LEARNING OBJECTIVES

1. Recognize the primary radiation standards bodies and their roles in establishing radiation protection requirements.
2. Identify how radiation protection standards are implemented at JLab.
3. Identify responsibilities of management, workers, RadCon, and ARMs in JLab's radiation protection program.
4. State the dose limits for the whole body, extremities, and lens of the eye.
5. Discuss emergency dose guidelines.
6. Differentiate between the units used for exposure, absorbed dose, and equivalent dose.
7. State the basic quantity of radioactivity. Convert units of activity.
8. Describe how radiation energy is deposited in material.
9. State the radiation weighting factors for alpha, beta, and gamma radiations and the range of W_R for neutron radiation.

STANDARDS, REGULATIONS, AND LIMITS

Definitions

For purposes of our discussion, the following definitions apply:

Standard - A practice recommended by a recognized consensus body, or a widely accepted “norm”.

Regulation - A specific set of instructions and requirements which must be demonstrably met by the regulated entity. Federal regulations are published in the Federal Register and become part of the Code of Federal Regulations (CFR). The limits and other requirements in regulations are usually based on published standards.

Order - Unique to DOE contractors, Orders are pseudo-regulatory requirements which are implemented to the extent agreed upon in the contract. If included in a contract, an Order caries regulatory weight, although enforcement is through a different pathway.

Limit - The maximum (or minimum) value allowed by a regulation for some measurable quantity - usually associated with personnel dose, releases to the environment, or radiation levels.

Bodies Involved in Development of Radiation Protection Standards and Regulations

International Standards

ICRP International Commission on Radiological Protection
ICRU International Commission on Radiation Units and Measurements
IAEA International Atomic Energy Agency

U.S. National Standards

NCRP National Council on Radiation Protection and Measurements
ANSI American National Standards Institute
HPS Health Physics Society

International Regulatory Agencies

IAEA

U.S. Regulatory Agencies

NRC Nuclear Regulatory Commission
EPA Environmental Protection Agency
DOE Department of Energy
DOT Department of Transportation
OSHA Occupational Safety and Health Administration

State Regulatory Agencies (VA)

DEQ Department of Environmental Quality
BRH Bureau of Radiological Health

Local Authorities

HRSD Hampton Roads Sanitation District

Recommendations and Limits Set by Various Bodies

ICRP

- All exposures = As Low As Reasonably Achievable (ALARA)
- Effective dose (whole body dose) = 5 rem/year
- Equivalent dose to lens of the eye = 15 rem/year
- Equivalent dose to individual organs (except lens of the eye) = 50 rem/year
- Planned special exposures = 2 x respective annual limit per event
= 5 x respective annual limit per lifetime
- Pregnant workers: limit work to conditions where it is unlikely that annual exposure will exceed 30% of annual limits.

NCRP

- All exposures = ALARA
- Effective dose equivalent = 5 rem/year
- Lifetime effective dose equivalent ≤ age in years x 10
- Dose equivalent to the lens of the eye = 15 rem/year
- Dose equivalent to individual organs (except lens of the eye) = 50 rem/year
- Planned special exposures = 10 rem effective dose equivalent/event; 1 event/lifetime.
- Dose equivalent to embryo-fetus = 0.5 rem; 0.05 rem/month

EPA

- All exposures = ALARA
- Effective dose equivalent = 5rem/year
- Dose equivalent to the lens of the eye = 15 rem/year
- Dose equivalent to individual organs (except lens of the eye) = 50 rem/year
- Dose equivalent to occupational workers under 18 years of age = 1/10 applicable limit for adults
- Dose equivalent to unborn child of declared pregnant worker = 0.5 rem/entire gestation period.

DOE Dose Limits

The goal of any program of radiation safety is to reduce exposure, whether internal or external, to a minimum. The external exposure reduction and control measures available should be of significant interest to all ARMs, in that the ARM may often be the first person encountering a new or unusual radiological situation. Keeping ALARA in mind should guide you toward actions that help prevent personnel exposures from which no benefit is obtained.

Annual exposure standards for occupationally exposed workers:

- Whole body - 5 rem (0.05 Sievert)
- Lens of eye - 15 rem (0.15 Sievert)
- Any other organ - 50 rem (0.5 Sievert)

Limit for an unborn child - entire gestation period - 0.5 rem (0.005 Sievert).

Minors - An individual under the age of 18 shall neither be employed in, nor allowed to enter, Controlled Areas in such a manner that he or she exceeds 0.1 rem (0.001 Sievert) per year (includes exposure to students under 18).

Public entering a Controlled Area:

- Dose received during direct onsite access shall not exceed 0.1 rem (0.001 Sievert) per year.
- Exposures shall not cause dose to any tissue (organ) to exceed 5 rem (0.05 Sievert) per year.

Planned Special Exposures (PSEs):

- For planned special exposures (non-emergency) in highly unusual situations where alternatives are not available, the total dose received in any year from PSEs (together with any other non-routine exposure) may not exceed 5 rem.
- Planned exposures must be approved in writing by the applicable DOE program office and the Assistant Secretary for Environment, Safety and Health.

Emergency exposure during rescue and recovery activities:

- Actions should only be performed by volunteers.
- Each emergency worker shall be trained, and advised of the known or estimated risk prior to participation.
- No rigid upper dose limit for rescue and recovery, but individuals shall not be required to perform activities that involve “substantial personal risk”.
- The recovery of deceased victims shall be controlled within existing exposure limits, including the Planned Special Exposure provision.

DOE guidance on emergency dose is found in the Radiological Control Manual.

Table 1: DOE emergency dose limits.

Dose Limit	**Activity Performed**	**Conditions**
5 rem	All	Routine
10 rem	Protecting major property	Only on a voluntary basis where lower dose limits are not practicable
25 rad	Lifesaving or protection of large populations	Only on a voluntary basis where lower dose limits are not practicable
>25 rad	Lifesaving or protection of large populations	Only on a voluntary basis to personnel fully aware of the risks involved

Table 2: DOE dose limits and JLab administrative control levels.

Category	**DOE Dose Limit**	**JLab Action Level**
Occupational - Whole Body	5 rem	1 rem
Occupational - Lens of the Eye	15 rem	3 rem
Occupational - Skin and Other Organs	50 rem	10 rem
Occupational - Extremities	50 rem	10 rem
Occupational - Declared Pregnant	0.5 rem (duration)	*
Member of the Public	100 mrem	10 mrem

*The JLab RadCon Manual states that once a pregnant female radiological worker has notified her supervisor, or medical services in writing of her pregnancy, JLab management "...should provide the option of a mutually agreeable assignment of work tasks, with no loss of pay or promotional opportunity, such that further occupational radiation exposure is unlikely." This policy is in effect a "JLab action level" which serves the same purpose as the other action levels listed. Should the declared pregnant worker desire to continue work in a manner which may cause exposure, more frequent dosimeter processing (monthly) would be established and an administrative guideline approximately equal to the minimum sensitivity of the dosimeter would be used.

Note: Limits are based on the sum of internal and external exposure.

Implementation of Regulations, Orders and Standards

It is useful to look at the implementation of the various requirements as a hierarchy. This helps put in perspective the priority for compliance. We'll just look at the DOE related requirements.

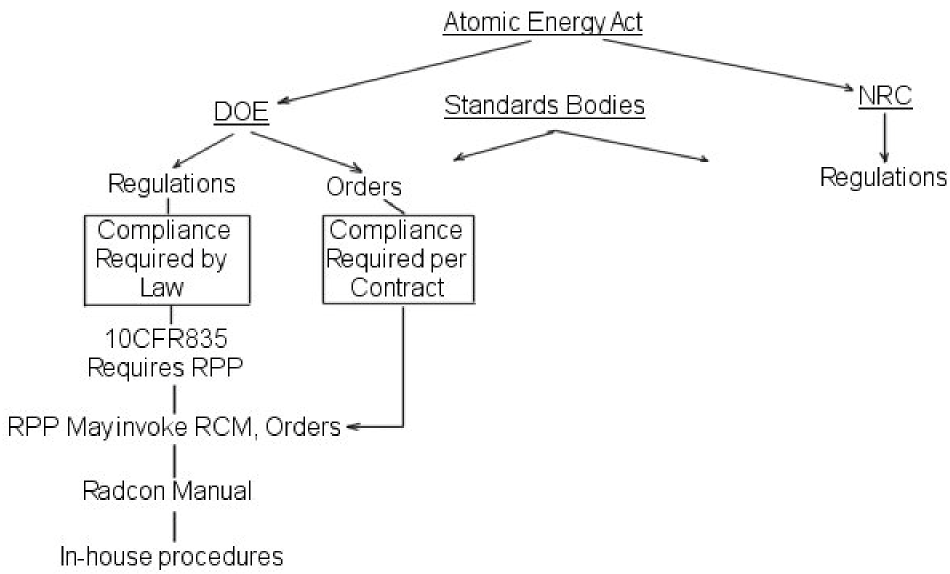


Figure 1: Hierarchy of regulatory requirements.

When the Atomic Energy Commission (AEC) was restructured into the DOE and NRC, each new entity was given authority to enact regulations appropriate to protect workers and the environment. The NRC promulgated its radiation protection requirements early on in 10CFR20. On January 1, 1996, the DOE enacted 10CFR835 - "Occupational Radiation Protection" - which, like 10CFR20, carries the force and effect of federal law. This regulation must be met and followed by all DOE contractor sites.

10CFR835 requires each facility to produce and operate in accordance with a documented Radiation Protection Program (RPP). The RPP is approved by DOE. At JLab, the RPP is a list of all the stated requirements in the CFR, along with a brief description of how we meet each requirement. If the RPP states that we meet a requirement through some provision of the Radiation Control Manual, that provision essentially becomes enforceable through reference as if it were part of the CFR. This same logic holds true for Orders or portions of Orders which we commit to through the RPP.

** A revision of 10CFR835 will go into effect in July of 2010. The main effect of the revision is to adopt a different set of dosimetric quantities and terms from the ICRP-60 standard. We will compare the old and the new quantities, and discuss some of the implications.

ARMs Duties and Relationship to RadCon

Assigned Radiation Monitors (ARMs) Duties

- Conduct and document routine radiation surveys and conduct non-routine surveys as requested by RadCon.
- Investigate the causes of radiation alarms.
- Correctly post Radiologically Controlled Areas and Radiation Areas on the basis of measurement.
- Promptly notify RadCon upon discovery of any un-posted High Radiation Area during a survey; secure the area to prevent access.
- Relocate CARM probes as requested by RadCon.
- Continuously monitor workplace activities for adherence to the RadCon Manual requirements.
- Monitor and control potentially radioactive components.

ARMs Relationship to Radiation Control Department (RadCon)

During the conduct of ARM duties, ARMs work for and are responsible to RadCon. When performing surveys or other radiation protection related work, the ARM's <u>number one priority</u> must be radiation safety. In effect, an ARM is a member of RadCon. To that extent, any abnormalities or difficulties encountered during the conduct of ARM duties should be reported to RadCon (and the Crew Chief). This includes anomalies noted during surveys, etc. and lack of support from line management in the conduct of duties. JLab senior management is holding laboratory staff, line management, and supervisors responsible for quality ESH&Q activity. Both acceptable and unacceptable conduct as an ARM may be reflected on job performance evaluations.

Tasks ARMs May Not Perform

ARMs Will Not:

- Free release any potentially radioactive component.
- Be a part of a work crew for any activity they monitor.
- Approve the release of water, other liquids or gases from potentially activated systems.
- Relocate RBMs, CARMs, or CARM probes; reset CARM trip levels; take failed CARMs or RBMs out of service; or modify CARMs or RBMs in any way without approval and specific instructions from RadCon.
- Evaluate sample analysis results, dosimetry results, or RBM data to determine compliance with state or federal requirements.
- Approve movement of radioactive material outside Radiologically Controlled Areas.
- Be responsible for posting, designating, or controlling access* to High or Very High Radiation Areas, Contamination Areas, or Airborne Radioactivity Areas.

*This means providing “coverage” or managing work/entry into the area. ARMs may act as a “guards” to temporarily prevent access to HRAs pending RadCon arrival, or in accordance with an RWP, from outside the HRA and in a fashion consistent with ALARA. Like all Radiation Workers, ARMs’ entry to or work in an HRA must be conducted in accordance with an RWP.

QUANTITIES AND UNITS

Radioactivity

Curie (Ci)- Originally, the Curie applied only to radium, being taken as the number of disintegrations per unit time occurring in one gram of pure radium. This unit was eventually standardized to any type of radioactive material and is defined numerically as 37 billion disintegrations per second (3.7×10^{10} dps). Equivalently, 1 Ci = 2.22×10^{12} dpm (disintegrations per minute). Subunits are usually used for the quantities of radionuclides found in the workplace (i.e. milli-, micro-, etc.).

The SI unit for activity is the ***Becquerel*** (Bq). 1 Bq = 1 dps.

Quantities of radioactive material in substances are usually given in µCi/g, pCi/l, etc. Air activity is usually reported in units of µCi/ml. For workplace measurement of surface contamination, dpm is often used to quantify radioactivity. Since instruments used to detect surface contamination usually read out in counts per minute (cpm), a simple conversion to dpm can be made by dividing the observed count rate by the counting efficiency of the instrument (count/dis). The activity stated in dpm can then be converted into Curies or Becquerels if desired.

Standard field contamination surveys are performed using filter wipes by "swiping" a surface approximately 100 cm^2 in area and using a "frisker" type instrument to obtain a count rate. Alternately, a direct frisk of the surface can be used where background radiation levels are low.

> <u>Example</u>
> A surface "swipe" of an item is counted on a frisker. The instrument has a background count rate of about 50 cpm. The total count rate of the sample + bkg is 200 cpm. What is the removable surface activity in dpm? In Ci, Bq? (Frisker efficiency is assumed to be approximately 10%.)

Exposure and Dose

The term "exposure" when used loosely means the condition of being exposed. However, when used as a unit, the term has a specific definition. ***Exposure*** is a measure of the ions produced, or ionizing ability of photons, and is quantified in units of charge liberation per volume or mass of air.

Roentgen (R)- The quantity of x or gamma radiation that will produce ions carrying one electrostatic unit (esu) of charge in 1 cubic centimeter of dry air under standard temperature and pressure conditions. In the SI system, exposure is measured in units of C/kg and there is no special unit.

1 R = 1 esu/cc
1 R = 2.58 E -4 C/kg

Exposure is a useful quantity because it can be directly measured (as charge or current flow). Exposure is limited in concept by several factors:

- it refers to photons only
- air is the only defined medium
- it is not defined at photon energies over 3 MeV

Absorbed Dose (D)- A measure of the energy imparted to matter by ionizing radiation per unit mass of the irradiated material.

rad (radiation absorbed dose):	1 rad = 100 ergs/gram
SI unit: ***Gray*** (Gy):	1 Gy = 1J/kg = 100 rad

Some features that distinguish absorbed dose:

- the quantity absorbed dose refers to all types of ionizing radiation
- the specification of D in any medium is appropriate
- the absorbed dose is a measure of the energy imparted, not charge produced

Equivalent Dose (H)- Laboratory and epidemiological observations have led to the conclusion that different types and/or energies of ionizing radiation can have differing biological effects in humans. To account and normalize for these differences the quantity H is used. Since equivalent dose is a measure of overall biological harm done, it is useful to think of it as a unit of relative risk for radiation exposure. Equivalent dose is not a physically measurable quantity - it is a *derived* quantity.

rem (Roentgen Equivalent Man)- The rem is historically defined as the amount of any type of ionizing radiation that would have the same biological effect as exposure to 1R of x or gamma radiation. Numerically, the rem is equal to the absorbed dose in rad times the radiation weighting factor (W_R).

$$H = DW_R$$

The SI unit for equivalent dose is the ***Sievert*** (Sv)

1 Sv = 1 J/kg = 100 rem

Note that the Sievert has the same dimensions as the Gray. However, it measures a different quantity.

The salient features of equivalent dose include:

- the equivalent dose is not a physical quantity, so it cannot be measured directly - it is derived from the measurement of one of the physical quantities (i.e. rad)
- the concept and quantity are useful for radiation protection work (i.e. risk management), not radiation physics
- the definition implies that the equivalent dose may vary depending on conditions of exposure, such as when the area of the body irradiated is not uniform (in this case, the concept of *effective dose* comes into play).

Radiation Weighting Factor (W_R)- This is a modifying factor used to calculate the equivalent dose from the average tissue or organ absorbed dose. The radiation weighting factors is used to relate absorbed dose from various types of radiation to the biological damage caused to the exposed tissue. The numerical value of W_R is based partly on the results of laboratory radiobiological experiments and partly on data from epidemiological studies. The final value of W_R is assigned to a particular radiation based on the available radiological data and other information related to the ionizing capability of the radiation.

Points to remember about W_R:

- W_R is for use in radiation protection work in deriving the relative risk from a given absorbed dose
- W_R is not an experimentally determined quantity, it is an assigned value
- W_R does not apply to acute exposures above about 10 rad

Table 3: Latest values for radiation weighting factors from ICRP 60 (previously Q)

Type and Energy Range	**Radiation Weighting Factor (W_R)**
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons, energy < 10 keV	5
10 keV to 100 keV	10
> 100 keV to 2 MeV/ unknown	20
> 2 MeV to 20 MeV	10
> 20 MeV	5
Protons, other than recoil, > 2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

It should be noted that an exposure of 1R in air causes an absorbed dose (in air) of about 0.87 rad. Moreover, that same exposure would cause an absorbed dose (on average) of 0.98 rad to soft tissue. In addition, the W_R for photon radiation is unity; therefore, for field measurements of roughly uniform, low dose rate photon radiation, it is acceptable to simply equate all three of the basic exposure/dose units.

For photon radiation:
1 R ≈ 1 rad ≈1 rem

Changes to dose quantities coming into usage in DOE
DOE has adopted the "protection quantities" from ICRP-60 (1990) for assessing and reporting individual doses (prior regulation was based on ICRP 26 (1977)). This implements two changes:

1) Protection quantities are not defined the same way as "operational quantities". The units of rem and rad are still being employed, but the concept of "equivalent dose" is replacing "dose equivalent". Imbedded in this change is the replacement of the quality factor with the "radiation weighting factor".
2) Radiation weighting factors are not the same as quality factors. This can potentially result in a factor of 2 difference for neutron dose in some situations.

For most this change will be completely transparent, other than the terminology change on their dose reports. However, these changes make for potential confusion in some radiation protection activities (wherever more than one regulatory agency is involved). For instance, the format is not consistent with what would be reported at an NRC-regulated facility.

Table 4: Comparison of old and new dosimetric terms.

Old Dosimetric Term	**New Dosimetric Term**
Committed effective dose equivalent	Committed effective dose
Committed dose equivalent	Committed equivalent dose
Cumulative total effective dose equivalent	Cumulative total effective dose
Dose equivalent	Equivalent dose
Effective dose equivalent	Effective dose
Quality factor	Radiation weighting factor
Weighting factor	Tissue weighting factor
Total effective dose equivalent	Total effective dose

Table 5: Comparison of dose depth terms.

Deleted Terms (not in ICRP 60/68)	**Replacement Terms (not added to definitions because meaning is clear)**	**Depth in Tissue (cm)**
Deep dose equivalent	Equivalent dose to the whole body	1.000
Shallow dose equivalent	Equivalent dose to the skin or an extremity	0.007
Lens of the eye dose equivalent	Equivalent dose to the lens of the eye	0.300

TYPES OF RADIATION, RADIOACTIVE DECAY, RADIATION INTERACTIONS

Types of Radiation

There are three common types of radiation emitted from the nucleus of radionuclides: alpha particle s, beta particles, and gamma-rays. Other radiation emissions occur as a result of high energy nuclear interactions. Also, extra-nuclear interactions (originating in the atomic electron cloud) can result in the emission of x-rays. All these radiations are collectively called ionizing radiation because they can cause the ionization of matter, they have/impart sufficient energy to produce ion pairs.

Alpha Particles - α

Alpha particles are equivalent to the nucleus of a helium atom. The alpha particle consists of 2 protons and 2 neutrons which are tightly bound together. An alpha particle has a +2 charge and a mass of 4 amu (atomic mass units).

Beta Particles - β

There are two kinds of beta particles:

1) ***Negatrons*** - β^-, e^-
The negatron is a negatively charged electron indistinguishable from the electron ordinarily found in matter.

2) ***Positrons*** - β^+, e^+
Positrons have the same mass as an electron but are positively charged.

Gamma Rays - γ

Gamma-rays are a type of electromagnetic radiation. They have no mass or charge and propagate at the speed of light.

Gamma-rays are similar to x-rays. The difference between gamma-rays and x-rays is their origin:

- gamma-rays originate in the nucleus of the atom.
- x-rays are generated within the electron orbitals of the atom.

Other Radiations

In addition to the three types of radiation listed above, there are a few radionuclides which emit either protons or neutrons.

Emission of protons is rare.

$$^{53m}Co \rightarrow {}^{52}Fe + \text{proton}$$

^{252}Cf undergoes spontaneous fission.
Although this is fission rather than radioactive decay it is an example of a release of neutrons.

Some nuclides undergo non-fission neutron emission, but their half-lives are so short that they do not persist in nature. Some of them are formed during fission, and are important in the control of reactors (delayed neutrons). Isotopic neutron sources can be produced by taking advantage of nuclear interactions (e.g., (α, n) reactions).

Protons, neutrons and other particles can be produced in copious numbers in particle accelerators. We will discuss interactions relevant to JLab accelerators in the next section.

Modes of Decay

Radioactive nuclides decay by one of several modes. Each radionuclide has its own characteristic sequence of decay modes.

Alpha Decay

When an alpha particle is emitted during radioactive decay it may or may not be accompanied by a gamma-ray.

