Tech Guide 238

Radiological Sources of Potential Exposure and/or Contamination

Approved for public release; distribution unlimited

U.S. ARMY PUBLIC HEALTH CENTER

January 2020

ACKNOWLEDGEMENTS

Project Manager:	Brian E. Livingston, CHP
Contributing Authors:	MAJ Thomas Costeira CPT Daniel Arguello COL (Retired) John Cuellar Dr. Gerald Falo, CHP
Past Edition Authors:	COL Ricardo Reyes Dr. Andrew L. Scott, CHP

Contact Information

U.S. Army Public Health Center
ATTN: MCHB-PH-HPH
5158 Blackhawk Road
Aberdeen Proving Ground, MD 21010-5403

Telephone: 410-436-3502
Fax: 410-436-8261

TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION 3

1.1. PURPOSE 3
1.2. SCOPE 3
1.2.1. Hazard Identification 3
1.2.2. Document Structure 3

CHAPTER 2. NUCLEAR FUEL CYCLE SOURCES 4

2.1. THE MINING OF URANIUM 4
2.2. URANIUM MILLING 4
2.3. CONVERSION 5
2.4. ENRICHMENT 5
2.5. FUEL FABRICATION 6
2.6. REACTOR OPERATIONS 8
2.6.1. Fission 8
2.6.2. Fissile, Fertile, and Fissionable Materials 8
2.6.3. Nuclear Power Plants 8
2.7. SPENT FUEL AND STORAGE 17
2.8. REPROCESSING 18
2.9. WASTES 19
2.10. HIGH LEVEL WASTE REPROCESSING 20
2.11. DISPOSAL 21
2.12. SUMMARY OF RADIATION SOURCES FROM THE NUCLEAR FUEL CYCLE 22

CHAPTER 3. BIOMEDICAL SOURCES 25

3.1. GENERAL SOURCES OF EXPOSURE FROM THE MEDICAL USES OF RADIATION 25
3.2. SOURCES IN NUCLEAR MEDICINE 25
3.2.1. Reactor-produced Isotopes 28
3.2.2. Generator/Accelerator-produced Isotopes 28
3.2.3. Radioisotope Generators 28
3.3. RADIOPHARMACEUTICALS 30
3.4. RADIATION THERAPY 31
3.4.1. Therapeutic Radioisotopes 31
3.4.2. Radiation Therapy machines Using Radionuclides 31
3.4.3. Brachytherapy 33

CHAPTER 4. ARMY COMMODITIES AND FOREIGN MATERIAL SOURCES 35

4.1. MAIN SOURCES IN ARMY COMMODITIES 37
4.1.1. Tritium (^{3}H) 37
4.1.2. Nickel-63 (^{63}Ni) 50
4.1.3. Cesium-137 (^{137}Cs) 50
4.1.4. Promethium-147 (^{147}Pm) 51
4.1.5. Radium-226 (^{226}Ra) 51
4.1.6. Thorium-232 (^{232}Th) 52
4.1.7. Depleted Uranium 53
4.1.8. Americium-241 (^{241}Am) 54
4.2. RADIATION SAFETY INFORMATION PERTAINING TO COMMODITIES 55

4.3. RADIOACTIVE SOURCES IN FOREIGN MATERIEL.....57

CHAPTER 5. INDUSTRIAL SOURCES AND THE TRANSPORTATION OF RADIOACTIVE MATERIAL.....59

5.1. THE USE OF RADIOISOTOPES IN INDUSTRY.....59
5.1.1. Gamma Radiography.....60
5.1.2. Gauging.....62
5.1.3. Gamma Sterilization.....63
5.2. TRANSPORTATION OF RADIOACTIVE MATERIALS.....64

APPENDIX A. REFERENCES.....69

APPENDIX B. RADIATION PROTECTION AND PRECAUTIONS.....72

B-1. GENERAL PRECAUTIONS WHEN DEALING WITH IDENTIFIED SOURCES OF EXTERNAL EXPOSURE.....72
B-2. GENERAL PRECAUTIONS WHEN DEALING WITH IDENTIFIED SOURCES OF EXTERNAL CONTAMINATION.....74
B-3. GENERAL PRECAUTIONS WHEN DEALING WITH IDENTIFIED SOURCES OF INTERNAL CONTAMINATION.....76
B-3.1. Precautions Recommended for Working in a Contaminated Area.....76
B-3.2. Precautions when Dealing with Equipment Containing Radioactive Sources.....77
B-4. PRECAUTIONS WHEN DEALING WITH TRITIUM SOURCES.....77
B-5. PRECAUTIONS WHEN DEALING WITH DU.....80
B-5.1. The Nature of the Potential DU Hazard.....80

