaller than the collective risk associated with various industries.

<table>
<thead>
<tr>
<th>Industry Type</th>
<th>Average Days of Life Expectancy Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mining &amp; Quarrying</td>
<td>328</td>
</tr>
<tr>
<td>Agriculture</td>
<td>277</td>
</tr>
<tr>
<td>Construction</td>
<td>302</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>43</td>
</tr>
<tr>
<td>Occupational Radiation Exposure</td>
<td>49</td>
</tr>
<tr>
<td>(340 mrem per year for 30 years)</td>
<td></td>
</tr>
</tbody>
</table>

Finally, some scientists today believe that low doses of ionizing radiation actually have a net health benefit. This concept is called "hormesis". The net beneficial or hormetic effect due to low doses of radiation is attributed to various adaptive processes that
appear to be initiated by exposure to ionizing radiation. This view is controversial at the present time.

The view that regulators and most advisory groups take is to assume a linear, no threshold model to describe the relationship between harm and dose at low levels. This cautious approach assumes that any level of radiation exposure carries a proportional risk, that is, there is no threshold for potential harm.

4.1.2. Genetic Effects

A mutation is an inheritable change in the genetic material within chromosomes. Generally speaking, mutations are of two types, dominant and recessive. The effects of dominant mutations usually appear in the first and subsequent generations while the effects of recessive mutations do not appear until a child receives a similarly changed gene for that trait from both parents. This may not occur for many generations or it may never occur. Mutations can cause harmful effects which range from undetectable to fatal. In this section mutational effects mean only those inheritable conditions which are usually severe enough to require medical care at some point in a person's lifetime.

In this context, it is currently thought that the upper-limit probability of radiation-induced severe hereditary effects in all descendents is approximately 1 chance in 10,000 per rem of collective preconception gonadal dose of the parents. About 30% of that risk applies to the first two generations, that is, to the children and grandchildren of the exposed parents.

4.1.3. Developmental Effects

An exposed unborn child may be subjected to more risk from a given dose of radiation than is either of the parents. The developmental effects of radiation on the embryo and fetus are strongly related to the stage at which exposure occurs. The greatest concerns are of inducing malformations and functional impairments during early development and an increased incidence of cancer during childhood. The most frequently radiation-induced human malformations are small size at birth, stunted postnatal growth, microcephaly (small head size), microencephaly (small brain), certain eye defects, skeletal malformations and cataracts. Fortunately, these effects are observed only for radiation doses much larger than those permitted radiation workers.

The current knowledge regarding developmental effects is as follows:

- Exposure of the embryo during the first 3 weeks following conception may result in a failure to implant or an undetectable death of the conceptus. Otherwise, the pregnancy continues in normal fashion with no deleterious effects. This "all or
nothing" response is thought to occur only for acute doses greater than several rem.

- After 3 weeks, malformations may occur which are radiation dose dependent but with a threshold dose estimated to be about 10 rem of acute exposure.

- From 3 weeks to the end of pregnancy it is possible that radiation exposure may result in an increased chance of childhood cancer with a risk factor of, at most, a few times (probably 2 to 3) that for the whole population.

- Irradiation during the development of the forebrain, in the period of 8-15 weeks after conception, may reduce the child's IQ by 0.3 point per rem, on the average, for relatively large doses.

These conclusions are reassuring for individuals who incur small work-related doses since the possible developmental effects are thought to occur only at much higher doses or to occur with very low probability, if at all.

5. SOURCES OF RADIATION EXPOSURE

It is important to recognize that humankind has always existed in an environment that includes exposure to ionizing radiation and, for perspective, to compare the levels due to natural sources to those from other sources. Although we have produced many sources of radiation, natural background sources remain a major contributor to radiation exposure of the United States population today.

In addition to natural background, we as a population are exposed to a number of man-made radiation sources. The primary man-made radiation exposures we receive are due to medical diagnosis and treatment. There are other sources that may come to mind, such as nuclear power, some consumer products, airport x-rays, or air travel itself, which also contribute small exposures.


5.1. Natural Background Sources

Four components of natural background radiation have been called out in detail in NCRP Report No. 160 (2009) (see figure below):

Terrestrial radiation results from the presence of naturally occurring radioactivity in the soil and earth (3% of total annual average).
Radon gas emanates from uranium-bearing soil, rock, and building materials into confined living spaces (38% of total annual average).

Cosmic radiation results from the interaction of particles originating in outer space with the earth’s atmosphere (5% of total annual average).

Your body incorporates internal radioactivity due to naturally occurring radionuclides that have been deposited in the human body through either ingestion or inhalation (5% of total annual average).

The annual radiation dose due to naturally occurring sources varies considerably within the United States depending on the location. For example, the cosmic component is dependent on the altitude with a value at 10,000 feet above sea level being about twice the sea level value. Similarly, the terrestrial component varies with the type of soil in a given area and its content of naturally occurring radionuclides.

The average annual effective dose equivalent in the United States from background sources is approximately 310 millirem (3.1 mSv), with approximately 230 millirem (2.2 mSv) attributed to radon gas.

5.2. Man-Made Sources

Four categories of man-made radiation sources are called out in detail in NCRP Report No. 160 (2009) (see figure above):

Medical radiation is the most significant source of ionizing radiation exposure to the general public of the United States. The beneficial uses of radiation for medical diagnosis and treatment account for approximately 295 mrem (2.95 mSv) per year, on an average per capita basis. For this purpose, medical radiation is divided into two components:

Medical X-rays, as a category, includes conventional x-rays and fluoroscopy, interventional fluoroscopy, and computed tomography (CT). Such sources contribute
the majority of the average person’s annual medical exposure (36% of total annual average).

_Nuclear Medicine_, as a category, refers to the use of radioactive materials administered to a person for tests or treatments. There is a medical benefit to the person receiving radioactive drugs or radio-pharmaceuticals (12% of total annual average).