- Alpha decay does not occur in nuclei with $A \leq 140$.
- It is thought that all nuclei with $A > 140$ undergo alpha decay, but for some the decay rate is so slow that alpha particle emission has not been detected.
- Alpha decay schemes are usually complicated.
- During alpha decay, A decreases by 4 and Z decreases by 2.

Isobaric Decay

Isobaric decay does not lead to a change in A but it does cause a change in Z.
Gamma-ray emission may or may not accompany isobaric decay.

There are three common types of isobaric decay:

Negatron decay occurs when there is a high n/p ratio, so there is a transition of a nucleon from its neutron to its proton energy state and Z increases by one (an isobar is formed).

- The negatron is emitted at high velocities.
- An antineutrino is emitted simultaneously with the negatron.
- Commonly, excited states are formed after negatron emission. These excited states lose energy by gamma-ray emissions.

Positron decay occurs in nuclei with low n/p ratios.

- During positron emission, there is a transition of a nucleon from its proton to its neutron energy state
- Z decreases by one and an isobar is formed.
- The positron is emitted at high velocities.
- A neutrino is emitted simultaneously with the positron.
- In positron emission there is always a 1.022 MeV difference in the kinetic energy of the positrons and the Q value.
    - The reason is that the parent atom loses a positron in the nuclear transition and the daughter atom loses an electron to become electrically neutral since Z decreases by one.
    - An energy of 1.022 MeV is equivalent to the rest mass energy of an electron and a positron.
- Positron emission is common with accelerator produced radionuclides.

Electron capture (EC), sometimes known as K-capture, is an alternate mode of decay to positron emission.

- Electron capture occurs when there is a low n/p ratio.
- Electron capture decreases Z by one and results in isobar formation.
- During electron capture the nucleus captures an extranuclear electron, usually from the K-level.
  - In the nucleus, a nucleon is transformed from its proton to its neutron energy state.
  - The neutrino is the only radiation that is emitted from the nucleus (unless the daughter is formed in an excited state).
- The capture of an electron leaves a vacancy in the level from which the electron was captured.
  - This vacancy is filled by an electron from the next higher energy level.
  - This electron readjustment may produce a characteristic x-ray of the product nucleus.
  - Rather than an x-ray being emitted, the energy may be transferred to an electron at a higher energy level.
    - This electron is then emitted with an energy equal to the characteristic x-ray energy minus its own binding energy.
    - The electron emitted is called an Auger electron.

  Example: In the decay of Fe-55, x-rays and Auger electrons are the only radiations emitted from the atom, other than the neutrino. Had the daughter, Mn-55 been formed in an excited state, gamma-rays would be emitted. Auger electrons have such low energies that they are usually not detected by common radiation detectors. Neutrinos react poorly with matter. Consequently, only x-rays can be detected.

  Example: In Na-22 electron capture and positron emission occur together.

- Generally, the Q value for both positron emission and electron capture is listed as Q_{EC} in a decay scheme.
- If the Q value for a nuclide with a low n/p ratio is less than 1.022 MeV, only electron capture can occur.
- Above 1.022 MeV, positron emission competes with electron capture more effectively the higher the Q value.
- On the other hand, increases in atomic number favor electron capture. With high Z, positron emission is rare. The potential barrier against positron emission increases with Z. The reason is that with higher Z, electron orbits are smaller, and there is a greater probability for an electron to be within the nuclear volume.

Isomeric Decay

The overall process whereby an energetically excited nucleus releases energy without a change in the structure of the nucleus, just a decrease in the energy level of the nucleus, is known as isomeric transition.

During an isomeric transition there is no change in A or Z. The nucleus goes from an excited energy state to a lower energy state or a ground state.

The transitions between excited states of nuclei usually occur within a very short time, about 10^{-13} to 10^{-16} seconds.

- These transitions proceed in accordance with the exponential decay law and have a characteristic half-life.
- If these half-lives are measurable, the excited states are called isomers, or ***metastable isomers.***

There are two categories of isomeric transition:

- When the excited nucleus emits a gamma-ray and goes to a lower energy state or to a ground state this is called ***radiative transition***. This can be further sub-divided into two processes:
    - Gamma-ray emission is the emission of one photon from the nucleus.
    - When two gamma-rays are emitted within a very short period of time from the same radionuclide these are called cascade gamma-rays. These must be emitted from the same nuclide and there may be two or more.
- A second type of isomeric transition is called ***internal conversion***.
    - The nucleus interacts with an orbital electron (K level predominates).
    - The internal conversion electron is emitted with an energy equal to the disintegration energy minus its own binding energy.
    - Both x-ray and Auger electrons accompany internal conversion (produced in a manner identical to their production in electron capture).
    - The excited nucleus interacts electromagnetically with the electron. No gamma-ray is produced.
    - Internal conversion is an alternate to radiative transition and frequently a nuclide decays by both gamma-ray emission and internal conversion (i.e. Cs-137/Ba-137m).
    - Internal conversion is favored by high atomic number and by low Q values.

Other Modes of Decay

- Proton emission (very rare)
- Spontaneous fission (this process occurs only with very heavy elements).
    - Delayed neutron emission occurs with nuclides with a high n/p ratio.
    - Several neutrons are emitted promptly, these are referred to as prompt neutrons.
    - Other neutrons are emitted in a very short time after fission and are referred to as a delayed neutron.

Interactions

Alpha Particle Interactions

Alphas interact by direct ionization/excitation (and in special cases by nuclear interaction). The highly charged alpha particle loses energy through Coulombic interactions in matter. Because of the high charge, it will interact with a high *specific ionization,* causing it to lose all its energy in a very short path length. The maximum range in air is several centimeters. The maximum range in tissue is less than 100 microns. Alphas are easily shielded by air, paper, clothing, or the dead layer of outer skin on the body (about 70 microns thick).

Beta Particle Interactions

Beta particles interact through direct ionization/excitation by charge interactions in matter, but the specific ionization is much lower than for alpha particles; hence, their range is greater. It is relatively easy to shield typical beta particles of moderate (~ MeV) energy. Good shields are low density materials such as Lucite and aluminum. The range of beta particles in air is about 3 m/MeV. Energetic betas may penetrate tissue to the depth of the lens of the eye (3mm) or further in some cases. Dose to the skin is the primary concern. (Beta particles >~ 2 MeV can reach the "deep dose" depth).

Beta particles (electrons) also interact by the Bremsstrahlung process. ***Bremsstrahlung*** is the emission of a photon (X-ray) by a charged particle when the particle encounters the dense electrical field in the vicinity of a nucleus as it traverses matter. This interaction "deflects" the path of the particle, drastically changing its momentum. In order to conserve momentum, a photon containing the balance of energy lost by the particle is emitted.

Bremsstrahlung production varies directly with both the Z of the material and the energy of the particle. For beta particles of 1MeV, only about 3% of the energy is converted to Bremsstrahlung in lead. In the case of high energy electrons, however, very intense Bremsstrahlung fields are created by the interaction of the electrons with matter. For medium Z materials, this radiative energy loss mechanism dominates the interactions above 50 MeV. Although Bremsstrahlung is possible with any charged particle, it is significant only with electrons (beta particles) due to their small mass.

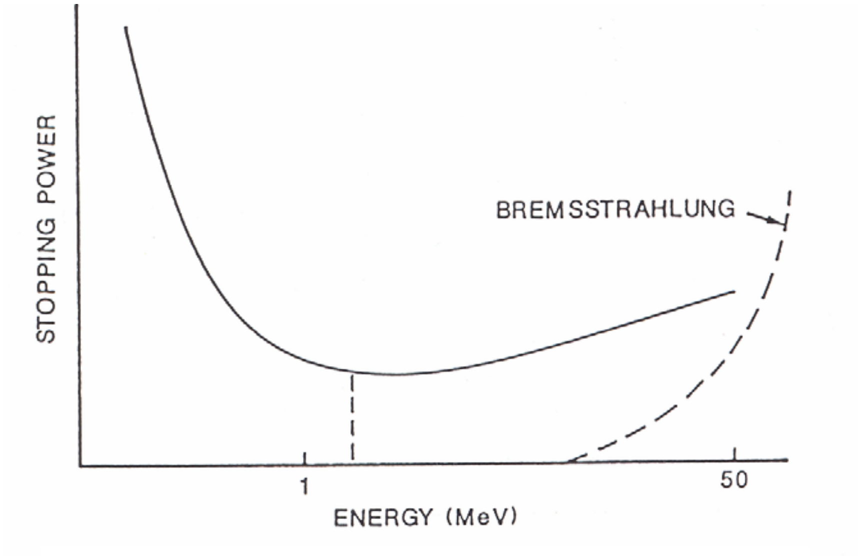


Figure 2: General shape of the beta stopping power curve.

At electron accelerators, bremsstrahlung radiation is the most important radiation emission process, as it produces a significant primary photon field, and initiates essentially all other radiation/radioactivity production mechanisms.

Photon Interactions

The three main types of interactions with matter for photons are: Photoelectric Absorption, Compton Scattering and Pair Production. At high energies (above ~ 10 MeV in most materials), photonuclear interactions begin to occur.

Photoelectric Absorption (Effect)

In the photoelectric effect, the photon transfers all of its energy to an orbital electron. In the process, the original photon disappears, and its energy is transferred to the electron as kinetic energy. The electron is elevated to a higher energy level and is ejected from its orbit, carrying the full photon energy (minus the binding energy). The resulting *photoelectron* can then go on to ionize other atoms. The photoelectric effect is important for photon energies < 1 MeV.

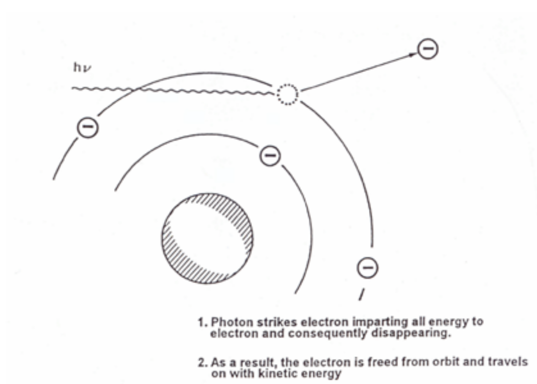


Figure 3: Pictorial representation of the photoelectric effect.

Compton Scattering

In Compton scattering, the photon can be thought of as scattering off of an electron, giving up a portion of its energy to it and continuing on with a lower energy. The electron moves away with the remaining portion of kinetic energy. More accurately, it is an absorption-re-emission process where the re-emitted photon and electron share the initial photon's energy. Compton scattering is important for photon energies between 200 keV and 5 MeV and predominates in most photon interactions in common materials.

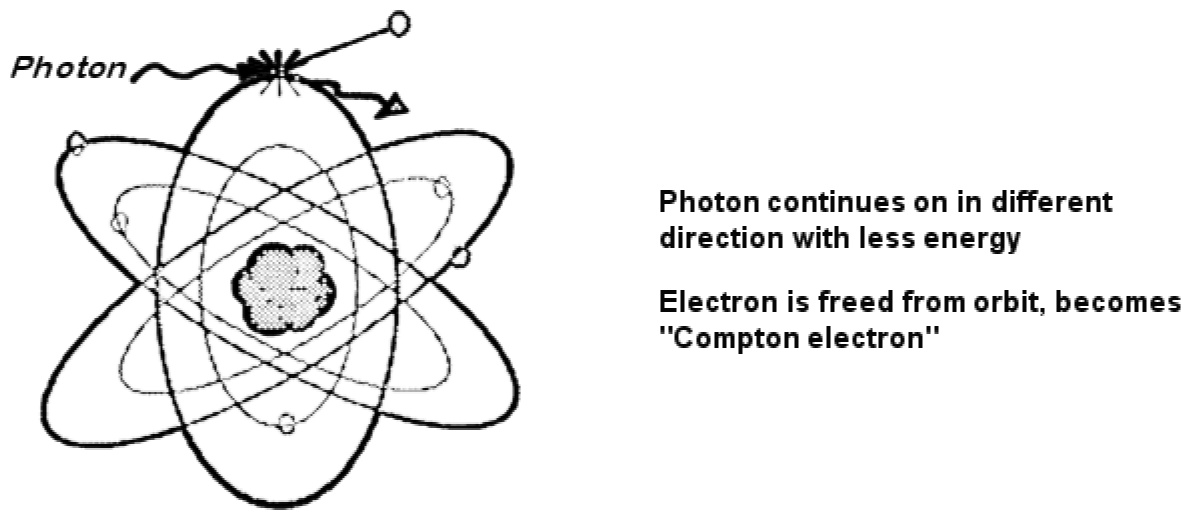


Figure 4: Pictorial representation of the Compton effect.

Pair Production

In pair production, a photon of sufficient energy gives up all its energy near the nucleus of an atom to form a *positron-electron pair*. Since the rest mass of an electron is 0.511 MeV, the formation of the pair requires a theoretical minimum photon energy of 1.022 MeV. However, the process does not become important until about 5 MeV, where it begins to dominate gamma interactions. In the process, the initial photon is eliminated, giving up its energy in excess of the threshold energy to the pair as kinetic energy (with a small amount given to the nucleus to conserve momentum).

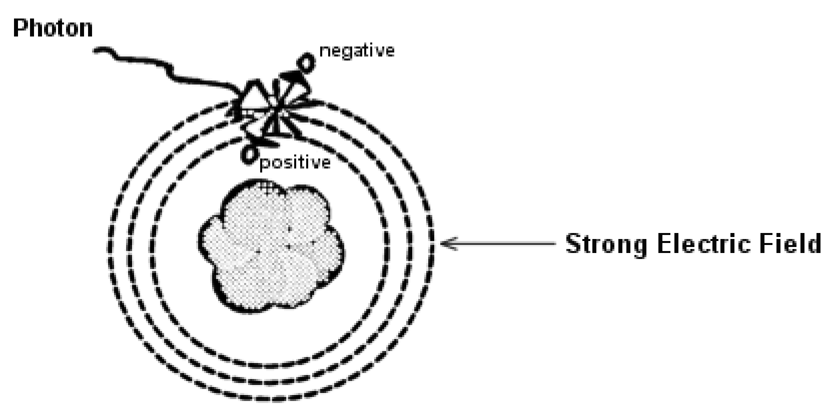


Figure 5: Pictorial representation of the pair production effect.

Photonuclear Interactions

When photon energy is above about 10 MeV, *photonuclear* interactions (such as γ-n) become an important interaction mechanism. The primary importance of these interactions at JLab is that they result in (1) a significant neutron flux being generated where beam interacts with matter, and (2) the production of *activation products* or radionuclides as a result of the nuclear disruption caused in the target nuclei.

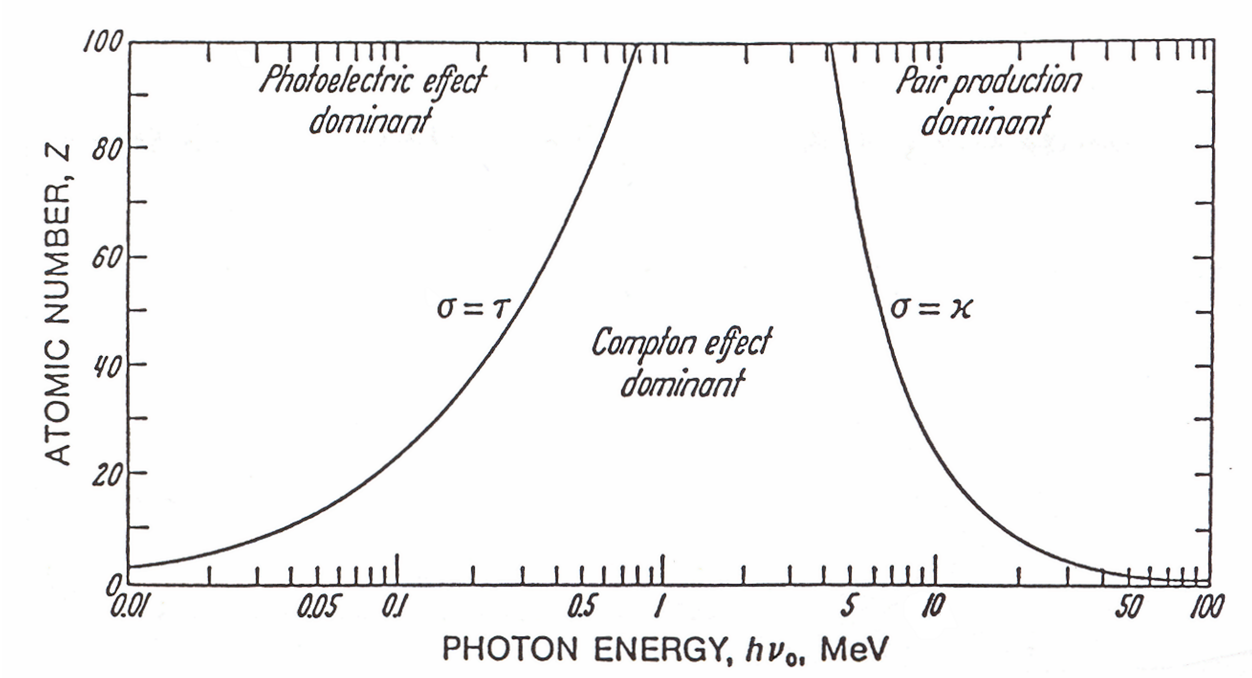


Figure 6: Effect of atomic number of target and photon energy on photon interaction mechanism.

Neutron Interactions

Neutrons are described in terms of broad energy range values such as *thermal*, *intermediate*, and *fast*. Neutrons do not interact directly with orbital electrons and hence are not directly ionizing. However, they undergo a variety of interactions which cause secondary ionizing events to occur. The interactions are generally classified under the broad classifications of Radiative Capture, Elastic Scattering, and Inelastic Scattering.

Neutron capture is dominant in the thermal energy range and also occurs at some intermediate energies. The result of the capture of the neutron is an excited nucleus which then emits a gamma-ray or charged particle. This secondary particle/photon causes the ionization in the material. For dose to tissue, the (n,γ) reaction in ^{1}H is an important contributor to dose. During the absorption process, a 2.23 MeV gamma-ray is emitted. The nucleus is changed to ^{2}H in the process. The absorption process is responsible for most *neutron* activation.

Elastic Scattering is a type of interaction in which kinetic energy is conserved. These interactions can be thought of as "billiard ball" collisions. Elastic scattering is important in fast and intermediate energy neutron interactions. The energy transfer in elastic collisions is greatest when the target nucleus has a mass close to that of the neutron (i.e., hydrogen). When energy loss is high, the result is greater attenuation of the neutron field. This is why hydrogenous materials such as water and polyethylene are commonly used as neutron shielding. By following up with a neutron absorbing material, an effective shield would first slow and then capture the neutrons.

Inelastic Scattering occurs in neutron interactions beginning with intermediate and going on to very high energy. In inelastic scattering, the scattering event itself does not appear to conserve momentum. Several types of inelastic events may take place - in most events the neutron is pictured as momentarily being absorbed by the nucleus, and then re-emitted with a lower energy. The nucleus is left in an excited state and then returns to the ground state by emission of a photon. For very high energy neutrons, inelastic scattering and other nuclear interactions (e.g., spallation) become dominant.

Thermal	~ < 0.5 eV*
Intermediate	~ 0.5 eV - 10 keV
Fast	~ 10 keV - 10 MeV
Relativistic	~ > 10 MeV

*Nominal energy for thermal neutron is 0.025 eV

References for Unit 1

1. *Radiological Safety Aspects of the Operation of Electron Linear Accelerators*, Swanson, IAEA Publication 188, 1979.
2. *Operational Health Physics Training*, Moe, ANL-88-26, 1988.
3. *The Health Physics and Radiological Health Handbook*, Shleien, 1992.
4. JLab Radiological Control Manual, May 24, 1999.
5. DOE Standardized Training for Radiological Control Technologists.
6. 10CFR835, Occupational Radiation Protection.

LEARNING OBJECTIVES

1. Describe prompt radiation production from electron beams.
2. Describe the characteristics of activation products at electron accelerators.
3. Characterize the relative amounts of exposure from various source terms at JLab.
4. Describe ancillary sources of radiation at JLab.
5. Describe the stochastic risk model and its inference regarding chronic exposure.
6. Differentiate deterministic risks from stochastic risks.
7. State the ALARA concept and its implementing tools.

SOURCE TERMS AT JLab

The phrase ***source term*** is used to describe the combination of various factors and conditions - from radiation production to physical locations, shielding, etc. - which result in personnel radiation exposure.

Accelerator sources can be split into two broad categories. These are direct or ***prompt*** radiation, and activation or ***residual*** activity.

Prompt Radiation

Photons

The dominant prompt radiation from electron beams of any energy is photon radiation**.** The initiating events are Bremsstrahlung interactions which cause a broad spectrum of x-rays to be produced up to nearly the initial electron energy. An electron may undergo multiple Bremsstrahlung interactions. At higher energies, when the photons produced exceed the pair production threshold, a secondary source of high energy electrons (the electron-positron pair) and photons (the annihilation radiation) are generated. In turn, these electrons and photons contribute to further electron-photon production through the Bremsstrahlung/pair-production process.