APPENDIX C. ACCELERATORS AND CLINICAL RADIATION GENERATORS.....82

APPENDIX D. POSTINGS IN A NUCLEAR/RADIOLOGICAL ENVIRONMENT.....86

APPENDIX E. NATURAL RADIOACTIVE SOURCES.....93

E-1. IONIZING RADIATION AND RADIONUCLIDES.....93
E-2. URANIUM.....94
E-3. THORIUM.....94
E-4. RADON.....95
E-5. RADIATION FROM THE GROUND AND OUTER SPACE.....96
E-6. RADIONUCLIDES IN THE HUMAN BODY.....96
E-7. NATURAL RADIOACTIVITY FOUND IN BUILDING MATERIALS.....97

APPENDIX F. IDENTIFICATION OF NUCLIDES AND THEIR SYMBOLS.....98

GLOSSARY.....101

PREFACE

Technical Guide (TG) 238 summarizes sources of potential radiological exposures or contamination to military personnel. Chapter 1 is a brief overview of this TG. Chapters 2 through 5 summarize sources of radiation exposures and contamination found in the nuclear fuel cycle, the biomedical sources field in Army commodities and Foreign materials, and in industry resources and the transportation of radioactive materials.

The purpose of this TG is to provide personnel with a guide to the potential sources of radiological exposures that may be encountered during combat or peacetime operations. This TG is intended for Nuclear Medical Science Officers (72As), Environmental Science Officers (72Ds), and other officers and enlisted who have basic knowledge-level training on radioactive sources.

The intent of this TG is not to alarm personnel, but to alert them to the possibility of exposures and contamination. Several accidental exposures have caused death and serious injury. The consequences of these accidents should not cause a fear of radiation, but should encourage a healthy respect and recognition of radioactive materials. To estimate the hazard presented by radiological exposure or contamination, personnel must be aware of their surroundings.

This TG identifies many sources of potential radiation exposure and contamination. The table below summarizes the most probable radionuclides found in the identified sources. A detailed isotope list can be found at the beginning of each chapter.

Operationally Important Radioactive Material

Radionuclide	**Radiation**	**Half-Life**	**Reference Chapter**
Depleted Uranium	α, γ	-	Nuclear fuel – 2; Army material - 4
^{3}H	β^{-}	12.33 years	Nuclear fuel – 2; Army material – 4; Industry – 5
^{14}C	β^{-}	5730 years	Army material – 4; Industry – 5
^{32}P	β^{-}	14.26 days	Hospitals - 3
^{60}Co	β^{-}, γ	5.3 years	Nuclear fuel – 2; Hospitals – 3; Army material – 4; Industry - 5
^{63}Ni	β^{-}	100.1 years	Army material – 4
^{90}Sr	β^{-}, γ	28.74 years	Nuclear fuel – 2; Hospitals – 3; Army material – 4
^{99m}Tc	γ	6.0 hours	Hospitals – 3
^{125}I/^{131}I	β^{-}, γ	8 days	Hospitals – 3; Army material – 4; Industry – 5
^{137}Cs	β^{-}, γ	30.17 years	Nuclear fuel – 2; Hospitals – 3; Army material – 4; Industry - 5
^{147}Pm	β^{-}	2.6 years	Army material – 4; Industry - 5
^{192}Ir	β^{-}, γ	73.8 days	Hospitals – 3; Industry - 5
^{204}Tl	β^{-}, γ	3.8 years	Army material – 4
^{226}Ra	α, γ	1600 years	Nuclear fuel – 2; Hospitals – 3; Army material – 4
^{232}Th	α, x-rays	1.4E10 years	Nuclear fuel – 2; Army material – 4
^{235}U	α, γ, n	7.04E8 years	Nuclear fuel – 2; Army material – 4; Industry - 5
^{238}U	α, x-rays, n	4.47E9 years	Nuclear fuel – 2; Army material – 4; Industry - 5
^{239}Pu	α, β^{-}, γ, n	2.41E4 years	Nuclear fuel – 2; Army material – 4; Industry - 5
^{241}Am	α, γ	432.2 years	Nuclear fuel – 2; Army material – 4; Industry - 5
^{252}Cf	α, n	2.645 years	Industry - 5