_Consumer Products_ and activities is defined by NCRP in Report No. 160 (2009) to include cigarette smoking, building materials incorporating coal combustion products, commercial air travel, mining and agriculture, combustion of fossil fuels, highway and road construction materials, glass and ceramics, dental prostheses, ophthalmic glass, luminous watches and clocks, smoke detectors, electron tubes, thorium-bearing gas mantles and welding rods, television receivers and video terminals, sewage sludge and ash, and tritium-bearing exit signs. These are listed generally in decreasing order of radiation exposure, and no single category contributes excessively. The average person’s exposure to such sources is highly variable (5% to 25% of total annual average).

_Other Sources_ as categorized by NCRP Report No. 160 (2009) were nuclear-power generation; Department of Energy installations; nuclear facilities decommissioning and waste management; industrial, medical and educational research; care-giving or other contact with nuclear-medicine patients; and security inspection systems. None of these contributes significantly to the population average (less than 1% of total annual average).

5.3. **Summary of Radiation Exposures**

The total annual effective dose equivalent in the United States is considered to be about 620 mrem (6.2 mSv), on the average, with roughly half from natural sources and half from medical uses and man-made sources.

6. **RADIATION DOSE RECOMMENDATIONS AND REGULATIONS**

No single agency regulates the radiation exposure of workers in the United States. This responsibility is carried out by the Department of Transportation (DOT), Occupational Safety and Health Administration (OSHA), Environmental Protection Agency (EPA), and the Nuclear Regulatory Commission (NRC) and by various agencies in each state. In addition, two organizations of professionals in radiation protection, the International Commission on Radiological Protection (ICRP) and the National Council on Radiation Protection and Measurements (NCRP), provide radiation dose recommendations that
generally have served as the bases for the regulations established by the state and federal agencies.

6.1. Federal Regulations

Regulations concerning occupational and public radiation exposure are implemented by the Nuclear Regulatory Commission, the federal agency responsible for radioactive materials used at our institution. The limits, listed below, include the contributions from both external and internal exposure.

Occupational Radiation Dose Limits

<table>
<thead>
<tr>
<th>Dose Category</th>
<th>Dose Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective dose equivalent (whole body)</td>
<td>5 rem per year</td>
</tr>
<tr>
<td>Lens of the eyes</td>
<td>15 rem per year</td>
</tr>
<tr>
<td>Extremity</td>
<td>50 rem per year</td>
</tr>
<tr>
<td>Any other organ or tissue</td>
<td>50 rem per year</td>
</tr>
<tr>
<td>Embryo/fetus of a declared pregnancy</td>
<td>0.5 rem per gestation period</td>
</tr>
</tbody>
</table>

General Public Radiation Dose Limit

<table>
<thead>
<tr>
<th>Dose Category</th>
<th>Dose Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective dose equivalent (whole body)</td>
<td>0.1 rem per year</td>
</tr>
</tbody>
</table>

These recommendations exclude contributions from naturally occurring radiation sources and from beneficial medical procedures.

6.2. NCRP Recommendations

The National Council of Radiation Protection and Measurements (NCRP) provides exposure guidance for both radiation workers and the public. The current guidance of the NCRP and the regulatory limits of the NRC are consistent. However, the NCRP provides additional guidance that is not incorporated as part of a regulation by the NRC. For example, the NCRP recommends that the effective dose equivalent (EDE) due to work-related exposure be controlled in such a manner to ensure that the numerical value of an individual worker's cumulative EDE in rem does not exceed the worker's age in years. To illustrate, it is recommended that the cumulative EDE of a worker of age 40 years should not exceed 40 rem. Hence, although the EDE limit for any one year is 5 rem, the guidance is that the average annual EDE should be substantially less than 5 rem per year over many years of work.
6.3. ALARA Philosophy

The NRC states that licensees of that agency should make every reasonable effort to keep radiation exposures, as well as releases of radioactive material to unrestricted areas, as far below the federal limits as is reasonably achievable. The phrase "as low as reasonably achievable" is the basis of the acronym ALARA. The NRC has issued various information relevant to ensuring that radiation exposures at all institutions will be as low as reasonably achievable. The NRC, based on an extensive collection of personnel exposure histories, feels that the implementation of the ALARA concepts should maintain radiation doses to personnel to values that are 10% or less of the federal limits on occupational exposure.

7. RADIATION SAFETY INSTRUMENTS AND DEVICES

7.1. Personnel Dosimeters

Personnel dosimeters are devices worn by individuals exposed to ionizing radiation to evaluate and document their cumulative external radiation doses. The Nuclear Regulatory Commission requires licensees to provide radiation dosimeters to workers who are likely to receive more than 10% of any of the applicable limits of external dose.

Personnel monitoring of external radiation can be achieved with a variety of methods or technologies. The body dosimeters used at our institution utilize a technology referred to as "optically stimulated luminescence" (OSL) while the ring dosimeters are "thermoluminescent dosimeters" (TLDs). Although not a subject of the examination, it may be of interest that OSL devices use a material for the detector that emits light (luminescence) as the output signal when exposed to the light of an intense ruby laser (optical stimulation). The quantity of emitted luminescence is an indicator of the material's previous exposure to ionizing radiation; similarly, TLD materials emit light (luminescence) when heated (thermo) with the quantity of luminescence being proportional to the material's prior radiation dose.

Body dosimeters (OSL), referred to by the supplier as "Luxel" dosimeters, are very sensitive to ionizing radiation. The minimum reported dose equivalent is one millirem. A measured dose equivalent of less than one millirem is reported as "minimal" and denoted with the capital letter M. The supplier, Landauer, Inc., is able to report 3 different doses for each Luxel body dosimeter as follows:

- Shallow dose – the dose equivalent computed for a tissue depth of 0.007 cm. This dose is also referred to as the skin dose.
• Deep dose – the dose equivalent computed for a tissue depth of 1.0 cm. The deep dose is used by the NRC as the appropriate estimate of a worker's effective dose equivalent (EDE) due to external radiation.

• Lens dose – the dose equivalent computed for a tissue depth of 0.3 cm, the thickness of tissue overlying the lens of each eye.

Ring dosimeters (Saturn) containing a single TLD chip of lithium fluoride are used to measure doses to the hand(s) of certain personnel. Ring dosimeters should be worn similar to a conventional ring. The minimum reported ring (or "extremity") dose equivalent is 10 millirem and is reported as a shallow dose. Measured doses of less than 10 millirem are reported as "minimal" and denoted with the letter M.