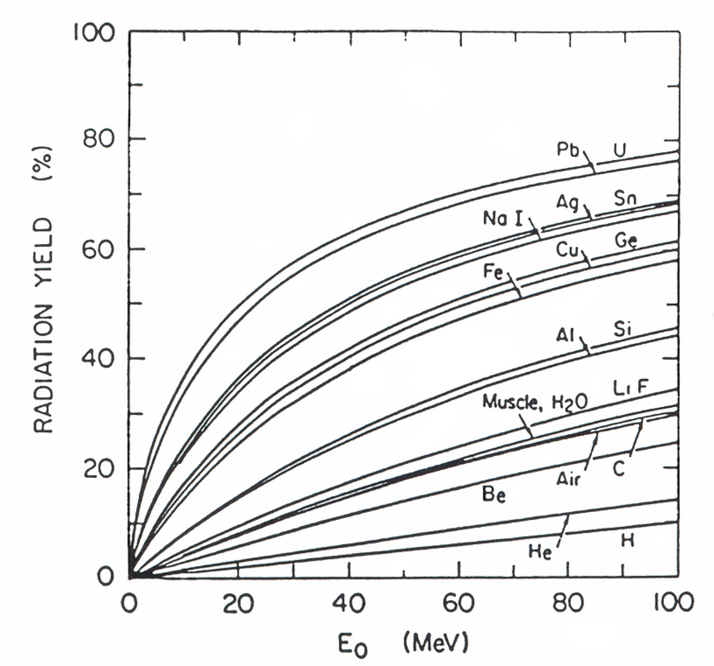


Figure 7: Photon yield as a function of photon energy in various materials.

This cascade of photons and particles is often referred to as an ***electron-gamma shower*** or ***electromagnetic cascade***. This shower propagates to some maximum depth (dependant on the material), where energy loss ceases to be dominated by radiative mechanisms, at which point the shower falls off. The external photon radiation emitted from some target will at first increase with the target thickness, reach a broad maximum, and then decline approximately exponentially. A target of the thickness which causes the maximum radiation is known as an "optimum" target. The radiation produced by such a target and all related references are described by the term "thick target".

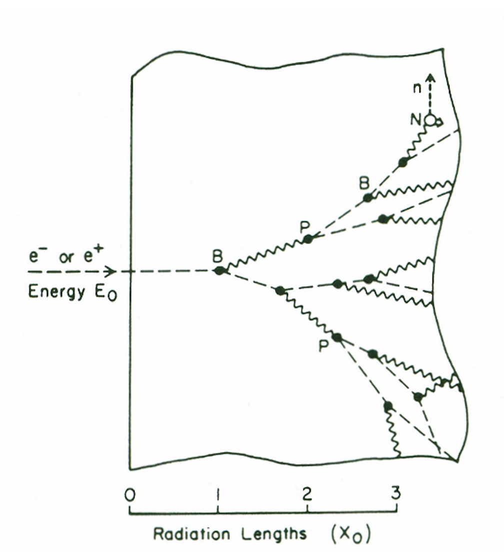


Figure 8: Representation of an electron-gamma shower.

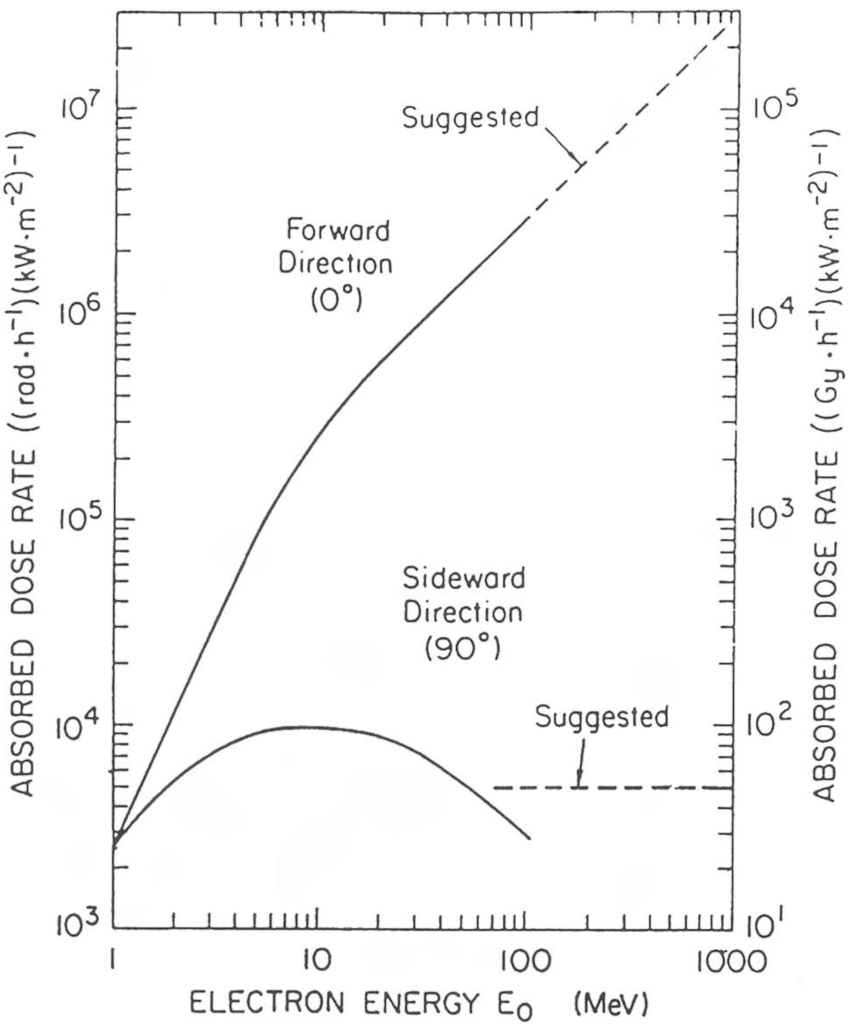


Figure 9: Thick target Bremsstrahlung.

Rule of Thumb, where E_o> 20 MeV:

For 0^o Bremsstrahlung: Dose rate at one meter (rad/min/kW) ≈ 500 E_o

For 90^o Bremsstrahlung: Dose rate at one meter (rad/min/kW) ≈ 83

Neutrons

Neutrons represent the second major source of prompt radiation at electron accelerators. Above a threshold energy (generally, about 10 MeV), neutron radiation will be produced by any material struck by the electron or photon beam. In effect, the gamma shower which occurs at lower energy is modified to become a "neutron/gamma shower" at energies above the neutron production threshold. It is of note that the neutron production from the photons is many orders of magnitude greater than from electrons for thick targets. In very thin targets, electron production of neutrons may dominate. It is the release (and to a lesser degree, the subsequent capture) of neutrons which produces the radionuclides found in accelerator components.

There are three main neutron production mechanisms. They are characterized by the energy ranges in which each dominates.

- ***The Giant Photonuclear Resonance*** - Between a threshold energy and about 35 MeV, giant resonance neutrons predominate. The process can be pictured as the transfer of energy from the electric field of the photon to the nucleus by the induction of an oscillation in which the protons as a group move oppositely to the neutrons as a group. One or more neutrons may be ejected as a result of the oscillation.

- ***The Quasi-Deuteron Effect*** - Above the giant resonance peak (30-40 MeV), the quasi-deuteron effect begins to dominate neutron production. This effect is thought of as an interaction between the photon and a neutron-proton pair within the nucleus; hence the name "quasi-deuteron". The production cross section for QD is about an order of magnitude below the giant resonance. This combination serves to add a high energy "tail" to the giant resonance neutrons.

- ***Photo-pion Production*** - Above 140 MeV, pi mesons become a source of high energy neutrons. Although the cross section for producing these neutrons is much smaller than that of the giant resonance, the neutrons produced are much more penetrating, and (for high energy machines) make the largest contribution to neutron dose rates outside the shielded enclosure.

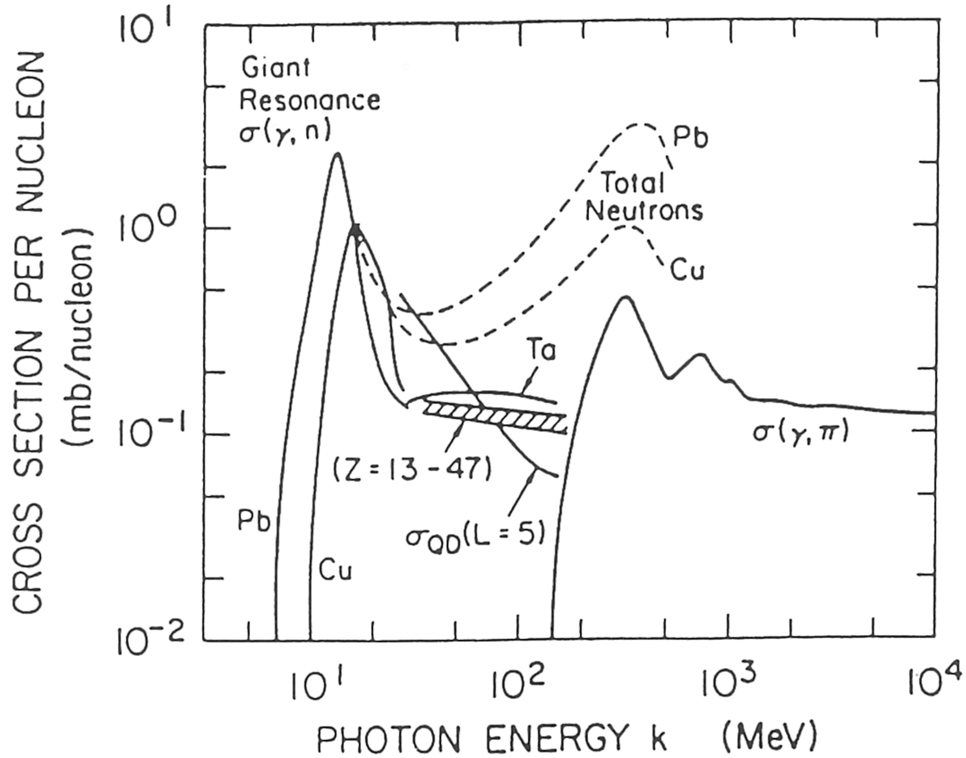


Figure 10: Neutron production cross sections.

Residual Radioactivity

In addition to direct radiation, many of the interactions just described give rise to induced radioactivity in accelerator components. The process is often referred to as "activation".

The activated materials can be broadly classified as ***photo-activation*** products and ***neutron-activation*** products.

Photo-activation

Photo-activation is caused mainly by:

- Loss of neutrons from giant resonance and quasi-deuteron interactions (γ,n), (γ, np), etc.
- High energy photo-spallation (γ, sp)

Components located close to the beam path are the most susceptible to photo-activation. The highest energy photons are produced in a forward directed beam. Objects in close proximity to the beam line are most susceptible to this beam. Components typically subject to photo-activation include:

- Dumps
- Targets
- Collimators
- Magnets
- Any narrow beam aperture (e.g., extraction septa)
- Any point of beam scraping or loss
- Dump cooling water

Photo-activated materials tend to:

- be neutron deficient
- have "short" half-lives (months)
- build up relatively quickly (as a function of their half-life)
- decay by positron or electron capture modes
    - positrons always result in photon (annihilation) radiation
    - electron capture decay has no charged particle emission (gamma only)

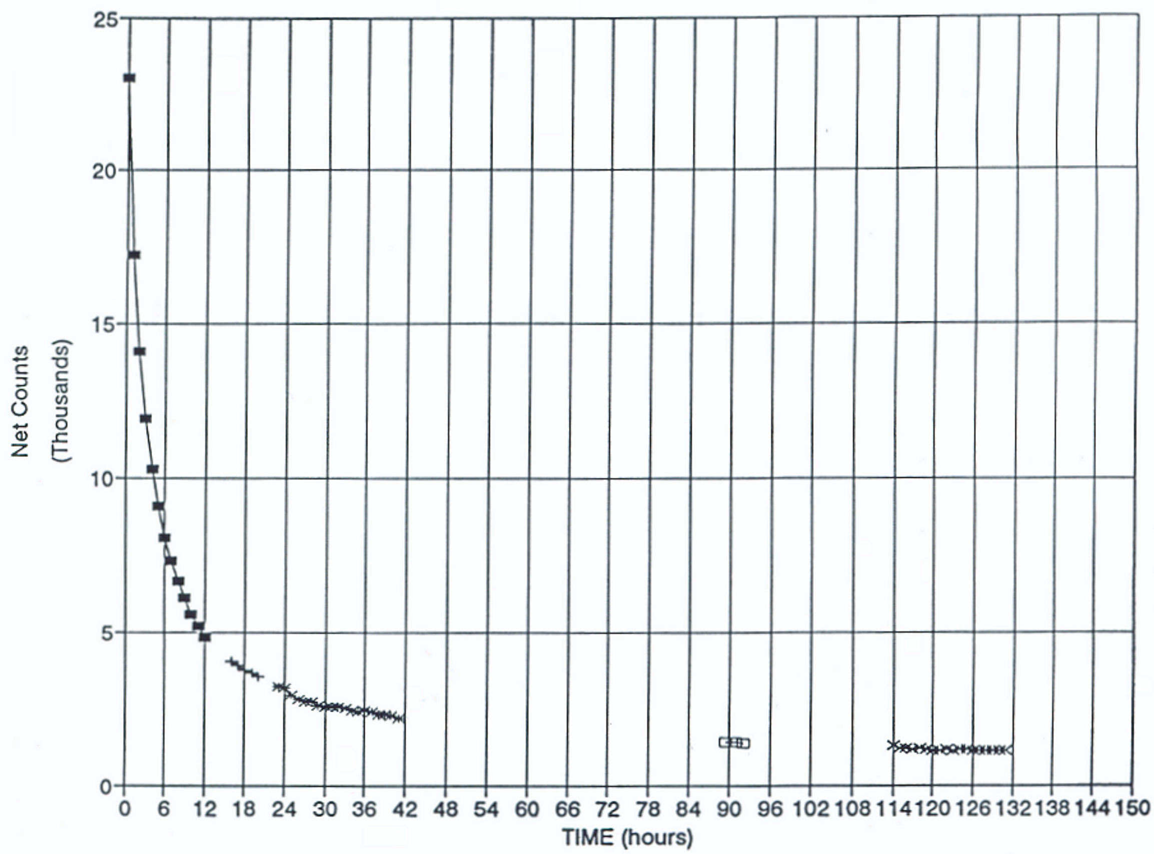


Figure 11: Decay for a sample of activated material removed from the CEBAF beam line. Most of the components in the material had half-lives on the order of days to months.

Neutron Activation

Neutron activation can occur from high energy neutron spallation or by the capture of neutrons which have been moderated to low energies.

Since this activation occurs in materials subjected to a nearly isotropic neutron flux rather than a directional high energy photon beam, items subject to neutron activation are not as restricted to near-beam line items as in the case of photo-activation products. Any material in a beam enclosure, including the structure itself, may be subject to neutron activation. The specific activity of this material tends to be much lower than for photon activation products.

In contrast to photo-activation, neutron activated materials tend to:

- be neutron rich
- have long half-lives (months to years)
- build up relatively slowly
- decay by beta emission
    - beta emitters often emit gamma radiation also

It is important to remember that activation can occur in any material subjected to the accelerator's activating primary radiation field. Materials, other than the more obvious beam line components, which may become activated include lubricants, cooling water, and air that are contained in spaces within the beam enclosure. Electronic components may be activated and/or damaged by the radiation flux. Lead used to shield dumps or experimental setups may become activated. Closed cooling systems associated with beam dumps are subject to a buildup of activation products that can present a radiation and contamination hazard during maintenance activities on these systems.

The main source of personnel radiation exposure at JLab during normal operation will be exposure to activation products during maintenance in the beam enclosure or on activated cooling water systems.

Table 6: Radionuclides detected in steel shielding.

TABLE XXVIIIb. RADIONUCLIDES DETECTED IN STEEL SHIELDING (special units)

Nuclide	Half-life	Specific activity (t = 0) [a] ($\mu Ci \cdot g^{-1}$)	Γ [b] Specific gamma-ray constant ($(R \cdot h^{-1})(Ci \cdot m^{-2})^{-1}$)	Specific exposure rate [c] ($(\mu R \cdot h^{-1})(g \cdot m^{-2})^{-1}$)
Mn-56	2.576 h	130.	0.86	111
Cr-51	27.8 d	16.	0.76	12
Mn-52	5.60 d	7.5	2.18	16
Mn-54	303 d	5.2	1.20	6.1
V-48	16 d	3.1	1.95	6.0
Fe-59	45.6 d	1.6	0.62	1.0
Sc-44m	2.44 d	1.0	1.47 [d]	1.5 [d]
Sc-46	83.9 d	0.35	1.09	0.37
K-43	22.4 h	0.21	0.57	0.12
Cr-48	23 h	0.19	0.97	0.18
Sc-48	1.83 d	0.17	1.78	0.30
Co-58	71.3 d	0.11	1.13	0.12
Co-60	5.263 a	0.060	1.30	0.077
Co-57	270 d	0.050	1.29	0.064

[a] At time of accelerator turnoff, t = 0.
[b] See Footnote 14 (Section 2.6).
[c] Exposure rate at 1 m, per g of activated steel, at time of accelerator turnoff. Uncorrected for self-shielding and distribution of activity.
[d] Includes Sc-44 daughter radiations.

Table 7: Photo-activation products from ^{16}O in water.

TABLE XXXIIb. PHOTOACTIVATION PRODUCTS FROM O-16 IN WATER (special units)

Nuclide	$T_{\frac{1}{2}}$		MPC_w [a] ($\mu Ci \cdot cm^{-3}$)	Γ [b] Specific gamma-ray constant ($(R \cdot h^{-1})(Ci \cdot m^{-2})^{-1}$)	Reaction type	Threshold (MeV)	Cross-section [c] σ_{-2} ($\mu b \cdot MeV^{-1}$)	A_s [c,d] Saturation activity ($Ci \cdot kW^{-1}$)
O-15	123	s		0.59 (β^+)	(γ,n)	15.67	75	9
O-14	70.91	s	–	1.60 (β^+)	(γ,2n)	28.89	(1)	(0.1)
N-13	9.96	min	–	0.59 (β^+)	(γ,2np)	25.02	0.9	0.1
C-11	20.34	min	–	0.59 (β^+)	(γ,3n2p)	25.88	3	0.4
C-10	19.48	s	–	1.01 (β^+)	(γ,4n2p)	38.10	(1)	(0.1)
Be-7	53.6	d	0.02	0.029 –	(γ,5n4p)	31.86	0.3	0.04
H-3	12.262	a	0.03	– (β^-)	(γ,H-3)	25.02	1.5	0.2

[a] ICRP recommendation for the general public, 168-hour week occupancy. See test for discussion.
[b] See Footnote 14 (Section 2.6).
[c] Values in parentheses are rough estimates.
[d] Saturation activity in water per unit electron beam power. Assume 100% direct absorption of electron beam power in water. Activity in water will be less in most situations where the beam absorber is water-cooled metal. Values shown are obtained directly from Approximation A and apply at high energies. For $E_0 \gtrsim 50$ MeV, the value for O-15 may be reduced by a factor of two, and others by an even larger factor.

Residual Contamination

Loose surface contamination can be caused by activation of:

- surface coatings - dust, paint, rust, or oxidation (even on stainless steel)
- sealants, grease, anti-seize compounds
- cooling water - photo-activation products cause high dose rates during operation. Activation of impurities in the systems is a long term contamination hazard
  - highest concentrations found in filter and resin media
  - "crud traps" accumulate contamination over the long-term
- air in the beam enclosure - particulate activation products may build up on surfaces or be concentrated in air handling and filtering systems

Because of the nature of these materials, they may not be accessible until maintenance or disassembly of the components and systems. Therefore, maintenance on items where contamination potentially exists requires RadCon surveillance.

Table 8: Activity induced in air.

TABLE XXXb. ACTIVITY INDUCED IN AIR (special units)

Produced nuclide			Parent nuclide				Cross-section[b]	A_s[c]
Nuclide	$T_{\frac{1}{2}}$	MPC (μCi·cm^{-3})	f Abundance[a]	Nuclide	Reaction type	Threshold (MeV)	$\Sigma f\sigma_{-2}$ (μb·MeV^{-1})	Saturation activity (μCi·m^{-1}·kW^{-1})
H-3	12.262 a	2×10^{-3} d	1.562 0.424	N-14 O-16	(γ,H-3)	22.73 25.02	(3)	(140)
Be-7[f]	53.6 d	1×10^{-6} d	1.562 0.424	N-14 O-16	(γ,sp)[f]	27.81 31.86	(0.6)	(30)[f]
C-11	20.34 min	3×10^{-6} e	1.5×10^{-4}	C-12	(γ,n)	18.72	0.011	0.5
			1.562 0.424	N-14 O-16	(γ,sp)[f]	22.73 25.88	(6)	(300)[f]
N-13	9.96 min	2×10^{-6} e	1.562	N-14	(γ,n)	10.55	310	14000
O-15	123 s	2×10^{-6} e	0.424	O-16	(γ,n)	15.67	32	1500
N-16	7.14 s	5×10^{-7} e	4.0×10^{-4}	O-18	(γ,np)	21.81	(0.01)	(0.5)
Cl-38	37.29 min	2×10^{-6} d	4.6×10^{-3}	Ar-40	(γ,np)	20.59	0.13	6
Cl-39	55.5 min	3×10^{-6} d	4.6×10^{-3}	Ar-40	(γ,p)	12.52	0.86	40
Ar-41[g]	1.83 h	2×10^{-6} e	4.6×10^{-3}	Ar-40	(n,γ)	–	–	–[g]

[a] Fraction of air by volume, multiplied by atoms/molecule.
[b] Abundance f times integral cross-section σ_{-2}. (See Eq.(8) of Section 2.2). Values in parentheses are rough estimates.
[c] Per bremsstrahlung pathlength in air (metres) and electron beam power (kW) incident on a thick high-Z target. Values in parentheses are rough estimates.
[d] Based on ICRP recommendation for radiation workers, 40-hour week, exposure from inhalation.
[e] Based on ICRP recommendation for radiation workers, 40-hour week, semi-infinite cloud (see text).
[f] Spallation reaction.
[g] Neutron-capture reaction. Occurs where high neutron fluences are moderated by water or concrete shielding.

Volume activated material normally does not present a loose contamination hazard except during activities such as:

- machining
- grinding
- burning/welding

Generally, where contact dose rates do not exceed a few millirem per hour, contamination from these activities is unlikely; however ARMs are not authorized to allow these activities on any activated material.