CHAPTER 1. INTRODUCTION

1.1. Purpose

This Technical Guide (TG) is intended to increase awareness of the potential for radiation exposure and/or contamination from radiation hazards existing in medical facilities, industry, and the environment. This TG provides guidance on the explicit identification of many radiological hazards in a deployment situation. The recommended precautions avoid or reduce the external exposure or contamination from all identified sources.

1.2. Scope

1.2.1. Hazard Identification

While conducting operations throughout the world, Soldiers might encounter radiation and radioactive materials. Broadly speaking, the term “sources of radiation” includes radioactive materials, machines that generate radiation (for example, medical x-ray machines), and contamination. The sources are potential hazards to any given mission and must be accounted in the mission’s risk assessment. The preventive medicine or Chemical, Biological, Radiological, and Nuclear (CBRN) Soldier must be able to identify potential sources of radiation to assess the risk to a mission. This TG emphasizes those sources of radiation that may be of operational concern to United States (U.S.) Soldiers.

This TG does not address the hazard severity or probability of an exposure event. The reader should consult doctrinal documents such as Joint Publication (JP) 3-11, Operations in CBRN Environments (Joint Chiefs of Staff 2018), or technical documents such as U.S. Army Public Health Center (APHC) TG 244: The Medical CBRN Battlebook for guidance on severity or probability issues.

1.2.2. Document Structure

Each chapter focuses on where the sources of radiation may exist, including: nuclear fuel cycle, biomedical, Army commodities and foreign material, and industrial sources. Appendix A contains references. Appendix B includes precautionary measures to prevent or reduce the possibility of radiation exposure or contamination. Appendix C identifies sources in accelerators and clinical radiation generators. Appendix D includes CBRN postings and warning signs. Appendix E presents a brief introduction to ionizing radiation and a description of sources of natural radiation. Appendix F contains a list with the name and symbol of all elements and a periodic table. Appendix G contains a glossary of acronyms.

Note: In this TG, scientific notation will be notated by “E” followed by the power. For example, the number 4E5 refers to 4 times 10^5, which is equal to 400,000.

CHAPTER 2. NUCLEAR FUEL CYCLE SOURCES

The nuclear fuel cycle includes all activities associated with nuclear reactions in reactors. It includes the following steps: mining, milling, conversion, enrichment, fuel fabrication, reactor operations, and disposal of waste.

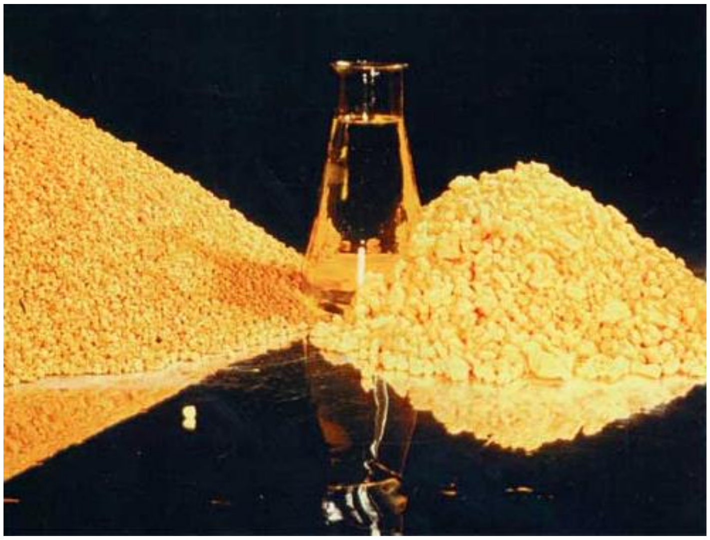
2.1. The Mining of Uranium

Underground open-pit mining and in-situ leaching techniques are used in the recovery of uranium. Open-pit mines require larger openings on the surface than the size of the ore deposit. In-situ leaching involves the pumping of a sulfuric acid solution into the ore bearing rock and collecting that solution for processing. Due to cost differences, the most common method of mining uranium is the open-pit method (IAEA 2000).