The following rules apply to the proper use of personnel dosimeters:

• They should be used only by the intended person, not as an area monitor and not shared with another individual.

• They should never be worn when an individual is exposed to medical or dental x-rays for personal health reasons.

• They should be stored in a radiation-free area when not being worn.

• They should not be taken home since this increases their chance of being lost or laundered.

• They should be worn as intended:
  • Whole body dosimeters should be worn at chest level.
  • Ring dosimeters should be worn inside the glove on the hand of primary exposure, with the label facing toward the primary exposure zone.

• They should be promptly returned to Radiation Safety for evaluation after completion of the use period.

7.2. Portable Survey Instruments

Radiation survey instruments are generally available in areas where radioactive materials are used. These portable survey instruments are used for a variety of tasks – to conduct the routine area surveys of a laboratory, to assist in the clean-up phase of experiments in which radioactivity is used, to monitor parcels of waste material prior to transferring them to Radiation Safety for disposal, etc. The portable survey instruments used at our institution are of three types:
7.2.1. Geiger-Muller (GM) Instruments

GM instruments are widely used for radiation survey work because of their reliability and cheap cost. The instruments are compact, lightweight units with rugged electronics (approximately 400 GM units are available for use at our institution). These units use a gas-filled detector that is capable of detecting beta, gamma, and x-ray radiation. Usually the detector is enclosed in a metal shield that precludes β-particle detection except through a thin portion of the shield that is called the "window". When the window is open, the probe can detect beta particles in addition to x-rays and gamma rays. With the window closed, it primarily detects x-rays and gamma rays. The exposure rate scale of a calibrated GM device, typically in mR/hr, will yield a fairly accurate indication of the true exposure rate only when exposed to x- or gamma- radiation. When the device is used to detect particle radiation (beta radiation), the exposure rate scale, in mR/hr, should not be used; only a counts per minute (cpm) scale is appropriate for particle detection. Thin-window GM's can even detect low energy beta-emitters with low efficiency (~ 10% for ¹⁴C & ³⁵S), but they do not respond at all to the very low energy betas from tritium.

A representative portable survey instrument (GM type) with a pancake probe

7.2.2. Ionization Chamber Survey Instruments

Survey instruments using an air ionization chamber are designed to measure radiation exposure in roentgens. They exhibit much less "energy-dependence" of response than GM devices and can be used at much higher exposure rate levels. These instruments are considerably more expensive than GM "counters" and are only occasionally used in our research laboratories.

7.2.3. Scintillation Survey Instruments

Portable survey units are available that use a solid sodium iodide crystal coupled to a sensitive photomultiplier tube as the detector. The solid scintillator provides excellent sensitivity making them ideal for locating a misplaced source or identifying areas of
contamination. These devices are fragile, expensive, very energy dependent and are rarely used in our research laboratories.

8. CONTROL OF RADIATION EXPOSURE

Good radiation hygiene for all of the radionuclides used at our institution can be achieved by (1) recognizing sources of potential external exposure and (2) controlling internal contamination.

8.1. Protection from External Radiation

8.1.1. X- and $\gamma$- Emitters

One should limit the involvement time and maximize the distance from the radioactivity within reason to control external exposure. In special cases shielding is used to achieve acceptable exposure levels. The three concepts of time, distance and shielding are considered the cardinal principles for controlling external radiation.

Time spent around sources of radiation should be minimized as much as possible. Areas and materials should be prepared in advance, and steps of the procedure should be practiced in “cold” runs, prior to the introduction of the radioactive material(s). Remember, the less time you spend around sources of radiation, the less dose you will receive.

Distance from the source is a valuable ally. The exposure level varies inversely with the square of the distance from the source (this inverse square relationship applies for distances large compared to the physical dimensions of the radiation source). Thus, doubling the distance will result in a 4-fold reduction of dose rate, tripling the distance will result in a 9-fold reduction, etc.

If $I_1$ is the radiation intensity (exposure rate in mR/hr, for example) at a distance, $d_1$, from a point source, and $I_2$ is the intensity at another distance, $d_2$, from the source, then the general expression for the inverse-square relationship is:

$$I_2 = I_1 \frac{d_1^2}{d_2^2} \text{ mR/hr}$$

For example, if you measure 3 mR/hr ($I_1$) at 2 feet from a $\gamma$-emitting source ($d_1$), what exposure rate ($I_2$) would you expect to find at 5 ft from the source ($d_2$)?

$$I_2 = (3 \text{ mR/hr}) \frac{(2 \text{ ft})^2}{(5 \text{ ft})^2} = 3 \frac{4}{25} \text{ mR/hr} = 0.48 \text{ mR/hr}$$
Commonly, the first distance \( (d_1) \) is 1 ft (or 1 m, or “1” of any other distance unit), reducing the expression to the more commonly recognized form (where \( d_2 \) must be in the same units as \( d_1 \)):

\[
I_2 = \frac{I_1}{d_2^2} \text{ mR/hr}
\]

For example, if a source gives 8 mR/hr at 1 meter, what would you expect at 2 meters?

\[
I_2 = \frac{8}{(2)^2} \text{ mR/hr} = \frac{8}{4} \text{ mR/hr} = 2 \text{ mR/hr}
\]

The inverse-square relationship holds when moving closer to a source, as well as moving away from a source. If in the previous example we moved closer, what exposure rate would you expect to measure at a half-meter distance?

\[
I_2 = \frac{8}{(0.5)^2} \text{ mR/hr} = \frac{8}{0.25} \text{ mR/hr} = 32 \text{ mR/hr}
\]

In both examples, the exposure rate is adjusted by the square of the distance. Just remember the radiation decreases as you move away from the source, and increases as you move closer.

**Estimating doses** – For convenience in estimating doses from \( \gamma \)-emitting sources, a standard gamma “exposure rate constant” is used. This constant, denoted \( \Gamma \), is a measure of the exposure rate in air due to a small unit source of activity at a standard unit distance (it is also referred to as the “gamma-factor”. ) For the commonly used \( \gamma \)-emitting radionuclides \( ^{51}\text{Cr} \), \( ^{125}\text{I} \) and \( ^{131}\text{I} \), the following table lists the "exposure rate constant". (The table also lists “half-value layer” values, which are discussed in the following section.) Using the gamma factor allows estimates of exposures to be made without having a source on hand for making measurements.