Where contamination is not likely, surveys may be limited to radiation dose rate surveys only. The activated materials are controlled based on external radiation levels.

Other Sources of Radiation

Muons

A few other sources and types of radiation bear mentioning. Along with the types of prompt radiations already mentioned, mu mesons may be part of the beam-generated flux emanating from targets and stops. Muons are charged particles similar to electrons but about 200 times more massive. Muons become a significant portion of the primary radiation beam only at energies above 1 GeV. This muon beam is very collimated in the forward direction. Some muons may be produced outside the end station shielding from the decay of pions. Muons interact only by ionization/excitation (they are too heavy to undergo Bremsstrahlung), and consequently have very long path lengths.

Non-Accelerator Sources

The most common non-accelerator sources of radiation are small isotopic sources or x-ray generators used in experimental detector setups and for instrument calibrations and checks. These sources are controlled by a source custodian. RadCon maintains custodianship of most sources and operates a system of source checkout to approved source users. Source users must:

- ensure the source tracking form is posted prominently in the vicinity of use
- ensure the sources are used in accordance with applicable restrictions
- return the source to locked storage when not in use, or ensure the source is installed in a configuration approved for long-term use

Radiation Generating Devices which can produce measurable external radiation fields must be used under the auspices of RadCon as delineated in a Radiation Control Operating Procedure or other safety procedure which addresses radiation safety requirements such as an OSP which has been reviewed by RadCon.

- EEL building
  - Source lab
  - Portable x-ray tubes
- Test lab
  - Vertical Test Area
  - Cryo-test cave
  - Injector test cave
- FEL
  - GTS
  - X-tech solid state X-Ray generator
- Portable X-Ray generating devices
  - Hand-held XRF gun

Klystrons produce x-rays (from Bremsstrahlung) when operating; however, the klystrons used in the CEBAF accelerator are self-shielded by design and operate at relatively low voltages. Klystrons used in the FEL require external shielding and may require area postings. Test Lab RF operations may also employ klystrons requiring local shielding and other controls. Any maintenance which disturbs the installed shielding or experimental work with these devices, or new designs and design changes should be brought to the attention of RadCon for evaluation.

In general, any device combining high voltage (>10 kV) and a vacuum is a potential x-ray hazard and should have a hazard analysis done prior to use.

RISK AND ALARA

Definitions

Somatic effect - Any effect which occurs in an exposed person.

Heritable effect (genetic) - Any effect which occurs in the offspring of exposed individuals (but does not include teratogenic effects). Such effects arise from changes in chromosomes in the sperm/ovary.

Teratogenic effect (pre-natal) - An effect which is caused by an exposure received *in-utero.*

Acute dose- A relatively large dose of radiation (for whole body dose, generally > 10 rad) in a short period (hours to days).

Chronic dose - A long-term or protracted exposure to radiation where the dose is relatively evenly distributed and received in small increments.

Stochastic - A dose-response relationship (risk model) in which the *probability of occurrence* of some effect is seen to increase with dose.

Deterministic - A dose-response relationship in which the *severity of the effect* increases with dose.

<u>Exposure/Risk Relationship</u>

The relationship between risk and exposure mode (acute or chronic) can be placed in a simplified matrix.

	Risk for Deterministic Effects?	Risk for Stochastic Effects?
Can acute dose cause -	Yes - Thresholds appear at various levels for different effects. Classified as "early" somatic effects.	Yes - Probability of occurrence varies in ~ linear manner with dose. Classified as "latent" effects.
Can chronic dose cause -	Some - A few deterministic effects can occur with long term exposure <u>IF</u> dose exceeds the threshold for the effect.	Yes – but occurrence is not measurable at occupational doses. Probability for occurrence is extrapolation from high doses.

		Therapeutic Range – 1 to 10 Sv			Lethal Range – Over 10 Sv	
Range:	Subclinical 0 to 1 Sv	1 to 2 Sv	2 to 6 Sv	6 to 10 Sv	10 to 50 Sv	Over 50 Sv
Incidence of Vomiting:	None	1 Sv: 5% 2 Sv: 50%	3 Sv: 100%	100%	100%	100%
Delay Time:	-	3 Hours	2 Hours	1 Hour	30 min	30min
Leading Organ:	None	Hematopoietic Tissue			G.I.Tract	Central Nervous System
Characteristic Signs:	None	Moderate Leukopenia	Severe Leukopenia, Hemorrhage, Infection, Purpura, Epilation Above 3 Sv		Diarrhea, Fever, Disturbance of Electrolyte Balance	Convulsions, Tremor, Ataxia, Lethargy
Critical Period Post-Exposure:	-	-	4-6 Weeks		5 to 14 Days	1 to 48 Hours
Therapy:	Reassurance	Reassurance, Hematologic Surveillance	Blood Transfusions, Antibiotics	Consider Bone-Marrow Transplantation	Maintenance of Electrolytic Balance	Sedatives
Prognosis:	Excellent	Excellent	Good Therapy Effective	Guarded Therapy Promising	Hopeless Therapy Palliative	
Convalescent Period:	-	Several Weeks	1 to 12 Months	Long	-	
Incidence of Death:	-	None	0 to 80% (Variable)	80 to 100% (Variable)	90 to 100%	
Death Occurs Within:	-	-	2 Months		2 Weeks	2 Days
Cause of Death:	-	-	Hemorrhage, Infection		Circulatory Failure	Respiratory Failure Brain Edema

Summary of Clinical Effects of Acute Ionizing Radiation Doses.[9]

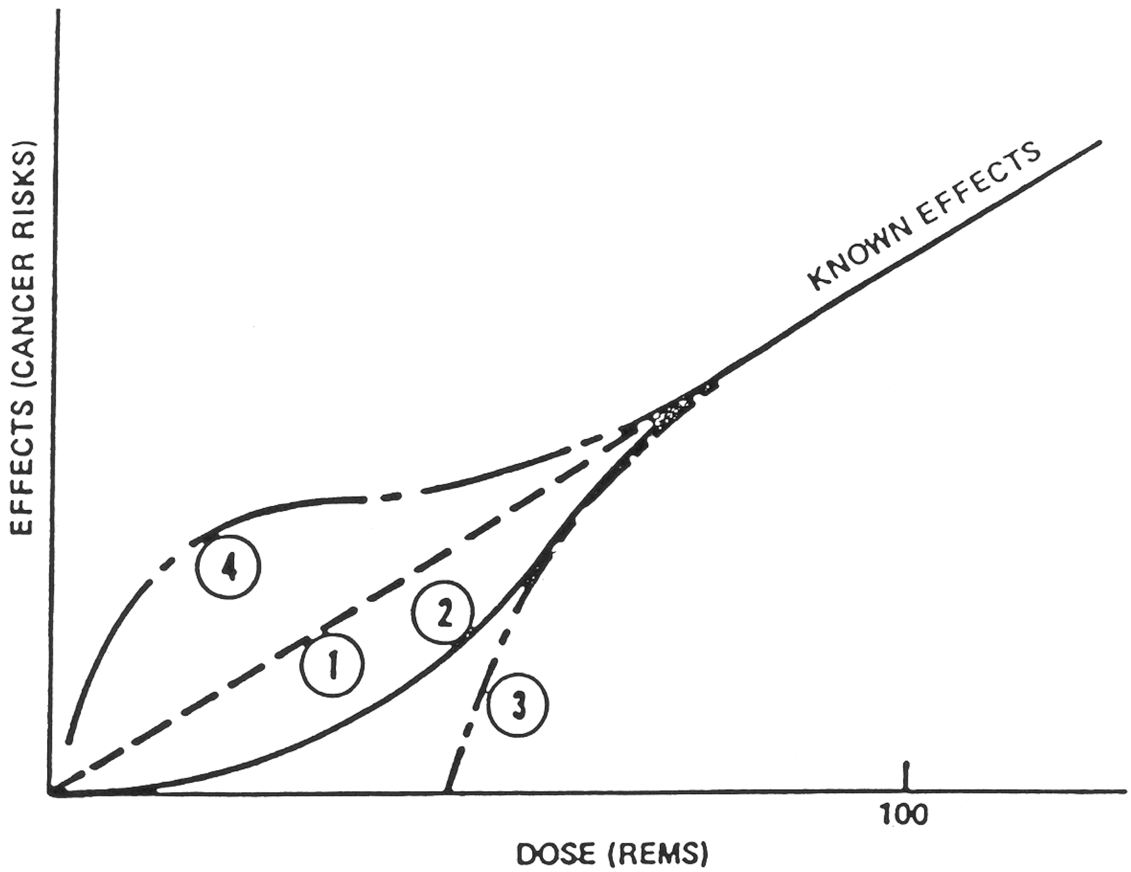


Figure 122: Dose-effect relationships: (1) linear-no-threshold, (2) linear-quadratic, (3) threshold, (4) supralinear.

Points to remember about latent risk estimates:

- Damage is known to occur, but is repaired, preventing prompt observable effects
- Risk for latent injury appears to be stochastic
- No threshold for risk is known, but background occurrence rates, low probability, and individual differences in response make finding a threshold impossible; therefore:
    - Risk is assumed to be non-threshold
    - Probability is simplified to a linear model (but is linear-quadratic)
    - Risk for cancer is ~ 4 per 10,000 person-rem (based on occurrence at high dose)
    - Risk for genetic effects is significantly lower - not demonstrated measurably in any exposed <u>human</u> populations

ALARA

The ALARA concept grows out of our assumption that any radiation exposure carries with it some risk. ALARA itself is the effort to maintain both individual and collective dose As Low As is Reasonably Achievable, taking into account the net benefit obtained as a result of the exposure. A fundamental principle underlying the ALARA concept and radiation control at JLab is that *"There should not be any occupational exposure of workers to ionizing radiation without the expectation of an overall benefit from the activity causing the exposure."*

Implementing ALARA at JLab

The Radiological Control Department is responsible for:

- Implementing radiological requirements, limits, guidelines, and procedures.
- Monitoring radiological work in progress to ensure radiologically safe practices are used.
- Measuring, documenting, and tracking personnel exposures and environmental impact of radiological work.
- Evaluating radiological performance and advising JLab management in implementing improvements.

AS AN EXTENSION OF RADCON, THE ARM MUST ACCEPT AND CARRY OUT ALARA RESPONSIBILITIES BEYOND WHAT IS EXPECTED FROM OTHER RADIATION WORKERS.

The ARM is often the first person to encounter radiological conditions which might have changed or which exceed criteria for additional radiological controls. You are expected to:

- Recognize conditions which require controls beyond those present
- Anticipate the effect of planned activities within a radiological area
- Keep ALARA in mind when performing radiation-related tasks
- Advise others on the radiological conditions
- Stop or prevent work or access to areas which requires additional controls
- Notify RadCon when conditions require it or when ALARA is not being observed

Hazard Mitigation (ALARA)

Radiological controls are all implemented for the goal of dose reduction. As with any hazard identification/mitigation system, the ALARA principle is applied through a combination of engineered and administrative controls.

Engineered Controls

Engineered controls are the preferred method of implementing ALARA. Engineered controls consist of equipment designed to protect personnel from a hazard by preventing access to enclosures, and/or providing a warning of the hazard or a means to remove the hazard. These controls may be active or passive. Examples of engineered controls include:

- Shielding
- Ventilation
- Interlocks
- Containment

Administrative Controls

Engineered controls alone may not completely remove a hazard. Administrative controls are often used in minimizing dose during work where there is a relatively low radiation risk. Examples of administrative controls are:

- Configuration control (used in conjunction with engineered controls)
- Training
- Posting
- Work control documents
- PPE

Remember the basic ALARA elements of Time, Distance, and Shielding. These simple ideas can be used to implement safe work practices in the most complex radiological situations.

A few basic practices related to time, distance, and shielding are listed below. Sometimes obvious ALARA techniques are overlooked - take the time to think about them.

Time- Delay entry or activity in the area if practical. Don't use a radiological area as a short cut.

Distance- Don't sight-see. Stand as far as possible from a source and help others do the same.

Shielding- Never move shielding without contacting RadCon. Keep in mind that things such as earth or water can provide shielding. Leaking water shields may look OK but become ineffective.

References for Unit 2

1. *Radiological Safety Aspects of the Operation of Electron Linear Accelerators*,
2. Swanson, IAEA Publication 188, 1979.
3. *Operational Health Physics Training*, Moe, ANL-88-26, 1988.
4. *The Health Physics and Radiological Health Handbook*, Shleien, 1992.
5. JLab Radiological Control Manual, May 24, 1999
6. DOE Standardized Accelerator Training
7. *Risks Concerning Occupational Radiation Exposure*, Nuclear Regulatory Commission, Regulatory Guide 8.29. RADIATION DOSE LIMITS

LEARNING OBJECTIVES

1. Describe the basic operating principles of gas ionization detectors.
2. Describe the process involved in the detection of radiation using scintillation detectors.
3. Describe the process of neutron detection using moderated BF_3 proportional counters.
4. Relate the concept of detector resolving time to considerations employed during the use of portable survey instruments.
5. Describe the operation of CARMs and the function they serve related to radiation protection.
6. Identify the various primary and supplemental dosimeters used at JLab.
7. Identify the following features and specifications for the listed portable instruments:

INSTRUMENT	FEATURES
Bicron Micro-rem	Detector Type
"Teletector" Instruments	Operating Ranges
NP-2, NG-2 (Snoopy)	Detector Shielding/Window
"Frisker" Instruments	Types/Energy of Radiation Detected
	Location of Detector Center
	Specific Limitations/ Characteristics

8. Identify the factors which affect the selection of a portable survey instrument.
9. State the calibration frequency requirements for portable survey instruments.
10. Describe the pre-use checks that must be performed when using portable survey instrumentation.

GAS FILLED DETECTORS

Overview of Gas Filled Detectors

Basic Construction

Any contained gas volume which has a pair of electrodes can serve as a gas filled ionization detector. These detectors are usually cylindrical. The cylinder wall is used as one electrode and an axial wire mounted in the center is used as the other electrode. Insulators support the axial electrode. The size, shape, and configuration are a function of the desired detector characteristics.

The gas used in the detector can be almost any gaseous mixture which will support ionization, including air. Some detectors, particularly ionization chambers, use only air, while other detectors use gas mixtures that ionize more readily to obtain the desired detector response.

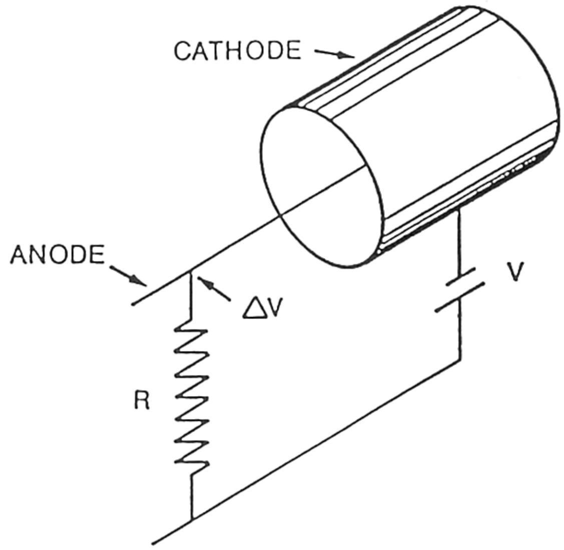


Figure 3: Two electrode, gas filled chamber.

For a gas filled ionization detector to be of value for radiological control purposes, the manner in which the response varies as a function of the energy, quantity, and type of radiation must be known. Factors such as the size and shape of the detector, the pressure and composition of the gas, the size of the voltage potential across the electrodes, the material of construction, the type of radiation, the quantity of radiation, and the energy of the radiation, can all affect the response of the detector. Detectors for a special purpose are designed to incorporate the optimum characteristics necessary to obtain the desired response.

Type and Energy of Radiation

Each type of radiation has a specific probability of interaction with the detector media. This probability varies with the energy of the incident radiation and the characteristics of the detector gas. The probability of interaction is expressed in terms of ***specific ionization*** with units of ion pairs per centimeter. A radiation with a high specific ionization, such as an alpha particle, will produce many more ion pairs than a radiation with a low specific ionization such as a gamma-ray. In the table below, note the magnitude of the difference between the specific ionization for the three types of radiation.

Table 9: Specific ionization in air at STP.

Radiation/energy	**Ion pairs/cm**
Alpha	
3MeV	55,000
6MeV	40,000
Beta	
0.5MeV	110
1MeV	92
3MeV	77
Gamma	
0.5MeV	0.6
1MeV	1.1
3MeV	2.5

Voltage Potential and Gas Amplification

Once the ion pair is created, it must be collected in order to produce an output pulse or current flow from the detector. If left undisturbed, the ion pairs will recombine, and not be collected. If an electric field is created in the detector by applying a voltage potential across the electrodes, the ion pairs will be accelerated towards the electrodes.

The stronger the field the stronger the acceleration. The accelerated ions may create secondary ionizations. The secondary ion pairs are accelerated towards the electrodes as well. Secondary ion pair collection results in a stronger pulse than would have been created by the ions from primary ionization.

If the applied voltage potential is varied from 0 to a high value, and the pulse size recorded, a response curve will be observed. For the purposes of discussion, this curve is broken into six regions. The ion chamber region, the proportional region, and the Geiger-Mueller region are useful for detector designs used in radiological control. Other regions are not useful. In the recombination region, the applied voltage is insufficient to collect all of the ion pairs before some of them recombine. In the limited proportional region, neither the output current nor the number of output pulses are proportional to the radiation level and calibration is impossible. In the continuous discharge region, the voltage is sufficient to cause arcing and breakdown of the detector gas.

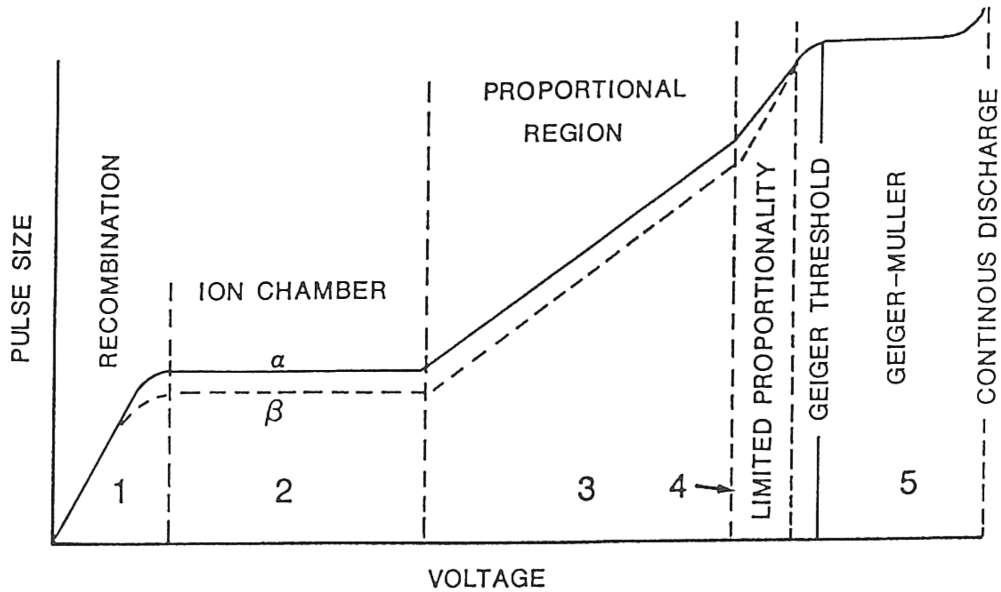


Figure 14: Pulse size as a function of bias voltage in an ionization chamber.

<u>Ion Chamber Detectors</u>

In the ion chamber region, there are an essentially equal number of ions collected as are created. No secondary ionization or gas amplification occurs. The output current of the detector will be proportional to the incident radiation intensity. Also, the output current will be relatively independent of small fluctuations in the power supply. An ion chamber is said to operate at "saturation", because of the unity gas amplification factor.

Advantages of Ion Chambers

- Relatively low operating voltage. DC voltage from a battery supply is sufficient. Relatively insensitive to voltage changes within the operating voltage range.
- Since the ion chamber measures primary ion current, its response is a measurement of exposure (exposure rate). Ion chamber instruments normally read in units of mR or R/hr. If measuring a typical gamma radiation field, this translates into a reasonably accurate absorbed dose rate for tissue (recalling the conversion of R to rad), and hence to equivalent dose.

Disadvantages of Ion Chambers

- Detector output current is small. Independent current pulses large enough to measure are not formed by each ionizing event. Instead, the total current output created by many ionizing events is measured. Therefore, the sensitivity of a small ion chamber is very poor because a few ionizing events per minute do not create sufficient currents to be measured. A typical commercial portable ion chamber has a detector which produces a current of about 2 E-14 amps per mR/hr.
- Very high impedance circuits are used (approximately 1 E15 ohms) to measure the small output currents.
- Ion chamber instruments are sensitive to humidity, temperature, and barometric pressure.
  - Humidity creates current leakage which causes erroneous instrument response.

- Changes in barometric pressure (or altitude) and/or ambient temperature change the density of the air in the chamber and can affect instrument response. For instance, the response of a typical commercial portable ion chamber instrument decreases by 2% for each 10 degree increase in temperature, or decreases by 2.3% for each inch of mercury decrease in barometric pressure (4.6% per psi).
- To correct for these effects (collectively called "drift"), most ion chamber instruments employ a "zero" adjustment.

Typical Applications of Ion Chambers
Many portable dose rate survey instruments are ion chamber instruments. Ion chambers are also used in several installed monitor systems, such as the "slow beam loss" ion chambers.

Proportional Detectors

In a proportional detector, the detector output pulse height is proportional to the total ionization produced in the detector.