Within underground uranium mines, special precautions consisting primarily of increased ventilation are required to protect against airborne radiation exposure. Since the concentration of uranium varies in mines, there are also variable concentrations of radium and radon and its progeny. The three countries with the highest production of mined uranium with 71% of the world output include Kazakhstan, Canada, and Australia (WNA 2019).

2.2. Uranium Milling

Newly mined ore is usually low-grade uranium and must be concentrated. Mills are usually located near the mines. The uranium-bearing ore is first broken and crushed into sand-sized particles, thereby freeing the uranium minerals. It is then chemically concentrated into “yellowcake” (see Figure 2.1). The concentration method varies from one mill to the next, depending on the characteristics of the ore.



Source: http://web.ead.anl.gov/uranium/guide/prodhand/sld013.cfm

Figure 2.1. Yellowcake, Uranyl Nitrate, and Solid Ammonium Diuranate

The mill tailings, or wastes, are stored in specially designed impoundments or old open-pit mines. The tailings contain elements such as thorium, radium, and radon, which are mainly products of the decay of Uranium 238 (^{238}U). Most of these elements are not removed in the uranium extraction process. Generally, tailings leave the mill as liquid sludge and are allowed to dry. They are collected in piles within enclosures.

Precautions (such as collecting contaminated water or air filtration) should be taken to prevent the tailings from contaminating groundwater or getting into the air as dust. For their radioactive content, tailings are no more dangerous than the ore that was removed from the earth. However, since tailings are brought to the surface and are converted into a new form, they may pose a hazard unless protective layers of soil are applied. The radon flux from tailings piles is often much higher than background levels. Placing a layer of soil that promotes vegetation ultimately reclaims the mine sites. Monitoring radiation levels is common after reclamation of soil.

2.3. Conversion

The product of a uranium mill is not directly usable as a fuel for a nuclear reactor. Additional processing, generally referred to as conversion, is required. At a conversion facility, uranium is converted to either uranium dioxide, which can be used as the fuel for reactors that do not require enriched uranium, or into uranium hexafluoride (UF), which can be enriched to produce fuel for the most common types of reactors.

2.4. Enrichment

A higher than natural concentration of Uranium 235 (^{235}U) (fissile isotope of uranium), is required to run most common types of nuclear reactors. This concentration is typically between 3.5 to 4.5% ^{235}U and is accomplished by enrichment, although some reactors can use natural uranium. The four main enrichment processes are gaseous diffusion, electromagnetic separation, gas centrifuge, and laser enrichment.

Enrichment by gas diffusion involves diffusing uranium hexafluoride (UF_6) through a porous membrane, which separates the ^{235}U and ^{238}U atoms due to their difference in mass. Gaseous diffusion plants use large volumes of water for cooling purposes and discharge heat to the surroundings. Liquid effluents from these plants may be diluted to a considerable extent with clean water prior to discharge, but low-flow collection areas might accumulate significant amounts of radioactive material. Moreover, liquids that may contain a significant concentration of uranium from the equipment cleanup or from auxiliary production facilities are collected in holding ponds. Radioactive sludge is deposited and can be removed for disposal (Bevelacqua 1995).

The mass difference between ^{235}U and ^{238}U is also the basis for electromagnetic separation. In this method, a uranium chloride salt (UCl_4) is heated to produce a vapor and ionized to give each molecule a charge. These molecules pass through a slit to create a beam and this beam travels a circular path due to a very strong magnetic field. While traveling this path, the molecules separate due to the mass difference between ^{235}U and ^{238}U atoms. When the beam separates into two beams, they travel through separate slits and are collected there. This method of enrichment is not very efficient; it is not currently used in the U.S., but it is sparingly used in China and Russia (U.S. Nuclear Regulatory Commission (NRC) 2008). A centrifuge is a device that rotates with a very high velocity. A gas centrifuge rotates gas, namely UF_6, very fast such that the heavier atoms containing ^{238}U are drawn to the outside. The UF_6 in the middle will be enriched with more ^{235}U than it originally had. The centrifuge method of isotope enrichment needs less than one-tenth the power required to operate an equivalent plant using gaseous diffusion. Gas centrifuges are the most commonly used method of uranium enrichment (Leclercq 1986).