**Gamma Factors and HVLs for Common Gamma Emitters**

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>( \Gamma ): for mR/hr per mCi @ 1 ft in air (mR-ft(^2)/mCi-hr)</th>
<th>HVL (mm of lead)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^{51}\text{Cr} )</td>
<td>0.2</td>
<td>1.8</td>
</tr>
<tr>
<td>( ^{125}\text{I} )</td>
<td>1.5</td>
<td>0.019</td>
</tr>
<tr>
<td>( ^{131}\text{I} )</td>
<td>2.3</td>
<td>2.9</td>
</tr>
</tbody>
</table>
For $^{51}\text{Cr}$, for example, what exposure rate would be expected from a 2 mCi source at a distance of 4 ft?

\[
\text{Exposure rate} = \frac{0.2 \text{ (mR-ft}^2\text{)/(mCi-hr}) \times 2 \text{ mCi}}{(4 \text{ ft})^2} = 0.025 \text{ mR/hr}
\]

**Shielding** – For shielding evaluations, it should be noted that half-value layers (discussed in section 2.1.1.4 Half-Value Layers, above) change markedly with photon energy. The HVL for $^{125}\text{I}$ (average photon energy ~ 28 keV) is very small – only 0.019 mm ($< 0.001$ inch) of lead while that for the much more energetic $^{51}\text{Cr}$ (320 keV) is about 1.8 mm.

As a combined distance and shielding example, consider the following situation: A vial containing 10 mCi of $^{131}\text{I}$ is to be stored in a location that is about 10 feet from a desk generally occupied by personnel. Predict the approximate exposure rate at the desk if the $^{131}\text{I}$ is placed in a lead shield of 12 mm thickness (approximately 4 HVLs):

\[
\text{Exposure rate} = \frac{2.3 \text{ (mR-ft}^2\text{)/(mCi-hr}) \times 10 \text{ mCi}}{(10 \text{ ft})^2 \times 2^4} = 0.014 \text{ mR/hr}
\]

You should recognize the radiation dose dependence on a) the distance from the source and b) the number of HVLs of shielding interposed between the source and the location of interest.

### 8.1.2. Beta Particle Emitters

Most of the pure $\beta$-particle emitting radionuclides used at our institution emit only low energy particles that are not very penetrating. The beta particles emitted by $^{3}\text{H}$ (tritium), $^{14}\text{C}$, $^{33}\text{P}$, $^{35}\text{S}$ and $^{45}\text{Ca}$ do not penetrate the walls of most containing vessels and, accordingly, pose little or no threat except for internal contamination. However, one extensively used radionuclide, $^{32}\text{P}$, emits beta particles of sufficient energy to penetrate both the container walls and the dead-layer of skin. The maximum range is 7 mm in unit density material (the range in other materials can be estimated by simply dividing the range in unit density material by the material’s specific gravity; thus, the range of the betas of $^{32}\text{P}$ in aluminum is 7 mm ÷ 2.7 = 2.6 mm). Significant skin and eye radiation doses can be incurred while handling $^{32}\text{P}$.

The beta dose incurred while handling $^{32}\text{P}$ or other high energy $\beta$-emitters can be maintained at a low level by a) keeping fingers as far from the radioactivity as possible (use tongs when feasible), b) using thick-walled containers and c) utilizing Plexiglass shielding to absorb the betas.
The use of a ring dosimeter is required of all personnel handling $^{32}\text{P}$ or other energetic beta-emitters in amounts exceeding 100 mCi per year or a few mCi at one time.

### 8.2. Protection from Internal Exposure

Fortunately, most of the radioactive materials used at our institution pose little or no external radiation threat (the average external exposure for all of the approximately 1,000 research workers handling radioactive material is less than 5 mrem per year). However, efforts to minimize internal contamination are important. To provide some perspective regarding the relative radiotoxicity of common radionuclides, the Nuclear Regulatory Commission lists maximum "annual limits of intake" (ALI). The concept of ALI is that it represents the quantity of a given radionuclide that, if ingested or inhaled by an individual will result in the same risk as that attributed to a radiation worker incurring the maximum permitted annual dose (this means that the ALI will result in a committed effective dose equivalent of 5 rem or in a committed "critical" organ dose equivalent of 50 rem, depending on which situation is more limiting). The most restrictive ALIs for the commonly used research radionuclides are as follows:

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Oral Ingestion ($\mu$Ci)</th>
<th>Inhalation ($\mu$Ci)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{3}\text{H}$</td>
<td>80,000</td>
<td>80,000</td>
</tr>
<tr>
<td>$^{14}\text{C}$</td>
<td>2,000</td>
<td>2,000</td>
</tr>
<tr>
<td>$^{32}\text{P}$</td>
<td>600</td>
<td>900</td>
</tr>
<tr>
<td>$^{33}\text{P}$</td>
<td>6,000</td>
<td>8,000</td>
</tr>
<tr>
<td>$^{35}\text{S}$</td>
<td>6,000</td>
<td>2,000</td>
</tr>
<tr>
<td>$^{45}\text{Ca}$</td>
<td>2,000</td>
<td>800</td>
</tr>
<tr>
<td>$^{51}\text{Cr}$</td>
<td>40,000</td>
<td>20,000</td>
</tr>
<tr>
<td>$^{125}\text{I}$</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>$^{131}\text{I}$</td>
<td>30</td>
<td>50</td>
</tr>
</tbody>
</table>

Most of the radionuclides used at our institution are considered only slightly radiotoxic with regards to internal contamination. However, the radioiodines, $^{125}\text{I}$ and $^{131}\text{I}$, are significant exceptions. Radioiodine is considered highly radiotoxic because of its specificity for the thyroid gland. Internal contamination via ingestion, inhalation, or skin absorption can result in a high thyroid dose.