As the voltage on the detector is increased beyond the ion chamber region, the ions created by primary ionization gain enough energy in the acceleration to produce secondary ionization. The secondary ions are also accelerated, causing additional ionizations. The large number of events (ion cascade) create a single, large electrical pulse.

The gas amplification factors for typical proportional detectors range from a few hundred to about a million.

Proportional detectors are widely used in laboratory counting instruments. The total current and pulse magnitude could be measured as is done with ion chamber detectors, but this is not usually done in proportional instruments.

In a proportional counter, high specific ionization radiations result in larger pulses. Since we can measure the individual pulse, it is possible to analyze both the rate of incidence and the relative energy with a proportional counter. This allows for discrimination of different types of radiation or different radiation energies by varying the high voltage (which affects the gas amplification factor) and employing a pulse height analyzer.

Advantages of Proportional Detectors

- A proportional counter can be used to discriminate between different types of radiation (using pulse height discrimination).
- A proportional counter output signal is larger and therefore a single ionizing event can be recorded individually (good sensitivity).
- When measuring current output, a proportional detector is useful for dose rates since the output signal is proportional to the energy deposited by ionization and, therefore, proportional to the true dose rate. Usually, they are operated in count rate mode with simple calibration of count rate to dose rate. Accuracy depends on calibration field energy.

Disadvantages of Proportional Detectors

- A proportional counter is sensitive to voltage changes because of the effect on the gas amplification factor. As a result, highly regulated power supplies are necessary for proportional counters. This may make the instrument larger or more expensive.
- Resolving time restrictions (see below) are usually not severe in a proportional detector unless count rates are very high ($>10^6$ cpm). Detector size can be used to compensate for this.

Typical Applications of Proportional Detectors

Proportional counters find wide application in industry. Gas flow proportional counters are commonly used for alpha/or beta counting on laboratory samples. Sealed proportional counters are commonly used for neutron monitoring, from portable neutron survey instruments to nuclear reactor neutron flux instruments. Some dose rate instruments (CARM) and field counting equipment (air monitors) utilize proportional detectors.

Geiger-Mueller Detectors

In a GM detector, voltage and detector gas combinations allow the ion cascade to grow into an "avalanche". In effect, an ion discharge occurs in the tube. This discharge, caused by a single ionization event, results in a single very large pulse. The electric field created by the produced ions essentially "cancels" the field created by the high voltage potential across the detector. When this occurs, the accelerating gradient decreases, preventing further secondary ionization and halting the avalanche.

In a GM tube, the gas amplification can range upwards to about 1E8. Since the tube is completely discharged with each event, the pulse size is uniform and independent of radiation energy or specific ionization (a 0.1MeV gamma creates the same size pulse as a 0.01 MeV beta). For this reason, GM, tubes cannot discriminate between different radiation types or radiation energies.

Any radiation event with sufficient energy to create the first ion pair can create a large pulse. For this reason, the GM detector is more sensitive than the ion chamber or proportional counter.

A GM detector can also be avalanched by the small amount of energy released by a positive ion when it is neutralized at the cathode. To prevent this undesirable occurrence, a quenching gas is added to the counting gas. Instead of causing ionization, this excess energy is expended in dissociating the quenching gas molecules. In effect, the quench gas acts as a low level discriminator, preventing counts from occurring from very low energy events. Without a quench gas, a GM tube would go into continuous discharge after the first ionizing event.

Resolving Time: After the ion avalanche occurs, it takes a finite amount of time for the ions to be collected and for the pulse to be generated. Resolving time is the total amount of time following a measurable detector response before another full pulse can be measured. In the proportional region, the resolving time is reasonably short, usually less than a microsecond. Resolving time does not lead to problems at low count rates, but can result in a considerable error at high count rates.

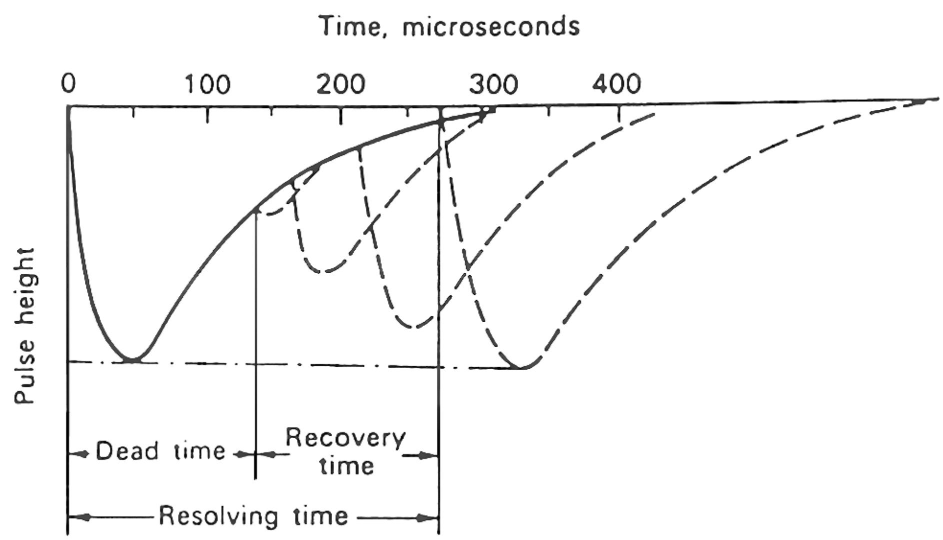


Figure 15: Relationship between dead time, recovery time, and resolving time.

Dead Time Considerations

In GM detectors, resolving time has great impact on detector response.

Several effects are apparent due to the long resolving time of the GM detector:

- The ability of the detector to measure high count rates accurately is reduced. For example, with a 200 μsec resolving time, a count rate of 10,000 cpm will be measured as 9,700 cpm, an error of 3%. At 100,000 cpm the measured count rate will be 75,000, an error of 25%. Many instruments have electronic dead time compensation circuits.
- Another effect in GM detectors is referred to as "paralyzation" of the tube. If the incident radiation events occur at an extremely high rate, a string of small pulses will occur. These pulses prevent the GM detector from completely recovering. Since a full size pulse does not occur, the electronics may not indicate that any radiation is present. Some instruments employ techniques to prevent paralysis.
- <u>GM detectors must be used with caution around pulsed radiation sources</u>. The operation of the GM tube is highly susceptible to tracking the pulse repetition rate of the radiation field, rather than the actual exposure rate. When surveying in a pulsed radiation field, an ion chamber should normally be used. Use of a GM detector should be limited to areas where pulse effects have been determined not to be a factor.

GM Detector Construction

GM detectors are usually sealed cylindrical tubes. The geometry of the tube is a function of the intended use (i.e. pancake). Many GM tubes employ beta windows– some with moveable window covers.

Advantages of GM Detectors

- GM detectors are relatively independent of the pressure and temperature effects which affect ion chamber detectors. This is because of the magnitude of the output pulse.
- GM detectors require less highly regulated power supplies. This is because the pulse repetition rate is measured and not the pulse height.
- GM detectors are generally more sensitive to low energy and low intensity radiations than are proportional or ion chamber detectors (there are exceptions).
- GM detectors can be used with simpler electronics packages. The input sensitivity of a typical GM survey instrument is 300-800 mV, while the input sensitivity of a typical proportional survey instrument is 2 mV.

Disadvantages of GM Detectors

- GM detector response is not related to the energy deposited; therefore, GM detectors cannot be used to directly measure true dose (or exposure), as can be done with an ion chamber instrument.
- GM detectors have a typically large recovery time. This limits their use in extremely high radiation fields. Dead time can be reduced by reducing the physical size of the detector. However, the smaller the detector, the lower the sensitivity. For this reason, wide range GM survey instruments, such as the Teleprobe commonly have two GM detectors - one for the low ranges, one for the high ranges.
- GM detectors cannot discriminate between different types of radiation (α, β, γ), nor between various radiation energies. This is because <u>the size of the GM avalanche is independent of the primary ionization which created it.</u>
- Detector paralysis and radiation pulse rate tracking are potential problems.

Typical Applications of GM Detectors

GM detectors are widely used in portable survey instruments due to their ruggedness and the simplicity of the associated electronics. GM detectors are also used for personnel monitoring for contamination (friskers), for process monitoring, and for area radiation monitoring. In addition, GM detectors are often used for laboratory counting when just a gross count is desired.

SCINTILLATION DETECTORS

Scintillation detectors measure radiation by analyzing the excitation of the detector material by the incident radiation. ***Scintillation*** is the process by which a material emits light when excited by radiation. In a scintillation detector, this emitted light is detected and measured to provide an indication of the amount of incident radiation. Numerous materials scintillate - liquids, solids, and gases. A material which scintillates is commonly called a phosphor or a fluor. The scintillations are commonly detected by a photomultiplier tube (PMT).

Scintillation Detector Components

Phosphors of interest in field applications of scintillation detection are generally classified as either organic or inorganic, and are usually solids or crystalline. The theory of operation, use, and response of these phosphors varies. The purpose of the phosphor is to convert the incident radiation to light.

PMTs have several common, typical components: the photocathode, the dynode assembly, an anode, a voltage divider network, and the shell. The PMT photocathode detects the light emitted by the phosphor, and converts it to an electrical pulse which is proportional to the deposited energy from the incident radiation. The signal is amplified in the dynode string, often with amplification factors over 10^6. The voltage divider network provides a potential to each dynode stage.

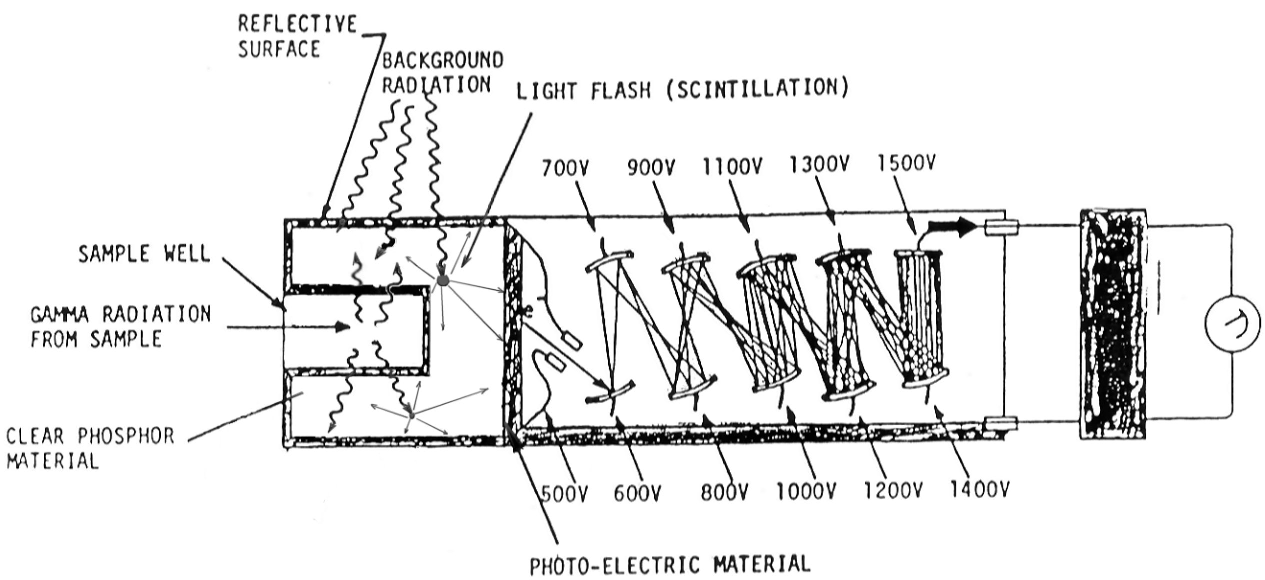


Figure 16: Cross section of a photomultiplier tube.

The photomultiplier tube provides an output pulse whose size is a function of the intensity of the light photons, and of the electron multiplication. Varying the HV to the photomultiplier tube varies the pulse height.

Advantages of Scintillation Detectors

- Ability to discriminate between alpha, beta, and gamma radiations and between different radiation energies with a moderate resolution.
- Organics (plastic): Durable, have energy deposition characteristics similar to tissue.
- NaI(Tl): High gamma sensitivity. Fair resolution.
- Liquids (usually organics): Good low energy response.
- ZnS(Ag): Good alpha detector. Poor resolution.

Disadvantages of Scintillation Detectors

- NaI(Tl): Usually no beta or alpha response, poor low energy gamma response due to encapsulation of crystal. Some special configurations allow this. Hygroscopic.
- Liquid: Relatively cumbersome. Usually used to mix with samples. Solution is one time use only. Time consuming lab process.
- Requires stable power supply, MCA, ADC, etc. for pulse height analysis.
- NaI(Tl) and ZnS(Ag): Detector is not a solid state device, needs to be handled with care.
- Plastics: Poor energy resolution.
- PMTs are susceptible to high magnetic fields, RF.
- Fragile.

Typical Applications of Scintillation Detectors

- Dose rate instruments/count rate meters (Microrem)
- Contamination monitors
- Laboratory instruments, spectrometers (LS Counting, gamma spec, neutron spec)
- Process/area monitors, environmental monitors

SPECIAL APPLICATIONS FOR NEUTRON DETECTION

Neutron detection often employs somewhat more complex techniques than other types of detection. The energy of the radiation field and nature of neutron interactions in matter are important factors that must be addressed when attempting to assess neutron dose quantitatively.

Slow Neutron Detection

Absorption by Boron

Slow neutron absorption in boron is a common method used for neutron monitoring. When slow neutrons are absorbed by atoms of B-10, an alpha particle is emitted. This alpha particle produces ionization which can be measured. A detector may be lined with Boron-10 or filled with boron-trifluoride (BF_3) gas. These detectors are usually operated in the proportional region. Since the BF_3 tube is also gamma sensitive, the instrument usually employs a pulse height discriminator to differentiate the large alpha pulse from the smaller photon pulses.

Fission Chambers

Slow (thermal) neutron absorption in U-235 can cause fission, with the two fission fragments produced having a high kinetic energy and causing ionization in the medium in which they are produced. The electrodes of an ion chamber may be coated with a thin layer of uranium enriched in U-235, creating a "fission chamber" which is sensitive to thermal neutrons.

Scintillation
Scintillation detectors can be designed to detect slow neutrons by incorporating boron or lithium in the scintillation crystal. The neutrons interact with the boron or lithium atoms to produce an alpha particle, which then produces scintillation.

Slow Neutron Thermoluminescence
Thermoluminescent dosimeters can be designed to detect slow neutrons by incorporating Li-6 in the crystal. This method is used frequently in TLD badges.

Activation Foils
Various materials have the ability to absorb neutrons of a specific energy and become radioactive through the radiative capture process. By measuring the radioactivity of thin foils such as gold, silver or indium, we can determine the number of neutrons to which the foils were exposed. Commercially available criticality accident dosimeters often utilize this method.

Fast Neutron Detection

Proton Recoil (Ion Chamber/Proportional)
When fast neutrons undergo elastic scattering with hydrogen atoms they frequently strike the hydrogen atom with enough force to knock the proton nucleus away from the orbiting electron. This energetic proton then produces ionization which can be measured. Most devices for measuring fast neutrons use an ionization detector operated in either the ion chamber or proportional region.

Thermalization (Slowing Down Fast Neutrons)
There are several methods for detecting slow neutrons, and few methods for detecting fast neutrons. Therefore, fast neutron monitoring usually involves “moderating” the energy of the fast neutrons, and detecting the slow neutrons. In this technique, the moderator is placed around the detector to “thermalize” the neutrons, which are then detected as above in the slow neutron detector.

At JLab, personnel neutron dose is measured by a device known as a neutron track-etch dosimeter. The track-etch dosimeter is responsive to fast neutrons in a direct way. The neutrons which interact in the material of the dosimeter (a poly-carbonate plastic) leave microscopic damage sites. Etching of the material following exposure allows the sites to be viewed under a microscope and counted. The number of sites (tracks) is related to the absorbed dose. The track-etch element has a fairly flat response to higher energy neutrons. The track-etch element in the JLab badge is enhanced to also be sensitive to slow neutrons.

A special type of fission detector called a fission track-etch detector has been historically used at JLab in association with the boundary monitors, but their use has been discontinued. A U-235 source is mounted adjacent to a special film. Fission events in the source liberate fission fragments, which create damage sites in the film. The foil is then etched in a chemical bath, and placed in an instrument that generates an arc through any etched site. These arc events are counted, and the number of sites is related to a dose through a calibration factor.

PASSIVE MONITORING

THERMOLUMINESCENT DOSIMETERS (TLDs)

Thermoluminescence is the ability of some materials to convert the energy from radiation to a radiation of a different wavelength, normally in the visible light range. In the case of the TLD, this emission of light is not instantaneous or spontaneous, but must be stimulated by the addition of heat energy.

In TL material, electrons are disrupted by ionization/excitation and moved into elevated energy states. The electrons are "trapped" in normally unoccupied energy bands by doped impurities in the crystal.

These trapped electrons represent stored energy for the time that they are held. This energy is given up (as light) if the electron returns to the valence band. This emission occurs when stimulated by heat.

TLDs can be used to measure beta, gamma, and neutron radiations. The neutron response of the TLD is very sensitive to the energy of the neutron field. In cases where the neutron energy is well known, neutron factors can be established to accurately determine neutron dose from TLDs.

Advantages of TLDs (primarily as compared to film badges)

- Able to measure a greater range of doses
- Response is linear
- Readout can be automated, and is very accurate if calibrated properly
- They can be read on site instead of being sent away for developing
  - Quicker turnaround time for readout
- Reusable

Disadvantages of TLDs

- Cannot be read out more than once (for a given dose) - the readout process effectively "zeroes" the TLD
- The result is not a "physical" record, as with film, but the readout parameters are stored electronically

OSL DOSIMETERS

JLab began using optically stimulated luminescence dosimeters (OSL, or OSLD) in 2008. The theory of operation is very similar to TLD, except that the energy that stimulates de-excitation of the trapped electron states is optical, as the name indicates. The OSL phosphor is exposed to a particular frequency band of light (by laser or LED), and the trapped electrons drop to ground state, emitting visible light. The emitted light is measured and quantified, just as in TLD processing.

Advantages of OSL (compared to TLD)

- Little or no signal "fade"
- Can be read out multiple times (~100s) with only minor loss of stored signal
- Theoretically lower minimum detectable signal level
- Easy to read onsite for quick checks

SUPPLEMENTAL DOSIMETERS

In addition to OSL, supplemental dosimeters are used at JLab. The term Self-Reading Pocket Dosimeter (SRPD) is used to describe any type of dosimeter that displays dose information directly to the user. At JLab "SRPD" usually refers to the digital dosimeter (electronic). SRPDs are not "dose of record" devices, but add real-time assessment capability, and (in the case of visitors) an easy way to verify that "official" monitoring was not needed.

- ***Digital dosimeters*** are used for both supplemental devices by Radiation Workers (for RWPs) and as temporary dosimeters for visitors who may be entering RCAs with an escort. Digital dosimeters used at JLab are actually small GM survey meters which integrate exposure. Because of the drawbacks of GM tubes, <u>digital dosimeters should not be used around pulsed radiation fields without other means to evaluate the radiation field.</u>
- ***Other SRPD***
    - ***Pocket ion chambers*** (quartz fiber electroscope) are small air-filled ion chambers. These SRPDs are no longer in common use at JLab.
    - ***Neutron bubble dosimeters*** contain a gel which holds a superheated liquid drop matrix. When neutrons interact in these superheated drops, the drops are vaporized by the deposition of the energy. The visible bubbles are counted and a calibration correction factor is applied to obtain the dose. These devices are not currently in use at JLab, due to the absence of neutron fields in occupied spaces that would trigger a need. But in the event of new or changing radiation environments, could be deployed.

FIXED RADIATION MONITORING INSTRUMENTATION

Stationary instruments are used to provide an indication of area radiation levels, provide a record of area dosimetry for ALARA purposes, and provide protective trip functions where they prevent situations which could cause persons to exceed certain dose limits. These instruments are used by RadCon staff and are not available for use by ARMs or others for radiation control functions except under the direct authorization and instruction of RadCon.

Types of stationary instruments used include:

<u>Controlled Area Radiation Monitor (CARM)</u> ADM-610 & ADM-616

- ~ 50 monitors in accessible areas near beam enclosure (units also in Test Lab)
- Photon (proportional) and neutron (BF3) channels
- Visible and audible alarms
- Interlocked to PSS to trip on high alarm and power loss
- Nominal trip point in RCA is 2 mrem/hr (may be unique to area)
- Readout through EDM screens

Boundary Monitors (RBMs) ADM-600

- Six units located at site boundary
- He-3 neutron detectors (sensitivity is fraction of microrem/h)
- Photon (GM or scintillator) channel relatively insensitive
- Readout through EDM screens (not PSS interlocked)
- New high pressure ion chambers in field use for gamma (sensitivity analogous to neutron channel)

Others (using similar technology)

- Test Lab interlocked areas use CARM equivalents
- Beam dump cooling water building access points (gamma probe)
- Beam dump building units have feedback to EDM (not interlocked)
- Rapid Access Monitors – gamma probes networked to "go-no-go" access beacon

RadCon may ask ARMs for their assistance in relocating fixed instrument detectors, visually checking the status of CARMs, operational/functional testing, and other periodic surveillance of the equipment. This is usually done in accordance with a commissioning test plan, TOSP, or other documented procedure. In addition, the ARM may respond to a trip of an interlocked CARM. Procedures for alarm response are covered in a later section.