However, personnel are able to handle large quantities of all of these radionuclides, including radioiodine, while maintaining annual intakes of less than 0.01% of the ALI's shown above. Practices that help to minimize internal contamination include:
• Wear laboratory coats or other protective clothing at all times when handling unsealed radioactive materials.
• Wear disposable gloves while handling unsealed radioactive material and be conscious of what you touch with the potentially contaminated gloves.
• Monitor hands, shoes, clothing and work area for contamination before leaving the area.
• Do not eat, drink, smoke, chew gum or apply cosmetics in areas where radioactive material is use or stored.
• Do not store food or beverages in areas where radioactive material is used or stored.
• Never pipette radioactive materials by mouth.
• Avoid contaminating objects such as telephones, light switches, faucet handles, doorknobs, etc.
• Use absorbent pads for easily containing and disposing of small amounts of contamination
• Conduct experiments or processes that either involve or evolve volatile radioactive materials in a fume hood specifically approved by Radiation Safety.
• Promptly clean up any spills of radioactivity. Briefly, one should inform persons in the area that a spill has occurred, cover the spill with absorbent pads, limit traffic to the area, start the cleanup, call for assistance (if indicated) and report the spill to your supervisor. Detailed instructions for handling a spill are posted in every laboratory authorized to use radioactive material.
• Faithfully check for surface contamination by periodically doing "wipe tests" and/or meter surveys.

9. SPECIFIC RULES THAT APPLY TO THE USE OF RADIOACTIVE MATERIALS

The Nuclear Regulatory Commission has many regulations that affect the use of NRC-licensed materials. The size of our institution (the collective grouping of the Medical Center members and the University Danforth Campus involves roughly 600 research personnel working in approximately 600 laboratories under the supervision of almost 200 faculty approved to use radioactive materials for research purposes) precludes the Radiation Safety group from performing many of the tasks required to ensure compliance with these regulations. Many of these tasks are the responsibility of the laboratory personnel. You should be aware of the requirements that apply to the use of
radioactive materials at this institution, especially those that may apply to your day-to-day use of the materials. They include the following:

9.1. Authorized Users

The Nuclear Regulatory Commission gives certain radiation safety oversight responsibilities to an institutional committee, the Radiation Safety Committee (RSC). The RSC, in turn, delegates certain responsibilities to research faculty members by approving them to use radioactive materials (the responsibility for the safe use of the radioactive materials comes with the privilege to acquire and use the materials). Approval to use radioactive materials, that is, to become an Authorized User, requires submission of an application with pertinent attachments to the RSC and subsequent approval. Authorizations are renewed every five years.

An amendment application must be submitted by the Authorized User and approved by the RSC prior to a) using a different radionuclide, b) obtaining increased amounts of approved radionuclides, c) beginning initial work with radioactive materials in live research animals and d) changing locations of use or storage.

An "Inactive" status category exists for an Authorized User (AU) who wants to have a radioactive materials authorization, but has no radioactive materials on hand and no firm plans to obtain materials within six months or more. "Inactive" investigators are still Authorized Users and can indicate as such on grant applications, etc., but are excused from many of the radiation safety compliance requirements, including the documented surveys of RAM laboratories.

9.2. Radiation Safety Examination

All personnel, prior to working with radioactive materials without the direct supervision of the Authorized User or designated Lab Contact, must pass the written examination given by Radiation Safety. The examination is based on the material in this training manual.

9.3. Annual ALARA Training Session

Annual training sessions must be provided by each Authorized User at which a discussion is conducted and information is provided regarding how personnel exposures to radiation can be maintained as low as reasonably achievable (ALARA) for the specific radioactivity work done in the laboratory. Guidance on how to perform this type of training is provided by Radiation Safety staff.
9.4. Annual Refresher Training

Certain information specified by the NRC is provided by Radiation Safety staff each year. This information, referred to as "refresher" information by the NRC, is distributed to Authorized Users and designated Lab Contacts and must be covered along with the annual ALARA training information.

9.5. Posting and Labeling

Laboratories, workspaces such as hoods or bench tops, and individual pieces of equipment used for work with radioactive materials are posted or labeled to identify the potential presence of radiation fields, radioactivity, or radioactive contamination.

Required laboratory postings are determined by the Radiation Safety Office and are provided, posted, replaced, or removed only by the Radiation Safety Office staff. Do not add unofficial postings because they may convey unintended regulatory meaning.

Radioactivity labels for workspaces and equipment within a posted space can be obtained from laboratory supply vendors, and are placed by each laboratory’s Authorized User (AU) (usually the PI), the lab’s designated radiation safety “Laboratory Contact” (LC), or the responsible laboratory staff trained to work with radioactive materials (“Radiation Workers” (RW)).

9.5.1. Radioactive Materials Area Posting

Three postings are conspicuously displayed at the entrance to all areas where radioactive materials are used or stored. They are the three-bladed “radiation symbol”, the words “Authorized Personnel Only”, and the words “Caution — Radioactive Materials”.

The signs are intended to inform individuals entering the rooms of a potential hazard, to restrict access to appropriate personnel, and to denote radiological safety evaluation and control of the area.
9.5.2. Radiation Area Posting

There are some laboratories in which significant amounts of gamma-emitting radionuclides are used such that the potential exists for an individual to receive more than 5 mrem in one hour at a distance of 30 cm (one foot) from the source. The entrances to these rooms have an additional posting bearing the words: “Caution — Radiation Area”.

There are other situations where additional or different postings are used for special cases, such as radiation areas created by radiation-producing machines, where radioactive materials are not present, or areas required to be posted as “high” radiation areas.

9.5.3. Airborne Radioactivity Area Posting

The “Caution — Airborne Radioactivity Area” sign is posted on fume hoods where volatile or potentially volatile forms of radioactivity are used in significant amounts.

9.5.4. Workspace and Equipment Labels

Radioactivity or radiation warning labels may be as simple as a sticker with the three-bladed trefoil used as the universal symbol for ionizing radiation. Other information may also be included, such as isotopes, exposure rates, contamination levels, survey dates, and names or initials of the responsible person. The colors of the radiation symbol must be the official magenta, purple or black on a yellow background.
Workspace labeling is used to denote the limited areas within a lab where radioactive materials are used. Most labs do not allow radioactive materials outside of the labeled space, which may be a specific alcove, a bench top or hood, or a portion of a bench top. Upon being labeled and used with radioactivity, lab spaces must remain labeled until specifically surveyed in a radioactive materials “close-out” by Radiation Safety Office staff.

Labeling of equipment, glassware, and tools to indicate they are used with radioactive materials is required so that anyone can recognize that the item or device may present a radiation exposure hazard, may be contaminated, or is dedicated to a specific purpose. Once labeled for use with radioactivity, equipment such as centrifuges, incubators, refrigerators, freezers, and so on, must remain labeled until specifically surveyed and released by Radiation Safety Office staff for non-radioactive use or disposal. The same applies to tools, glassware and other expendables, which may in the end need to be disposed of as radioactive waste.

9.6. Eating, Drinking and Related Activities in Laboratories

Eating, drinking, smoking, gum chewing, the application of cosmetics, the storage of food and beverages or similar activities are not permitted in laboratories or other facilities where hazardous materials are used, handled or stored. Such activities are permitted only in “break areas” (defined as a room with floor to ceiling walls and a closed door) separated from the laboratory space. If a break room can only be accessed by going through the laboratory, then only covered food or beverage items may be carried through the laboratory. Food or beverage containers may not be stored in the laboratory and washed drinking cups, food containers or eating utensils may not be dried on laboratory drying racks. Refrigerators used for storing food or beverages should be dedicated to food only and should be located outside of the laboratory.
9.7. Personnel Monitoring

Personnel body dosimeters are provided to individuals conservatively evaluated by Radiation Safety as likely to incur more than 100 mrem of "deep" dose per year due to external radiation sources (the 100 mrem per year criterion represents 20% of the level at which the NRC requires the provision of body dosimeters). Similarly, individuals who are expected to handle PET isotopes or more than certain activities, for example, more than 100 mCi per year or more than a few mCi at a time of $^{32}$P, are provided ring radiation dosimeters. If you are provided radiation dosimeters, it is very important that you wear them as intended and return them promptly to Radiation Safety for processing.

9.8. Prenatal Monitoring

All radiation workers should be aware and understand the special precautions concerning exposure during pregnancy, especially that the dose equivalent to the embryo or fetus from occupational exposure of a declared pregnant woman should not exceed 0.5 rem (500 mrem) total, or 0.05 rem (50 mrem) in any month and the reasons for it. Pregnant women exposed to ionizing radiation are encouraged to declare their pregnancy, in writing and in confidence, to the Radiation Safety Officer (WUSM Box 8053), so that the above limits may be applied. For questions, the Radiation Safety Officer can be reached at 362-2988. Supplementary monthly "fetal' dosimeters will be provided after the formal declaration of pregnancy, for the remaining duration of the pregnancy, if the expected annual body dose is more than 10% of the above limits, or upon request.

9.9. ALARA Program

The Nuclear Regulatory Commission expects licensees to take the necessary measures to maintain personnel doses and environmental releases of radioactive materials as low as reasonably achievable. The phrase "as low as reasonably achievable" is the basis of the acronym ALARA. The NRC has issued regulatory guides containing information relevant to ensuring that radiation doses at institutions will be as low as reasonably achievable. Many of the recommendations are incorporated as license conditions and are implemented in the institutional radiation safety program.

All reported external doses and all measured bioassay values are reviewed for unusually high levels. A member of the Radiation Safety staff investigates significantly elevated external doses or internal contamination levels, makes recommendations of how to prevent recurrences and reports the investigations to the Radiation Safety Committee. In addition, periodic reviews of environmental releases, that is, releases of
materials to the sanitary sewers and releases of airborne activity to the atmosphere, are conducted to document that ALARA goals are being accomplished.

9.10. Procurement of Radioactive Material

The acquisition of radioactive material is controlled by requiring all purchases to be routed through the Radiation Safety Office, with a few specifically approved exceptions.

9.10.1. Central Receiving of Packages of Radioactive Materials

All incoming packages of radioactive materials intended for research use, with a few exceptions, are delivered to the Radiation Safety Office. Each package is examined and surveyed by Radiation Safety staff to fulfill certain NRC requirements, and is then delivered to the location specified when the order was placed. The Radiation Safety staff member who delivers the package is required to obtain the signature of the person accepting the package, on our delivery list.

Each package is accompanied by a Radioactive Shipment Receipt Report, commonly called the “yellow sheet” (see Figure 1). This form documents the receipt and use of the radioactive material, and is retained by the laboratory in its radiation safety records “forever”. When the package is delivered to the lab, the top two sections of the yellow sheet will have been filled in.

9.10.2. Radioactive Materials Package Inspection/Survey

A final visual inspection and radiation survey of each package of radioactive materials is required and must be documented by a laboratory radiation worker when the package is received. The required actions, documented in the third section (see Figure 1) of the Radioactive Shipment Receipt Report form (“yellow sheet”) that accompanies each package, include (a) verification that the material (according to the label and packing slip) is what was ordered and arrived undamaged, (b) performance of a survey instrument reading and wipe test on the packing materials before they are properly disposed of and (c) wipe test of the received stock vial if exposure rates allow, (d) the signature of the person conducting the inspection and survey, and the date.

9.10.3. Radioactive Materials Accountability

A record or log of the receipt, use, transfer and disposal of all radioactive material must be kept for each lot or container of material. The Accountability Form is the bottom portion of the Radioactive Shipment Receipt Report form (“yellow sheet”) that accompanies each package. Entries are made on the Accountability Form as the radioactive material is removed from the vial. It is to be kept up to date at all times, and
**Figure 1. “Yellow Sheet”**

Radiation Safety Exam Study Guide  
For Users of Radioactive Material  
February, 2022
signed to document final disposal of the vial. The "yellow sheet" is to be retained in the laboratory radiation records until the laboratory closes ("forever"). At that time, the laboratory radiation records are transferred to Radiation Safety for storage.

9.11. Bioassays

Individuals handling certain levels of radioactivity must be monitored for internal contamination using a bioassay measurement. The bioassay tests we use are urine sample analysis and external monitoring of the thyroid.