PORTABLE SURVEY INSTRUMENTS

Types Available and Their Applications

Bicron Microrem
Detector Type - Plastic (tissue equivalent) scintillator
Radiation Detected – Photon (LE version may see beta)
Readout - Analog, microrem/hr
Range - Up to 200 mrem/hr in five scales
Uses - Area surveys, entry to tunnel after shutdown, item release surveys
Specific Limitations - Response falls off in magnetic field

Teleprobe (FAG) (extendable survey meter)
Detector Type - GM (2 tubes) with dead time correction
Radiation Detected - Photon (some have beta window)
Readout - Digital, auto-ranging
Range - Up to 1000 R/hr (hand held base unit goes to 1 R/hr)
Uses - Area surveys, good for reaching overhead or getting distance from high dose rates
Specific Limitations - Pulse sensitive, accuracy poor at background levels

Nuclear Research ADM-300 (base unit)
Detector Type - GM
Radiation Detected - Photon (has beta window, but not calibrated for beta)
Readout - Digital auto-ranging
Range - Up to 1000 R/hr
Uses – "Special re-sweep" procedure (used as an alarming dose rate meter)
Same limitations as other GMs

Nuclear Research NP-2 and NG-2
Detector Type - BF3 proportional (NG-2 also has GM tube for gamma)
Radiation Detected - Neutron (NG-2 also sees photons)
Readout - Analogue (NP-2) or Digital (NG-2), microrem or millirem per hour
Range - Calibrated up to 100 mrem/hr
Uses - Area neutron dose rates, NG-2 has dose logging, dose integrator
Specific Limitations - Very slow response, response not well characterized above ~10 MeV

Ludlum-3 and others with "Pancake Probe" (includes A/C powered versions)
Detector Type - GM
Radiation Detected - Beta, gamma (sees alpha, but not calibrated)
Readout - Counts per minute
Range - Up to 500 kcpm in four or five scales
Uses - Surface contamination surveys either direct or on swipes, some activation surveys
Specific Limitations - Relies on proximity to surface, gamma sensitivity low, dead time

Selection and Use of Portable Survey Instruments

Measurements using portable radiation survey instruments provide the basis for assignment of practical external exposure controls. In order to establish the proper controls, radiation measurements must be an accurate representation of the actual conditions.

Many factors can affect how well the measurement reflects the actual conditions. These include:

- Selection of the appropriate instrument
- Correct operation of the instrument based on its characteristics and limitations
- Calibration of the instrument to a known radiation field similar in type, energy and intensity to the radiation field to be measured.
- Other radiological and non-radiological factors such as radioactive gases, mixed radiation fields, humidity, temperature, and the presence of electromagnetic fields.

Once the proper type of instrument has been identified, a pre-operational check is essential and must be performed in accordance with appropriate procedures.

Pre-use Checks

1. Physical inspection for obvious defects or damage that would render the instrument unusable.
2. Ensure that the instrument is within its calibration period. For portable instruments, the calibration frequency is semiannual.
3. Check for a current response check. All portable instruments must be source checked at routine intervals to ensure operability. If the response check is overdue (indicated by a dated label on the instrument), do not use the instrument.
4. Perform a battery check. Most instruments have a battery check position or pushbutton battery check. If the instrument does not respond properly to the battery check, do not use it - remove it from service and tag it for repair. (Changing batteries is permitted on most instruments)
5. If appropriate, perform a zero adjustment for the meter. This is common on ion chambers.
6. On instruments that respond at background dose rates, select the lowest range and verify proper response to the background.

If any of the pre-use checks are not satisfactory, DO NOT USE THE INSTRUMENT.

References for Unit 3

1. *Operational Health Physics Training*, Moe, ANL-88-26, 1988.
2. *The Health Physics and Radiological Health Handbook*, Shleien, 1992.
3. JLab Radiological Control Manual, Jan 1, 1994
4. DOE Standardized Training for Radiological Control Technologists, May 1994
5. *Introduction to Health Physics*, Cember, 1983.

LEARNING OBJECTIVES

1. List the criteria for posting Radiologically Controlled Areas, Radiation Areas, and Hot Spots.
2. Describe administrative and physical area controls.
3. State the conditions requiring an RWP.
4. Describe the process of RWP initiation.
5. State the requirements for entering, working in, and exiting High Radiation Areas.
6. Describe area controls and access requirements for Contamination Areas.
7. Describe the use of Radioactive Material Tracking Forms and RCOPs.

ADMINISTRATIVE CONTROLS

Definitions

Whole Body: Dose rate measurement made 30 cm from a radiation source or a surface through which radiation penetrates.

Whole Body: As applied to personnel dose, a dose from penetrating radiation (deep dose) received by the head and trunk, arms extending to the elbows, and legs extending to the knees.

General Area: Taken to be approximately one meter from a radiation source or in the generally accessible area or walkway/work area.

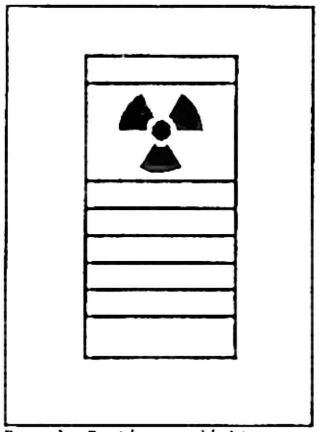
Contact: Within an inch of a radiation emitting surface or item.

Postings (signs, labels, etc.) and identifiable boundaries (such as fences, doors, and ropes) are used extensively in radiation protection work to communicate radiological conditions to personnel. Since radiation and contamination are not detected by the senses, these administrative controls are the only method available to communicate these conditions in the absence of the full-time presence of personnel or monitoring systems to perform this task. It follows that these administrative controls must be used in a consistent fashion and must follow strictly prescribed rules for use.

In the absence of doors or other physical entry points, yellow and magenta rope, tape, chains or other barriers are used to designate the boundary. The boundary must be placed where the dose rate is less than or equal to the trigger for the posting.

Specific requirements for postings are found in 10CFR835 Subpart G. The JLab-specific signage protocol is shown here.

AREA DEFINITIONS AND POSTINGS



Example Posting - slight variance permitted with RCO concurrence.

INSERT HIERARCHY

Insert Section 1 - Hazard Level

Insert Section 2 - Hazard Type
Insert Section 3 - Area Modifiers
Insert Section 4 - Notifications or other postings

NOTES:

1. Section 1 shall be used for identifying the hazard level, (i.e. Caution, Danger, Grave Danger).
2. Section 2 shall be used for the area hazard type (i.e. Controlled, Contamination, etc.) only. The only exception for this section is to avoid double posting.
3. Section 3 - Area Modifiers refers to the secondary postings required in some areas. For example, if an "Airborne Radioactivity Area" was being posted, the modifier could be "Contamination Area". If no area modifications are required, place Section 4 requirements in this section.
4. Section 4 - Place informational inserts here.

Figure 17: Required hierarchy of area postings.

Controlled Area

An area to which access is controlled in order to protect individuals from exposure to radiation and radioactive materials is defined in 10CFR835 as a Controlled Area. It is a boundary area around other radiological areas. The JLab site (fenced in area bounded by locked or guarded access gates) has been designated as a Controlled Area. Other Controlled Areas are posted in the Test Lab, EEL, RadCon compound, and potentially at other locations.

Note: Controlled Areas are administratively determined by RadCon. The ARM is not expected to determine or designate Controlled Areas.

<u>Radiologically Controlled Area</u>
At JLab, areas where personnel may receive more than 100 mrem in a year are posted as RCAs. In the absence of specific occupancy factors, these areas must be posted when the whole body dose rate exceeds 0.05 mrem/hr. The RCA is used to define the threshold for when Radiation Worker training and dosimetry is required, based on potential for dose in the area.

Note: 10CFR835 does not define RCAs, instead it uses the term Radiological Area (not to be confused with RCA) to define a *class* of areas, that includes: Radiation Area, High Radiation Area, Very High Radiation Area, Contamination Area. Note that 10CFR835 requires written work authorizations for entry into radiological areas.

The posting hierarchy for the RCA is as follows:

- Hazard Level = CAUTION (Hazard level is optional on RCA)
- Hazard Type = Radiologically Controlled Area
- Area Modifiers = If the RCA contains radioactive material, this will be included
- Notifications = Dosimetry required for entry

Figure 18: Example of an RCA/RMA posting.

<u>Radiation Area</u>
According to 10CFR835 any areas where the whole body radiation dose rate is >5 mrem/hr at 30 cm

- Hazard Level = CAUTION
- Hazard Type = Radiation Area
- Area Modifiers = Any secondary area postings such as "Contamination Area"
- Notifications = Usually, Radiation Areas require at least RadCon concurrence for work (assuming the area is within a beam enclosure). If trigger values are exceeded, "RWP Required" is posted (we will discuss triggers later).

A rope or other indication of the boundary is necessary. At a minimum, stanchions with signs attached can be used to provide this boundary, but they must be placed frequently, and be <u>visible from any angle</u> of approach.

High Radiation Area
In 10CFR835, any areas where whole body radiation dose rates are >100 mrem/hr.

- Hazard Level = DANGER
- Hazard Type = High Radiation Area
- Area Modifiers = Any secondary area postings such as "Contamination Area"
- Notifications = "RWP Required" is normally posted. Others such as "Supplemental dosimetry required" are optional.

Note: ARMs are not normally expected to post or survey High Radiation Areas. However, suitable access controls and/or postings and barriers should be instituted pending RadCon assistance.

Very High Radiation Area
JLab has historically designated VHRA as any area with a whole body dose rate greater than 5 rem/hr. The DOE definition is much less conservative, 500 rad/h at 1m. JLab is revising its definitions for consistency.

- Special access controls are required to prevent unauthorized entry
- Entry/work in the area could cause individuals to exceed the site administrative dose control level, so access is normally not permitted.
- Emergency entry is allowed with senior management approval.

The ARM is not expected to determine the posting requirements for Very High Radiation Areas.

Hot Spot
A spot (usually small) where the dose rate on contact is greater than 100 mrem/hr and at least five times the whole body dose rate. The contact dose rate is written on the Hot Spot label.

Note: Hot Spots found during a survey by an ARM may not require posting if other administrative controls are in place. This will be covered more in the survey practice section.

Contamination Area
10CFR835 requires these to be posted when measured or suspected loose surface contamination levels are above 1000 dpm/100 cm^2 (for beta-gamma emitters).

Requirements for entry include:
- RWP
- PPE
- RW-II training

The ARM is not expected to determine the posting requirements for Contamination Areas.

Airborne Radioactivity Area

An area in which airborne concentrations of radioactive material exceed or may exceed the Derived Air Concentration (DAC) values listed in 10CFR835, or in which a person could receive an intake of 12 DAC-hrs in a week.

Requirements for entry

- RWP
- RW-II training**
- Respiratory protection training**
- RP equipment**

** These requirements apply when the hazard is due to airborne particulates. The RP equipment is not automatically imposed in Airborne Radioactivity Areas, but is used based on an ALARA assessment. No special access controls are necessary when the hazard is due only to gaseous activation products. Parts of the accelerator enclosure are posted Airborne Radioactivity Area due to N-13 and other activation gases. The General Access RWP suffices as "written work authorization".

The ARM is not expected to determine the posting requirements for Airborne Radioactivity Areas.

Radioactive Material Area

This area is required by 10CFR835 whenever radioactive materials above certain specified quantities are contained in a room or area. Since it is generally not practical to keep close track of the total amount of radioactive material in a given area, any area having known or potential radioactivity of any significance is posted as an RMA. Within a posted RMA, individual items of radioactive material are not strictly required to be tagged or labeled; however, RadCon attempts to tag all known RAM in RMAs (unless it's installed equipment) to provide hazard identification, help control unauthorized movement, and as an ALARA tool. This is particularly true in RMAs outside of beam enclosure areas.

The ARM is not expected to determine the posting requirements for Radioactive Material Areas.

Table 10: Summary of areas.

Location	**Dose Rate Criteria (WB)**	**Posting**
Controlled Area	n/a (potential for occupational dose)	“Controlled Area”
Radiologically Controlled Area	> 0.05 mrem/hr (>100 mrem/yr)	“Radiologically Controlled Area, (or 'RCA') Dosimetry Required for Entry”
Radiation Area	> 5 mrem/h	“Caution Radiation Area”
High Radiation Area	> 0.1 rem/h	“Danger High Radiation Area”
Very High Radiation Area	> 500 rad/h at 1m	“Grave Danger Very High Radiation Area”
Hot Spot	> 0.1 rem/h on contact, and > 5X WB reading (at 30cm)	“Caution Hot Spot”
Contamination Area	Removable contamination >1000 dpm/100 cm^2 (β-γ)	“Caution Contamination Area”
Airborne Radioactivity Area	Exceeds DAC, or person could get12 DAC-hrs in one week	“Caution Airborne Radioactivity Area”
Radioactive Material Area	Contains RAM above certain limits in 10CFR835	“Caution Radioactive Material”

ADMINISTRATIVE WORK CONTROLS

Radiological Work Permits (RWP)

10CFR835 requires “written authorization” for entering and performing work in radiological areas. JLab typically implements this requirement through the use of RWPs. The DOE definition of Radiological Area, as discussed earlier, includes Radiation, High Radiation, Contamination, and Airborne Radioactivity areas.

For accelerator enclosure RCAs, 10CFR835 requirements are met by the use of a ***General Access RWP***. This RWP applies to general work and imposes “hold points” where further evaluation is required. When controls beyond the scope of the General Access RWP are needed, a ***Job Specific RWP*** will be issued. If the Job Specific RWP covers a repetitive or ongoing task, it may take the form of a ***Standing RWP***, which may be authorized for up to one year.

Purpose of an RWP (Note: RWPs may be required in addition to OSPs, RCOPs, etc.):

- Inform workers of area radiological conditions.
- Inform workers of entry requirements into the areas.
- Provide access control for radiological areas.
- Provide a means for dose tracking and work history documentation

The process of RWP generation should be initiated by the work group anticipating the need for access or work. For General Access RWPs, RadCon will issue the RWP when it is evident entry is necessary

Standard triggers for Job Specific RWPs are as follows:

- Entry into High Radiation Areas
- Work in areas where whole body dose rates >25 mR/hr.
- Anticipated dose to a worker of 25 mrem in a shift.
- Work on a component that measures >250 mR/hr on contact.
- Entry into Contamination Areas, or work that may generate contamination
- Entry into an Airborne Radioactivity Area (where hazard is inhalation, not immersion)
- Job Specific RWPs may also be used at the discretion of RadCon to control work in other radiological areas where appropriate. Examples may be when machining radioactive components or during radiography.

Entry Requirements for Radiation and High Radiation Areas

Radiation Areas

- Radiation Worker I training (minimum)
- Read, understand, and sign in on the appropriate RWP (in beam enclosures, entry to areas up to 25 mrem/hr may be permitted with RadCon concurrence under provisions of the General Access RWP)
- Dosimeter (supplemental dosimetry may be required in accordance with dose rate triggers above)
- Radiation survey prior to entry after any operation that may have changed the conditions in the area
- Concurrence from RadCon representative (RCT)

High Radiation Areas

- Radiation Worker I training (minimum)
- Read, understand, and sign in on the appropriate RWP (*not* General Access RWP)
- Regular and supplemental dosimeter (supplemental dosimeter required by 10CFR835)
- Radiation survey prior to entry after any operation that may have changed the conditions in the area
- Concurrence from RadCon representative (RCT)

Additional requirements when dose rates are > 1000 mrem/hr

- Formal radiological review of non-routine or complex work
- Determination of the worker's current dose
- Documented pre-job briefing
- Continuous RadCon coverage
- Alarming dosimeter
- Physical access controls

<u>Practices During Work in Radiation and High Radiation Areas</u>

- Don't loiter
- Stay in designated low-dose rate areas when not immediately involved in the work
- Strict observance of stay time limits and other requirements of the RWP
- In the event of dosimeter alarm, malfunction, or anomaly
  - Stop work
  - Alert others
  - Exit the area immediately
  - Notify RadCon
- When exiting:
  - Observe all posted or RWP requirements for frisking
  - Have any equipment removed from the area surveyed prior to removal
  - Complete the RWP log entry

<u>Radiological Control Operating Procedures (RCOP)</u>

RCOPs are used for controlling work which may produce changing radiation levels such as operating Radiation Generating Devices (RGDs) or other tasks involving direct manipulation of radiation sources or radiological equipment.

Typical applications include:

- Operation of accelerator components or other RGD in an unshielded, unusual, or temporary configuration
- X-ray tubes or machines
- Use of radioactive material in an industrial process
- Use of sealed sources that may produce a Radiation Area
- Special commissioning tests or configurations

Radioactive Material Controls

If a survey indicates that an item requires classification as radioactive material, it must be stored in a Radioactive Material Area within a Controlled Area (all beam enclosure spaces except the CEBAF injector are RMAs). Unless the item is part of installed hardware, it should be labeled as radioactive material.

If it is necessary to remove the item from the beam enclosure RCA, the following requirements apply:

- A radioactive material tag or appropriate label must be affixed.
- It must be moved to an approved storage area.
- If the dose rate from the item exceeds the level delineating an RCA, the storage area must be posted as such.
- RadCon must authorize the movement and update the location tracking on the item.
- A custodian for the material will be designated and identified on the RAM tag.

PHYSICAL ACCESS CONTROLS
The following is an excerpt from the JLab RadCon Manual.

Jefferson Lab Radiological Control Manual
PHYSICAL ACCESS CONTROLS FOR HIGH AND VERY HIGH RADIATION AREAS

1. One or more of the following features shall be used for each entrance or access point to a high radiation area where radiation levels exist such that an individual could exceed a deep dose equivalent to the whole body of 1 rem in any one hour at 30 centimeters from the source or from any surface that the radiation penetrates:
   a. A control device that prevents entry to the area when high radiation levels exist or upon entry causes the radiation level to be reduced below that level defining a High Radiation Area
   b. A device that functions automatically to prevent use or operation of the radiation source or field while personnel are in the area
   c. A control device that energizes a conspicuous visible or audible alarm signal so that the person entering the High Radiation Area and the supervisor of the activity are made aware of the entry;
   d. Entryways that are locked, except during periods when access to the area is required, with positive control over each entry
   e. Continuous direct or electronic surveillance that is capable of preventing unauthorized entry;
   f. A control device that will automatically generate audible and visual alarm signals to alert individuals in the area before use or operation of the radiation source and in sufficient time to permit evacuation of the area or activation of a secondary control device that will prevent use or operation of the source. Prior to operation of the accelerator:
      1. An announcement indicating that a tunnel sweep will commence within a certain period of time
      2. A sweep (physical search) of the accelerator enclosure which requires a sequential key activated enabling of Run/Safe boxes. Run/Safe boxes visually indicate accelerator state and allow for emergency shutdown of the accelerator
      3. A second announcement indicating that radiation producing activities will begin in the enclosure followed by a dimming of the enclosure lighting
   g. In addition to the above requirements, additional measures shall be implemented to ensure that individuals are not able to gain unauthorized or inadvertent access to Very High Radiation Areas.
   h. Physical access controls over High and Very High Radiation Areas shall be established in such a way that does not prevent a person from leaving the area.

LEARNING OBJECTIVES

1. Describe the proper technique for performing each of the following types of surveys:
    a. Area surveys, including beam enclosure surveys
    b. Entry to areas with suspected high or unknown radiation levels
    c. Item surveys
    d. Personnel contamination surveys.
2. Discuss posting requirements normally associated with beam enclosure surveys.
3. Describe the requirements for proper survey documentation.
4. Identify typical radiological conditions and examples of unusual conditions in beam enclosure areas and the proper response to discovery of conditions such as unposted High Radiation Areas.
5. Describe the characteristics of Hot Spots at JLab.

RADIATION SURVEYS

Radiation surveys are a primary tool for ensuring that: (1) personnel do not exceed radiation exposure limits or receive unnecessary exposure, and (2) the requirements for posting radiological areas and radioactive materials are met. It is vital that proper procedures and techniques be used to ensure the quality and accuracy of the measurements made. Many of these measurements are specifically related to regulatory requirements.

<u>General Procedures for Radiation Surveys</u>

The minimum level of "resolution" for a survey is normally "Whole Body". The survey must be able to provide answers to the questions: (1) what is the maximum whole body dose rate?, and therefore (2) what is the proper designation for area posting?

Area Surveys

It is important that the survey instrument be appropriate for the type and energy of the radiation encountered in the area. The general guidance here is intended to meet the needs of most beam enclosure entries and other general area surveys performed by ARMs. The survey meters that may be appropriate include the Bicron Microrem, the FAG Teleprobe, and the Thermo 6112 telescoping meter. The telescoping meters are preferable in many areas because of the advantages of the long reach and the wide dose rate range. In some areas, specific instruments may be necessary due to the existence of magnetic fields, or because of specific sensitivity requirements.

<u>Ensure the appropriate pre-use checks are completed</u>. This should include a source check.

If equipped, turn on the instrument's audible function. An audible indication is useful for scanning areas as it will give a more rapid indication of elevated exposure levels than the meter readout, and it frees the user from constant observation of the meter.

When entering an area where radiation levels are unknown and potentially high, enter the area with the instrument on the highest scale (if applicable). Upon entry, stop and move down through the scales until an on-scale reading is obtained. Then proceed on with the survey.

Hold the instrument at approximately waist height, and slowly walk through the area. Periodically move the instrument (or detector) vertically between the knee and head level. Unless the actual source of radiation is well known, stop and execute a full turn periodically to ensure the body is not shielding a radiation source. This is not usually necessary for beam enclosure surveys.
For beam enclosure surveys, pay particular attention to:

- Checking ALL beam line passes that have had beam present in them.
- Areas where there are abrupt changes in the beam path.
- Any known areas of scraping or beam loss (any area on a beam line that has been discolored by beam scraping).
- .
- Surveys on magnets (especially strong permanent magnets, i.e. ion packs) - the magnetic field will affect some instruments.
- Contact dose rates above 100 mrem/hr.
- Potential shielding of Hot Spots by magnets and other components or shielding.
- Possible streaming of radiation from behind shielded areas or tunnels, tubes, ducts.

For surveys in areas where radioactive material is stored, pay attention to:

- Any potential movement of material which may have affected the boundary.
- The proper labeling of materials within the area.

For all surveys watch for:

- The presence of radiation levels which would require a different posting or movement, modification, or addition to a boundary.
- The presence of radiation levels which require more stringent administrative controls such as an RWP.
- Streaming of radiation through gaps in shielding.

Material Release Surveys
ARMs are <u>not</u> authorized to release potentially radioactive material from a Radiologically Controlled Area. This automatically includes any trash from the beam enclosure, and any other item present in an area which has seen an activating field. There are a few exceptions to release surveys for certain beam enclosure areas. These will be covered shortly.

ARMs may conduct surveys on items for purposes of relocating the item from the beam enclosure to a specifically designated and posted staging area for subsequent release survey by RadCon.

Any item which has potential for contamination (removed from known contaminated system or there is suspected contamination based on knowledge of process) should not be relocated to the staging area without RadCon authorization. Such items/systems include:

- Items from the inside of ventilation systems.
- Items associated with cooling water systems (other than LCW).
- Vacuum pumps.
- Ventilated electronic equipment (i.e. power supplies with fans) or equipment from ventilated electronic rack spaces.
- Equipment associated with condensate drains or collection systems, dehumidification equipment, sumps, etc.
- Items directly irradiated by beam (windows, targets, radiators, etc.).

RadCon should be notified immediately upon discovery of an item known to be contaminated outside a posted Contamination Area.

- If an item being relocated to the interim storage area is measurably radioactive, RadCon should be notified.
- If the dose rate from an item being relocated is over 100 mrem/hr on contact, or produces a Radiation Area (> 5 mrem/hr at 30 cm), RadCon should be notified immediately. These items are not candidates for transfer to the staging area.
- Always check the radiation levels at the boundary to the storage area to ensure that the addition of an item has not changed the boundary delineation.

Self Monitoring

The technique for personnel contamination surveys is similar to that for surveying any other surface; however, a standard procedure ensures that particular attention is paid to critical areas and that areas are not likely to be overlooked.

- Verify the instrument is on, <u>set to the lowest scale</u>, and the audible can be heard.
- Survey the hands <u>before</u> picking up or touching the probe
- Hold the probe within 1/2" of the surface of the body and move the probe slowly over the surface at ~1" per second.
- Proceed to survey the entire body in the following typical order
    - Head - pause at the mouth and nose for approximately 5 seconds
    - Neck and shoulders
    - Arms - pause at the elbows
    - Chest and abdomen
    - Back, hips and seat of pants - check closely if you have been seated in the area
    - Legs - pausing at the knees
    - Tops of shoes
    - Bottoms of shoes - usually done while stepping onto a step-off pad
- Any personal items - pens pencils, dosimetry
- If the audible count rate increases, pause for 5-10 seconds over the area to give time for instrument response.

Initial Entry Surveys

The scope of the initial entry survey performed by an ARM is to identify work area radiation levels and the presence of any areas exceeding existing posting levels or that might require additional controls to those present. These surveys are appropriate for entries to perform routine diagnostic evaluations or equipment repair in the enclosure. They should not be used as the basis for controlling complex radiological work.

ARMs surveys are conducted under a Standing RWP. This RWP authorizes entry to Radiation Areas (with dose rates above the normal hold points for Radiation Workers) for short durations to get survey data. In addition, it includes a section that is used to invoke physical access controls when necessary.

ALARA Responsibilities During Access Surveys

When conducting access surveys, particularly "escorted" surveys, it is important to remember that you are entering an area containing "unknown" conditions. You may find unposted radiological areas (Radiation, High Radiation Areas), spills and leaks, damaged equipment, and other conditions which may require specific actions or notifications. Use the triggers mentioned earlier to guide your notification of RadCon, and keep in mind your additional ALARA responsibilities. These include attention to the following:

- Notifying accompanied personnel of locations and extent of any unposted Radiation or High Radiation Areas, and maintaining surveillance of such areas until posted or the access is complete.
- Determining the intended locations and scope of work during the access (particularly escorted access) and noting those on the survey sheet.
- Considering follow-up radiological needs – is equipment being removed which will need release surveys, is controlled shielding being dismantled – remind the workers of applicable requirements.
- Reminding workers of limitations applicable to their work (i.e. does it appear RWP might be needed).
- Identifying potential need for *physical access controls* for High Radiation Areas

Survey Documentation

It is important that surveys done for purposes of radiation protection be documented correctly. In effect, if you do not document a survey, it was not performed. Important types of surveys which ARMs perform that require documentation include:

- Surveys for entry into beam enclosure following operation of beam
- Surveys performed in conjunction with posting radiological areas and verifying boundaries
- Surveys performed for purposes of de-posting or down-grading of postings

Information Required on the Survey Sheet

- Your name, date, time of survey, instrument used, calibration due date.
- Accelerator conditions prior to shutdown.
- Reason for the survey - Examples: Reboot computer, Check target vacuum, Open for maintenance day.
- Units - i.e. mR/hr

- Type of measurement - i.e. contact, WB, or GA. A legend that explains both units and type of reading is preferred. Each survey data point on the sheet should be identifiable as to the nature of the reading.
- Boundaries - All boundaries should be indicated on the map, and the type of posting on the boundary. Boundary dose rates should be shown that confirm the proper placement of the boundary.
- During partial survey situations (see below for applicability), indicate areas people entered, WB and contact dose rates in the work areas, and note specifically that the work party had continuous ARM surveillance.
- Type of survey – initial entry, partial or complete survey, etc.

Disposition of Survey Forms

When completed, all original survey forms should be routed to the MCC. It is a good practice to also keep a copy available in the applicable counting room (for hall surveys) or FEL control room, or to post a copy at the entrance, especially if a long access is foreseen. The radiological information should be available to anyone entering the area.

Area-Specific Items

Hall A and C are generally comparable, and the requirements for surveys are the same. Expect Radiation Areas at the targets and dumps. During high power operations (> 50 uA) these often become High Radiation Areas. Assume that the beam line downstream of the target chamber is contaminated for the first two or three meters. Do not allow direct handling of this portion of the beam line even if the area is not posted as a Contamination Area. Always get RadCon concurance for work in this area. As the WB dose rate at the target increases, there is an increased probability that the pivot is contaminated. As a rule of thumb, if the dose rate at the target/exit area is high enough to trigger an RWP, assume there is a need for evaluations of surface contamination on the chamber, pivot, and immediate surrounding areas (this is conservative, but useful).

In Hall B, there is no reason to suspect any surface contamination problems. Air activation is negligible, so air handling equipment is not a concern as in other areas. There are no sources of contaminated water in Hall B. Hall B has an "exemption" from the normal item release survey requirements. If an item coming out of the Hall was associated with the actual beam line (including mechanical support hardware), then it requires a release survey. If it is support equipment (computers, dewars, tools, parts, etc.) which was not directly associated with the beam line (and not within 1 meter of the beam line), it does not require a survey. Of course, in the other halls, all items of any kind that were in the hall during beam ops need a survey (RadCon may allow removal of some items on a case basis for subsequent survey based on process knowledge).

TYPICAL CONDITIONS ASSOICATED WITH ACCELERATOR OPERATION

For areas accessible in beam enclosures after shutdown, typical areas where Radiation, High Radiation, or Very High Radiation Areas may occur include:

- The vicinity of a beam dump, target chamber, and intermediate beam line
- The vicinity of any point of significant beam loss (Hot Spots)
- Near closed-loop beam dump cooling water systems after beam shut off (i.e. BSY)
- In general, the following beam enclosure areas (when accessible)
    - Extraction region (YA, YB magnets)
    - Spreader/recombiner regions
    - Beam switchyard
    - Extracted beam transport channels
    - End station target chamber
    - End station dump entrance transition area

  Note: End station conditions apply to Halls A and C only

Other areas with potential for significant dose rates include:

- Near operating accelerator components such as cavities, electron guns, etc.
- Above unshielded penetrations, equipment hatch covers, end station roof during operations
- In beam dump cooling water buildings
    - Very high levels present when beam is on
    - Radiation or High Radiation Area when beam is off

Areas or items with potential for contamination:

- Leaks and spills from contaminated systems (dumps, radiators, diffusers, condensate)
- Internals of air handling equipment operating inside the enclosure
- On Hot Spots
- On and near target chambers and the immediate downstream beam line
- End station dump entrance transition area (as well as in dump tunnel)
- During some conditions of operation, inside electronic racks, on electrically charged surfaces, or potentially, in general areas of the end stations

Hot Spots

Beam line Hot Spots tend to be <u>very</u> small, intense sources, approaching point-source geometry. The inverse square relationship causes dose rates to be relatively low at a distance of 1-2 meters. This can be misleading.

<u>Example</u>:

- If you are 2m from the beam line and measure a dose rate of 1 mrem/hr, assuming all the radiation is coming from a small point source, the contact dose rate is in excess of 10 rem/hr.
- In practice, the relationship between whole body and contact dose rates on Hot Spots tends to be on the order of a factor of ten.

A Hot Spot may be present when the whole body dose rate is below the criteria for posting a Radiation Area. Follow the guidance below to ensure your survey is sensitive to this. Hot Spots occurring due to significant beam loss may exhibit signs of heating. This results in vaporized metal on the surface – a surface contamination issue. Contamination may be present even when no visible signs of heating occur.

Do not allow hands on work on Hot Spots without RadCon concurrence. Note Hot Spots on the survey sheet.

<u>When to Get Contact Dose Rates</u>

Scenarios

(1) Areas not meeting the definition of Radiation or High Radiation Area- take contact readings when WB dose rates are > about 2 mrem/hr.
(2) Within Radiation/High Radiation Area- after finding the maximum WB dose rate, identify the spot and the contact reading associated with it.

Limitations

High Radiation Areas:

You may not enter any posted HRA or any area you discover with WB dose rates > 100 mrem/hr. If continuation of the survey requires entry to any such area, you must stop and get assistance from RadCon. Most beam enclosure High Radiation Areas are small enough to be surveyed adequately from outside the boundary.

Radiation Areas:

You may enter radiation areas to perform surveys, in accordance with the ARM survey RWP. But in many cases, it is not necessary. Keep ALARA in mind.

Contamination Areas:

Do <u>not</u> enter any area posted as a Contamination Area to perform surveys. If you cannot get the required survey data from outside the area, call RadCon for assistance. Many Contamination Areas will be contiguous with Radiation or High Radiation Areas.

In addition to the beam line itself, remember to obtain general area dose rates, and check boundaries to posted areas to verify the placement of the boundary.

Ask the following questions:

- Are the dose rates at boundaries appropriate to the type of boundary?
- Is there any area that meets a posting trigger that is not posted?
- For the contact dose rates, consider:
    - Is a Hot Spot posting required?
    - Does the reading suggest the presence of contamination?
    - Does the reading suggest the presence of a Radiation/High Radiation Area which you have not already identified?

Rules of thumb to help with this are:

Radiation Area is likely if contact dose rate > 150 mR/hr
Contamination is probable if contact dose rate > 250 mR/hr
High Radiation Area is possible if contact dose rate > 500 mR/hr

When you have gathered all the necessary data and determined that boundaries are correctly placed with appropriate postings, you are free to allow general access to the enclosure.

When to Post

- When a partial survey/escorted access is conducted:
  - Posting of areas and Hot Spots is not required if
    - You inform all personnel in the area of the existence of the area and the levels found
    - No one will be working in the area or on the Hot Spot
    - You can adequately ensure control of the area and prevent uninformed entry (i.e. through direct surveillance and access control through the SSO)

  Note: All areas should be noted on the survey map, along with adequate notations regarding type and location of work, and any administrative controls/RadCon concurrence, etc.

- When a full survey is conducted (for Controlled or Restricted Access):
    - Post any Radiation Areas and call RadCon for guidance if necessary
    - Verify Radiation and High Radiation Area boundary conditions
    - Post Hot Spots if they exist outside the boundary of a posted area
    - Do not drop to Restricted Access if there are unposted areas

When to Call RadCon

- Discovery of a High Radiation Area that was not previously posted (includes an area that has grown in size, or grown from a Radiation Area to a High Radiation Area).
- Discovery of an area with whole body dose rate > 1000 mrem/hr
- Any conditions that indicate the presence of contamination in the work area
- Any work requiring access to a Radiation Area (or higher)
- Hands-on work on a Hot Spot

Exceptions to the Default Methods

Normally the surveyor(s) enters alone first and surveys the area, then when (s)he is satisfied that conditions are acceptable to general entry, contacts the SSO to allow access.

The only exceptions to this are when you:

A. "Partial survey" - directly escort the work party to the work location, and remain in the area
B. "Post exclusion zones" - post barriers to areas that have not been surveyed, and ensure that the accessible area is thoroughly surveyed and properly posted as described above (if not remaining in the area)

When option (A) is used, you should provide radiological information to the work crew - if a Hot Spot or Radiation Area exists in the work area, you must make sure that the worker(s) know the extent of the area and what the levels are. Refer to the RWP trigger values, and call RadCon if there is any question as to the need for an RWP. Do not allow direct hands-on work on a Hot Spot without RadCon concurrence. The partial survey must be noted as such on the survey sheet. When this option is used, once the ARM and work party leave, any subsequent entry to the area requires another survey.

If option (B) is used, the barriers posted must be shown on the survey sheet along with any other posted areas. Once the survey and posting is complete, unescorted entries are allowed. This method is restricted to the CEBAF accelerator tunnels and the FEL only. Postings should read, "Danger. Do not enter. This area has not been surveyed". If process knowledge suggests that High Radiation Areas may exist in the unsurveyed area (known high beam loss, vacuum event, etc.), do not use this option.

Option (A) is preferred when a full survey is not performed.

Default Postings for Injector, Hall B and FEL

Due to typically low levels of activation in Hall B and the FEL, and no expectation of activation in the CEBAF injector, the radiological designation of these areas may change with access conditions. These areas are considered RCAs during Controlled Access (just as any other enclosure area), but may be de-posted conditionally afterward. This determination must be made by RadCon.

The CEBAF injector is an RCA only, not an RMA. Radioactive materials should not be stored or staged in the injector. The main reason for the RCA designation is the potential for elevated dose rates in the injector when the North Linac is running RF.

Hall B and the FEL both require a full survey to change status to Restricted Access.
The posting status of Hall B and FEL does not change during Restricted Access.

RAPID ACCESS SYSTEMS

General

There are "rapid access" systems present in the CEBAF injector, Hall B and FEL. These systems use a network of area detectors that feed back to a central monitor. If the dose rate is below the trip point on all detectors, Controlled Access is allowed without a specific survey of the area. When using the rapid access method of entry, the SSO instructs the initial entrant to functionally test the beacon at the entry point. In Hall B and the FEL, persons entering are instructed that they are not permitted to perform hands-on activities on beam line or target components without a survey (ARMs are permitted to conduct this survey). There is no requirement for this in the injector, because there is no beam line activation in the injector.

FEL Rapid Access Conditions

1. Only RCTs may reduce the posting level of the vault to non-RCA. This will be done for maintenance periods lasting three work days or more or if authorized by the RCM. Otherwise the vault will remain posted as an RCA/dosimetry required.

2. The region west of the last crossover "bridge" (enclosing dump area as well as a section of the third cryo module) will be "semi permanently" posted as "Danger, do not enter, potential high radiation area, this area has not been surveyed" or words to that effect.

3. ARMs may survey and de-post the aforementioned HRA if extended access needs exist, or they may provide partial surveys for incidental entries during Controlled Accesses.

4. If the aforementioned "potential HRA" is de-posted in accordance with the above, it is the responsibility of FEL operations staff to replace the boundary/postings prior to operations. This will be documented on the pre-operational checklist (to be performed by FEL operations personnel or RadCon personnel).

5. Controlled Accesses may be conducted without surveys provided the Rapid Access System beacon is not illuminated**.** NOTE: Operability of the system must be verified during first entry by depressing the "test" button.

6. Any hands-on beam line work during Controlled Access requires a survey of the area(s) affected.

7. Changing state to Restricted Access requires a full survey of the vault.
   NOTE: The state change does <u>not</u> automatically invoke a posting reduction (see item 1).

8. RCT weekly survey for 3 months to verify functionality of the system (i.e., there are no Radiation Areas "undetected" by the Rapid Access System.)

9. Violation of the Rapid Access System (i.e., entry into the FEL without a survey when a probe is alarming/flashing) will result in loss of the Rapid Access System.

References for Unit 5

1. JLab Radiological Control Manual, May 24, 1999.
2. DOE Standardized Training for Radiological Control Technologists.
3. 10CFR835, Occupational Radiation Protection.

LEARNING OBJECTIVES

Identify the correct responses to radiation alarms, spills, and emergencies.

EMERGENCY RESPONSE PROCEDURES

The ARM is expected to respond appropriately to the following potential scenarios:

- CARM alarms
- Loss or damage to radioactive materials or sources
- Injured person in a radiological area
- Direct beam exposure accident

General Guidelines

CARM Alarms

- Ascertain location of the CARM
- Observe the current readings (screen captures may be helpful for elog purposes).
- If the condition caused an accelerator trip (High Alarm), verify that the dose rate is not sustained. The alarm will reset in no more than 30 seconds once the condition has stopped. An alarm that continues longer than this indicates either the radiation condition still exists, or the unit has failed. The audible alarm can be acknowledged locally at the CARM, but this should not be necessary.
- For the first event, if unit resets and operations can be resumed, write an Ops-PR for the event – do not check "requires further attention". If the unit causes a second trip, investigate further to see if cause can be isolated and call RadCon with all available information.
- In the case of an "Alert" alarm (no trip), again check the dose rate, and if necessary acknowledge the alarm (Alert alarms will likely be noted by the local intermittent alarm). If the dose rate is sustained, display the output of the unit on the datalogger. If the display indicates long term (significant portions of an hour) sustained dose rates above the alert threshold, and operational adjustments do not correct the condition, call RadCon. Write an Ops-PR, same as above, even if unit returns to normal quickly.
- Do not relocate the probes or attempt to reset the alarm levels or clear the probe dose without specific authorization from RadCon.
- Once resolved, if an alarm condition reoccurs, call RadCon.

Note: Communications failures on CARMs do not cause the accelerator to trip. If there has been a trip of the machine which appears CARM-related, and the screen indicates a communication failure, the communication failure is not the cause of the trip. However, the failed communication link may have been *caused* by the same root condition that caused the trip. This is often the case when a power supply to a building or region of a building housing a CARM fails. This causes the beam to trip because of multiple system failures (the CARMS fail safe on power loss), including the CARM, box supplies and other hardware. It also causes the CARM to show a communication failure.

Rule of thumb: any time you see a magnet or RF system failure at the same time as a CARM trip, the root issue is a power failure. Probably no need to call RadCon; fix the power supply and only call RadCon if the CARM doesn't come back to normal operation.

Radiation Monitoring on MEDM

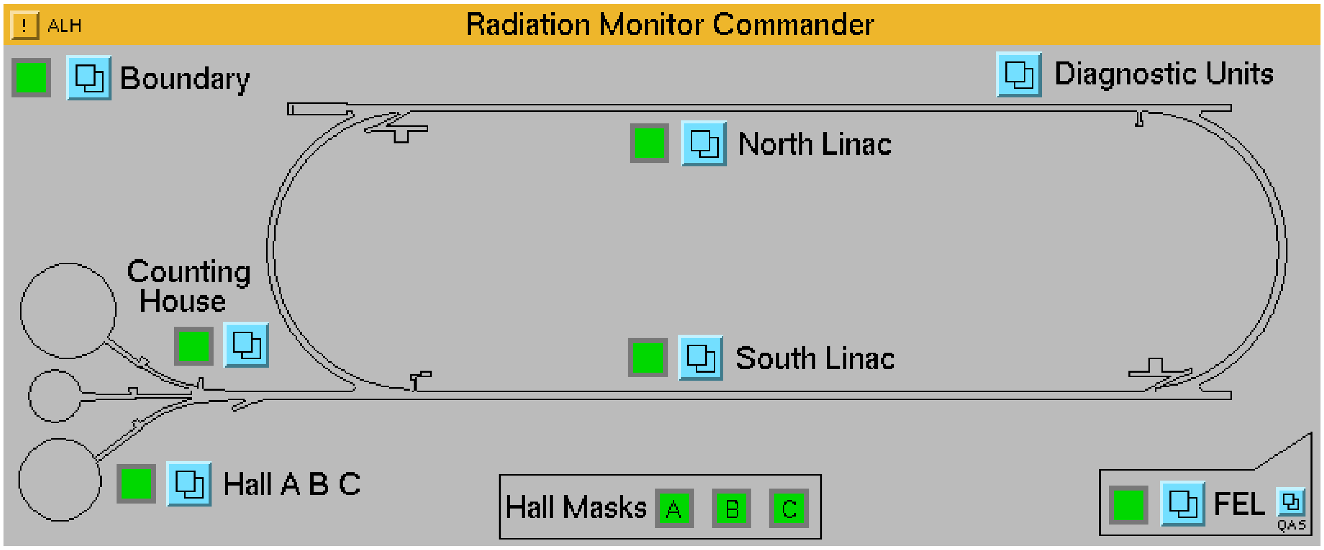


Figure 19: Main view.