The external monitoring thyroid bioassay is required of individuals who handle more than 1.0 mCi of unsealed or unencapsulated radioiodine at any one time and the tests are performed quarterly by Radiation Safety staff. The cause of radioiodine contamination is investigated if the "action level" of 30 nCi (nanocuries) for $^{125}\text{I}$ and $^{131}\text{I}$ is exceeded.

Urine bioassay samples may be required to be collected and submitted within 72 hours after radioactive material use, for individuals who handle relatively large amounts of other radionuclides in unsealed form. Urine bioassay containers and instructions are included with the radioactive material delivery when such bioassay may be needed. Radiation Safety staff analyze the bioassay samples by liquid scintillation counting.

9.12. Sealed Sources

Sealed sources are sources of radioactive materials that are encapsulated to prevent accidental spread of the radionuclide. The sources must be (a) used in accordance with the instructions provided by the supplier, (b) periodically tested by Radiation Safety staff for evidence of contamination, if necessary, (c) appropriately labeled, (d) secured against theft or unauthorized removal and (e) never altered in any physical way, for example, bent, opened, cut, etc.


Radioactive materials, sealed or unsealed, must be kept secure against theft or unauthorized removal. The NRC requires us not to leave radioactive materials unattended, even for brief periods of time, unless secured against theft. When all personnel leave a laboratory in which radioactive materials are present, the materials must be either secured in a locked, non-removable storage container or the laboratory must be locked.

Fume hoods used in conjunction with volatile radioactive material are tested annually and must have an adequate air flow at the sill opening height used while working with the material.

9.15. Survey Instrument Calibration

Portable survey instruments, for example, Geiger Mueller (GM) survey meters, are calibrated annually, and are tested against a reference source of radiation by Radiation Safety staff during every compliance inspection of the laboratory.

9.16. Periodic Radiation Surveys

Periodic radiation surveys must be conducted and documented by a laboratory radiation worker in all areas in which unsealed radioactive materials are approved for use or storage. The surveys are conducted once a week or once a month depending on quantities used in single operations. Each survey could include a test for removable contamination, the so-called "wipe test", and a survey instrument reading of the exposure rate level (mR/hr), depending on the kinds of isotopes present in the lab.

The wipe test consists of wiping a surface with a piece of filter paper or cotton swab and then assaying the removed radioactivity. The criterion for acceptable removable activity is 200 disintegrations per minute per 100 square centimeters of surface tested, that is, 200 dpm per 100 cm² (200 dpm/100 cm²). If the assay indicates removable activity in excess of the 200 dpm/100 cm² level, the area must be cleaned and re-tested until the removable level is acceptable. A record of each survey and of any corrective actions taken when excessive levels are identified must be made. A typical wipe test survey of a laboratory consists of about 10-20 wipes of areas commonly contaminated when unsealed radioactive materials are used, for example, bench tops, the floor, door knobs, telephones, desks, sinks, the front of fume hoods, etc.

9.17. Radioactive Waste

Radioactive waste must be segregated according to waste category, safely stored and periodically transferred to Radiation Safety staff for disposal. An exception is the drain release of water soluble low-level activities. These in-the-lab drain disposals must have prior Radiation Safety approval, be less than specified limits, be recorded and reported quarterly to Radiation Safety.
9.18. **Radiation Emergencies**

The most common radiation emergency involves handling a spill of radioactive material. Each laboratory is expected to be able to respond to and clean up most minor spills, and is required to have decontamination supplies on hand. Guidance is provided on a chart “Instructions Regarding Accidents Involving Radioactive Material”, posted in all areas where unsealed radioactive materials are used or stored (see Figure 2).

The “Instructions Regarding Accidents Involving Radioactive Material” (a) describe the immediate actions to be taken in order to prevent further contamination of personnel and work areas, (b) specify the names and telephone numbers of the responsible persons to be notified in case of an emergency, (c) describe appropriate methods for decontaminating areas and (d) provide basic guidance for personnel decontamination. You should be familiar with these emergency instructions.

9.19. **Annual Inventory**

An annual inventory that specifies the on-hand activity of each radionuclide in the possession of each Authorized User must be prepared and submitted to Radiation Safety staff upon request.

9.20. **Laboratory Inspections**

Radiation Safety staff conduct routine compliance inspections of all research and laboratory medicine areas in which radioactive materials could be used or stored. These inspections vary in frequency from quarterly to annually depending upon the isotopes used, the amounts used, how they are used, and the inspection history of the laboratory. The inspectors monitor the laboratory practices involving the use of radioactive materials and report the findings of each inspection to the responsible Authorized User(s) and/or designated Lab Contact(s).

9.21. **Laboratory Decommissioning**

Radiation Safety must be notified well in advance of the move or closure of a laboratory. Normally the Radiation Safety inspector who serves the lab is notified when planning begins if you will discontinue the use of radioactive materials in one or more areas, either permanently or even temporarily, so the required closeout inspections and surveys can be conducted by Radiation Safety staff. Similarly, notifications must be made prior to any construction, renovation or repair of a radioactive materials area or any disposal, repair or transfer of a piece of equipment formerly used with radioactive material or that contains a radioactive source.
# INSTRUCTIONS REGARDING ACCIDENTS INVOLVING RADIOACTIVE MATERIAL

## MINOR SPILLS

<table>
<thead>
<tr>
<th>Activity</th>
<th>Activity</th>
<th>Activity</th>
<th>Activity</th>
<th>Activity</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 - C</td>
<td>1,000</td>
<td>125 - I</td>
<td>10</td>
<td>32 - P</td>
<td>100</td>
</tr>
<tr>
<td>45 - Ca</td>
<td>100</td>
<td>131 - I</td>
<td>10</td>
<td>33 - P</td>
<td>1,000</td>
</tr>
<tr>
<td>51 - Cr</td>
<td>1,000</td>
<td>22 - Na</td>
<td>10</td>
<td>35 - S</td>
<td>1,000</td>
</tr>
<tr>
<td>3 - H</td>
<td>1,000, except for nucleotides</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**NOTIFY**
Inform persons in the area that a spill has occurred.