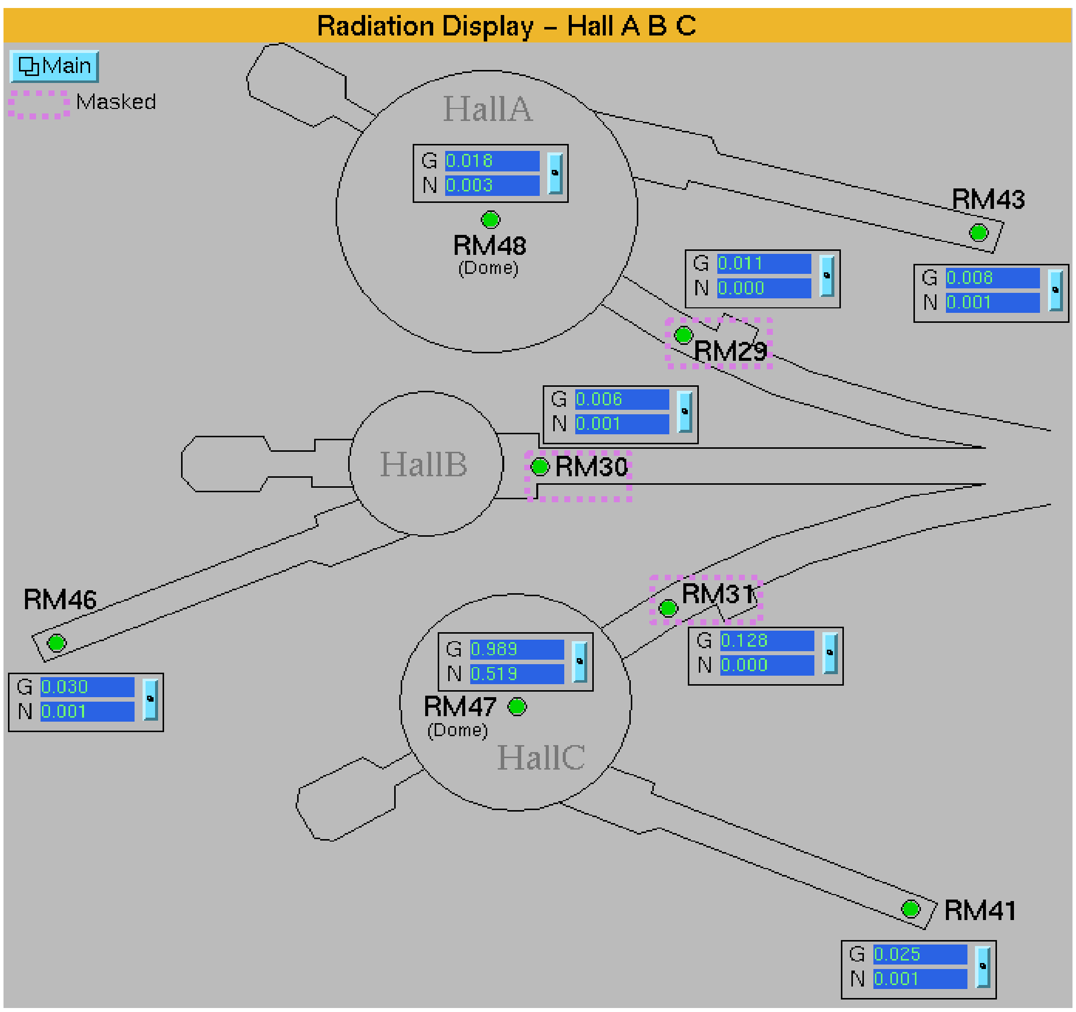


Figure 20: Halls view.

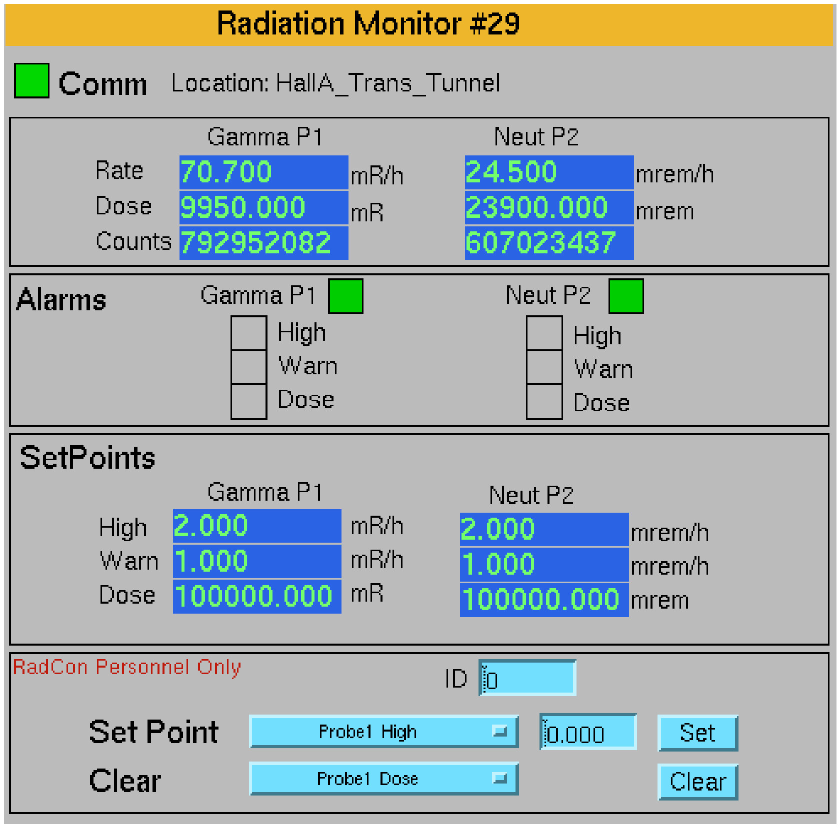


Figure 21: Monitor view – ADM-610.

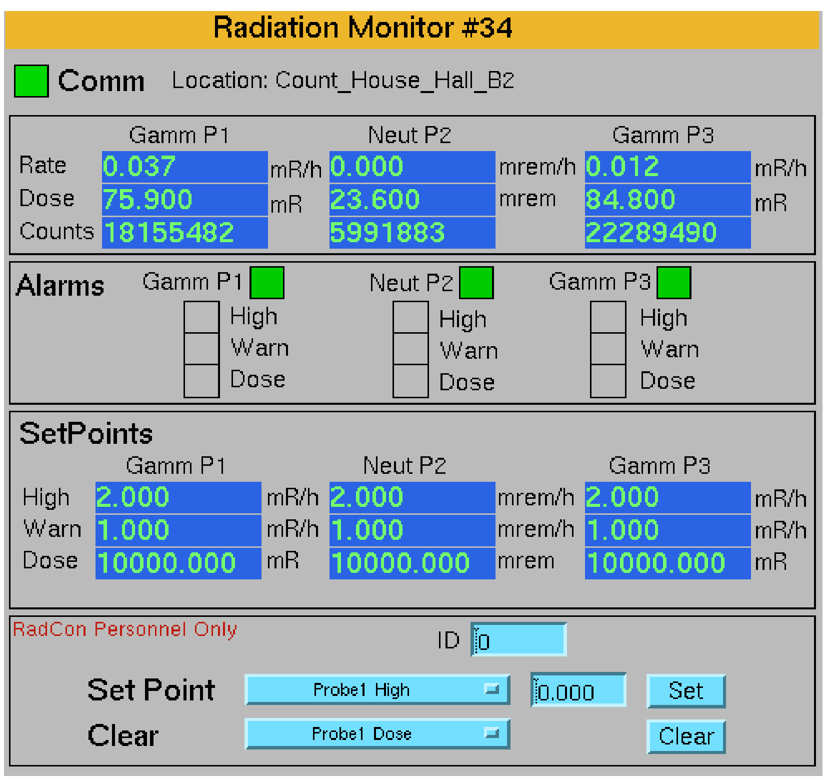


Figure 22: Monitor view – ADM-616.

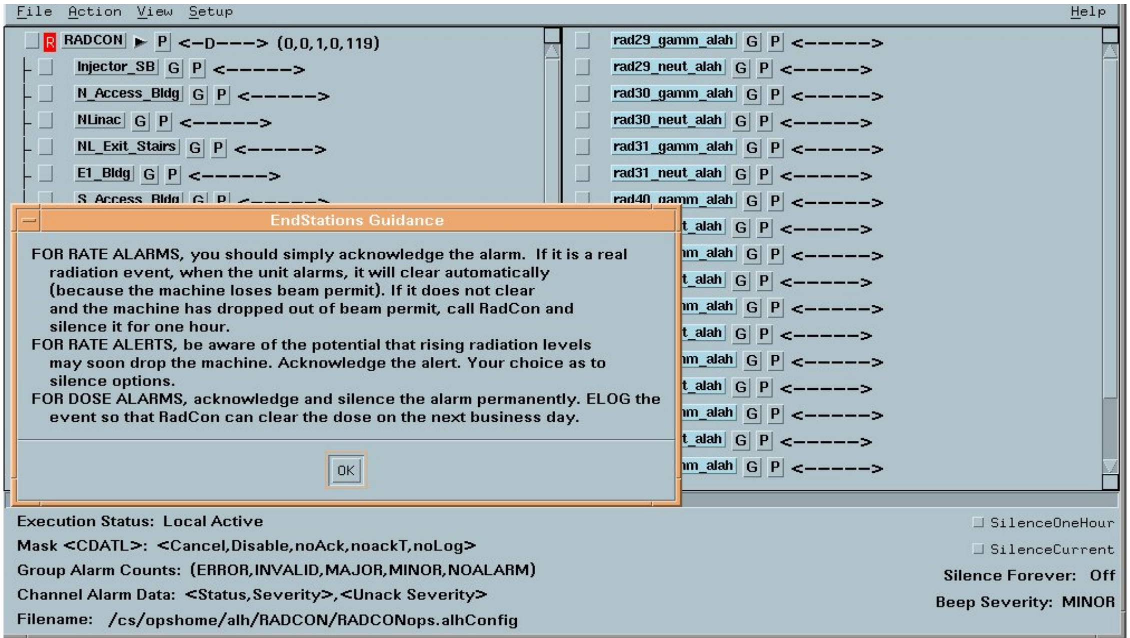


Figure 23: Alarm Handler with standard CARM guidance displayed.

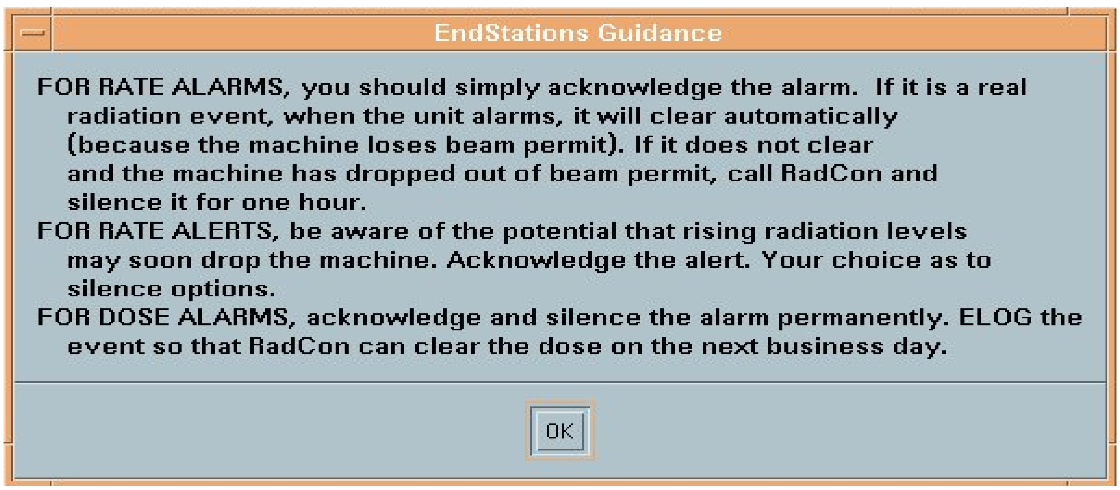


Figure 24: Standard CARM guidance.

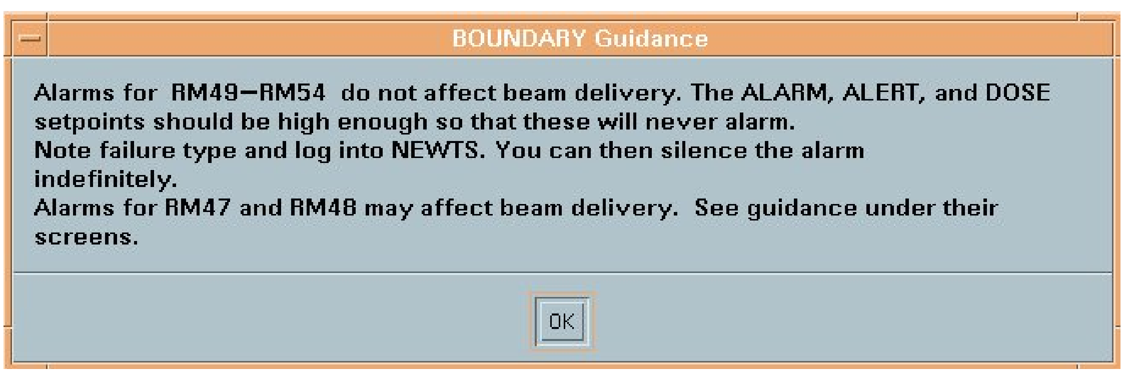


Figure 25: Boundary monitor guidance.

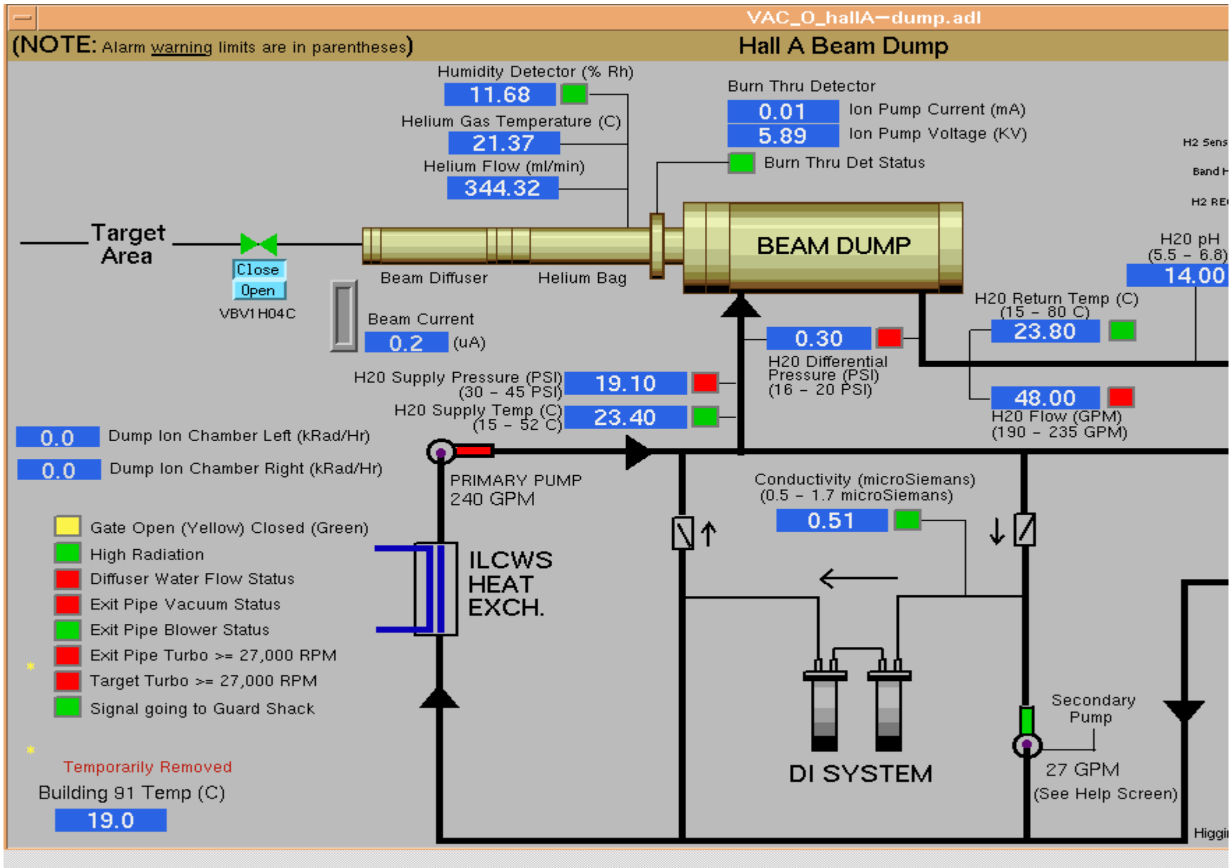


Figure 26: Beam dump screen.

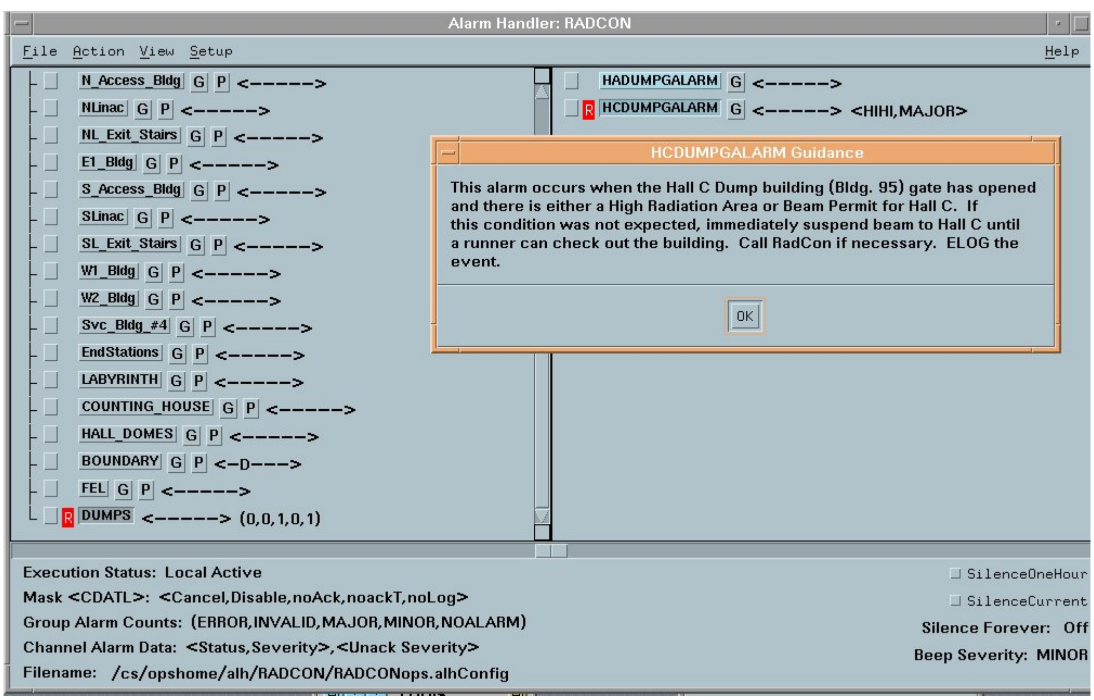


Figure 27: Beam dump building alarm guidance.

Other Radiation Related Alarms

Beam Dump Cooling Water Building Radiation Alarms
Monitoring of buildings 91 and 95 is performed with RM-606 (CARM analog) monitors. These units measure the dose rate at the door leading into the buildings. The units are set to alarm at 100 mR/hr. Activation of the alarm sends a data bit to the EPICS/EDM system. The entrance door and the outer gate remain locked at all times during beam operations in the applicable hall. The outer gate also sends status data to the operations system.

An alarm will occur on the RadCon alarm handler under the following conditions:
1. If the applicable hall is in Beam Permit, and the outer gate is open
2. If the gate is open and the monitor is registering an alarm (regardless of machine status)
3. If there is a power loss to the monitor or the interlock signal

Note: This system is **not** part of the PSS, and is **not** interlocked to trip off the accelerator.

If an alarm occurs, contact RadCon and follow the onscreen guidance in the alarm handler.

Non-Accelerator Systems Alarms
The VTA and Cryo-test caves contain local interlocked PSS systems. Local procedures require notification of RadCon anytime an alarm occurs. Where temporary establishment of interlocked radiation detectors exists, RadCon must be notified when radiation alarms occur.

Spills or Loss of Control of Radioactive Material
Take appropriate and responsible actions to protect life, property, and the environment. If there is an injury, THE INJURY SHALL ALWAYS TAKE PRECEDENCE OVER RADIOLOGICAL CONTROLS, to the extent of the potential seriousness of the injury.

Practice ***SWIM'N***
- **S**top the spill or activity causing it
- **W**arn others in the vicinity not to enter or stay where they are
- **I**solate the area to the extent practicable to prevent accidental entry
- **M**inimize your own exposure to the material
- **N**otify RadCon & the responsible oversight authority (custodian, crew chief, etc.)

Beam Related Exposure Accidents
Refer to the Radiation Control Emergency Procedure kept in the MCC.
- Terminate the exposure-producing activity immediately
- Note operating conditions of the machine at the suspected time of exposure
- If there is obvious injury, give top priority to treatment
- Retain all personnel not injured or providing medical treatment
- Notify the MCC and RadCon immediately
- Perform a radiation survey on the individual(s) (if possible, place the detector on the abdomen and have the person bend at the waist to surround the detector). Record the reading.
- Retain activated articles of clothing, jewelry, or coins and preserve the identity of the owner.
- Attempt to ascertain the locations and time spent in each location of the affected individuals.

Remember that the victim of a direct beam exposure accident would not be a hazard to emergency responders. The victim would not be contaminated, and, therefore, would not need to be handled with any special protective measures or PPE. Handling body fluids is dealt with by standard medical procedures. There would likely not be any readily detectable radioactivity in body fluids or personal items removed for analysis.

Emergency Dose Guidelines

There is no strict upper limit for activities such as lifesaving. The senior manager in charge during the emergency with input from EH&S and RadCon personnel must make judgments that weigh benefits of any action with risks of further injury and the potential for saving and protecting life and health.

If the situation involves a substantial personal risk, volunteers will be selected based on their age, experience with the particular problem, and their previous dose.

Refer to Section I for specific dose guidelines