**PREVENT SPREAD**
Cover the spill with absorbent pads or other absorbent material.

**IDENTIFY THE AREA**
Mark off the contaminated area with chalk, marker, tape, etc.

**RESTRICT TRAFFIC**
Limit access to the area to those assisting in the cleanup. Do not allow anyone to leave the area without first being monitored to be sure they are not contaminated.

**DECONTAMINATE**
Start the cleanup as soon as possible. Use disposable gloves and, if available, long-handled tongs. Begin at the periphery of the area and work inward, systematically reducing the contaminated area. Carefully insert the absorbent material into a plastic bag and dispose as dry radioactive waste. Dispose of other contaminated items, e.g., gloves, similarly.

**SURVEY**
Use a thin-window survey meter and/or do wipe tests to monitor the effectiveness of the procedure, including the clothing and shoes of personnel in the area. Continue decontamination until the residual surface activity is less than the action level assigned for this area.

**DOCUMENT**
Record details of the spill and of the subsequent decontamination efforts and file with the survey records of the laboratory. If you have any questions, call RADIATION SAFETY @ 362-3476.

## MAJOR SPILLS

Activities **GREATER** than those specified above for MINOR SPILLS

**CLEAR THE AREA**
Inform all persons not involved in the spill to vacate the area.

**PREVENT SPREAD**
Cover the spill with absorbent pads or paper, but do not attempt to clean it up. Request potentially contaminated personnel to remain in a designated area immediately outside the room.

**SECURE THE AREA**
Leave the room and lock the door[s]. Notify the security office for your building and request assistance in restricting access to the area if needed.

**NOTIFY**
Report the incident to the authorized user responsible for this laboratory. Notify RADIATION SAFETY @ 362-3476. If the call is during "off hours," i.e., evenings and weekends, the call to 362-3476 will give you the option of directly paging Radiation Safety personnel for help. If assistance cannot be obtained proceed with the cleanup using the instructions described above for a minor spill.

**DECONTAMINATE PERSONNEL**
Remove contaminated clothing, place in a plastic bag and retain for Radiation Safety to evaluate.

## PERSONNEL CONTAMINATION

**WASH**
Flush contaminated skin with lukewarm water and then wash with mild soap. Be careful to avoid irritation of the skin. Do not use abrasives, highly alkaline soaps or organic solvents. Wash contaminated area 2-3 minutes being careful not to spread contamination. If contamination is extensive, promptly shower.

**RINSE**
Thoroughly rinse with lukewarm water.

**MONITOR**
Test the effectiveness of the procedure using a survey meter, if applicable.

**REPEAT**
Repeat procedure 3-4 times, using a soft brush if necessary, being careful to avoid irritation of the skin. If the radiation level is still excessive (> 0.1 mR/hr @ 2 cm), call RADIATION SAFETY @ 362-3476.

**PROTECT SKIN**
Apply lanolin or other hand cream to prevent chapping.

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Figure 2. “Spill Poster”

The Manual for Use of Radioactive Materials details the radiation safety program for using radioactive materials in research and laboratory medicine at Washington University and the affiliated institutions of the Medical Center.

10. OBLIGATIONS AND RIGHTS OF PERSONNEL HANDLING RADIOACTIVE MATERIALS

10.1. Obligations

According to the NRC, persons working under the supervision of faculty approved to use radioactive materials (the NRC refers to these individuals as Authorized Users) must (a) follow the safety instructions of the Authorized User, (b) obey the applicable requirements of the NRC and (c) report unsafe conditions to their supervisor(s).

10.2. Rights

Federal law prohibits an employer from firing or otherwise discriminating against any employee for reporting a safety concern. You should feel free to contact the Radiation Safety staff concerning any specific concerns you may have or with any questions about radioactive materials or radiation safety by calling 362-3476.

Persons who use radioactive materials in their work have the right to examine certain documents. These documents include (a) the current regulations of the NRC, (b) the license that authorizes the use of radioactive materials at our institution, (c) the operating procedures applicable to licensed activities, (d) any notices of violations involving working conditions, any proposed imposition of a civil penalty, or any order issued by the Commission and (e) any responses from our institution addressing violations or orders issued by the NRC. Access to these documents, which are maintained at the Radiation Safety Office, can be obtained by calling 362-3476.

In addition, each worker who has been (a) monitored for external exposure or (b) checked for internal contamination, has the right to obtain a copy of their external exposure and bioassay records that are maintained by the Radiation Safety staff. These records may be obtained by submitting your request to Radiation Safety, Campus Box 8053 or Radiation Safety, 660 S. Euclid Avenue, St. Louis, MO 63110 whether you are still employed by our institution or not.
11. EXISTENCE AND ROLE OF REGULATORY AGENCIES

The radioactive materials used at our institution are under the authority of a federal agency, the Nuclear Regulatory Commission (NRC). Congress determined in 1946 that the processing and utilization of source material (natural uranium and thorium), special nuclear material (plutonium-239, uranium-233 or uranium enriched in U-233 or U-235) and byproduct material (radioisotopes produced during the operation of a nuclear reactor) must be regulated in the national interest, in order to provide for the common defense and security and to protect the health and safety of the public. The Atomic Energy Act of 1946, as amended by the Energy Reorganization Act of 1974, provides for a program of government control of the possession, use and production of atomic energy. This control is exercised by the NRC. The NRC licenses users, issues regulations, inspects licensees to determine compliance with Commission requirements and enforces the regulations.

Prior to 2005, the NRC did not have authority over naturally occurring and accelerator produced radionuclides, except for natural thorium and uranium. The use of these radioactive materials, referred to as NARM (naturally occurring and accelerator produced radioactive materials), at our institution was controlled by the State of Missouri. The Energy Policy Act of 2005 expanded the definition of “byproduct material” to include “any discrete source of Radium-226; any material that has been made radioactive by use of a particle accelerator; and any discrete source of naturally occurring radioactive material, other than source material, that the Commission determines would pose a threat similar to the threat posed by Radium-226...”. Subsequently, NRC now has regulatory authority over all radioactive materials in use at our institution.