The laser enrichment process relies on the difference in the wavelength of light absorbed by atoms of ^{235}U and ^{238}U or by molecules of their components. Corresponding combination of lasers are used to selectively excite one or the other isotope. In the process of molecular laser isotope separation, a laser is used to excite the molecules of UF gas containing $^{235}UF_6$, diluted in helium at about 220 degrees Celsius (°C). The laser does not affect the molecules containing the isotope ^{238}U. A second laser is used to dissociate the excited molecules to form uranium pentafluoride, which is then recovered as a white powder. In the Atomic Vapor Laser Isotope Separation process, an ingot of uranium metal in a vacuum enclosure is heated locally to 3,000°C by a focused electron beam. The ^{235}U in the resulting vapor is ionized by a laser and the ions collected electromagnetically (Leclercq 1986).

The laser separation processes are extremely promising; they require little power and involve only one separation step. These processes are used in the U.S. and France. A copper vapor laser is used to excite the molecules and a dye laser is used to selectively excite and ionize the ^{235}U atoms. The combined action of the electric and magnetic fields separates the isotopes.

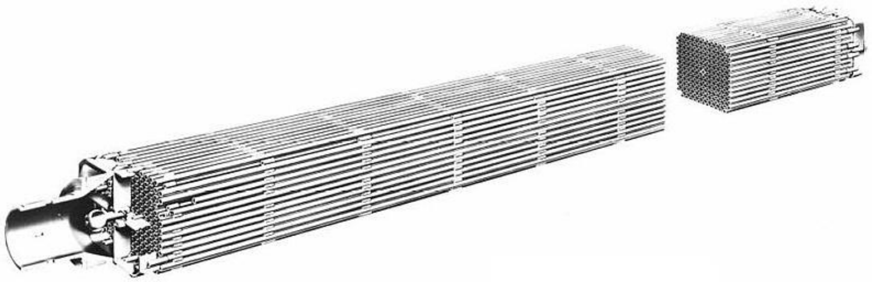
The primary acute hazard in methods involving gas forms of uranium are releases of UF_6 from the processing equipment. ^{235}U and ^{238}U are alpha emitters, so they are very harmful if inhaled. Also, when UF_6 is exposed to moist air, it combines with air to create gases that are highly corrosive and toxic. In facilities where a high volume of uranium is processed, the equipment builds up a large amount of waste that might cause a chronic exposure if not routinely cleaned. Additionally, when large amounts of waste builds up in one place, there is a chance of a criticality occurring that would result in acute exposures to personnel nearby. Eliminate buildup with proper geometry and batch controls.

2.5. Fuel fabrication

Fuel fabrication is the process in which the enriched UF_6 is used to produce uranium dioxide, which is generally used to make the reactor fuel as ceramic pellets. These pellets are formed from pressed uranium dioxide, which is sintered at a high temperature (over 1,400°C). Then, the pellets are encased in metal tubes, which are arranged into fuel assemblies ready for introduction into a reactor. The dimension of the fuel pellets and other components of the fuel assembly are precisely controlled to ensure consistency in the characteristics of fuel bundles and they vary among different plant designs. Figures 2.2 and 2.3 are pictures of UO_2 fuel pellets and fuel rods in the final stages of fuel fabrication.

Source: https://commons.wikimedia.org/wiki/Category:Uranium_pellets#/media/File:Nuclear_fuel_pellets.jpeg

Figure 2.2. Uranium Fuel Pellets



Source: https://commons.wikimedia.org/wiki/File:Nuclear_fuel_element.jpg

Figure 2.3. Uranium Fuel Rods

Mixed-oxide (MOX) fuels are commonly made by mechanically mixing plutonium and uranium dioxide powders. The uranium and plutonium powders are mixed and pressed into pellets at the fuel fabrication plant. The pellets are sintered, grounded to final dimensions, cleaned and loaded into long, thin tubes of zirconium alloy (for light water reactors (LWR)) or stainless steel (for fast breeders). The procedures are similar to that for fabrication of uranium dioxide fuel elements, except for the precautions taken to minimize release of the plutonium (NRC 1976).

The scrap material from the mixed-oxide fuel fabrication is described as “clean” or “dirty.” The clean scrap consists mainly of rejected fuel pellets that do not meet the specifications and powders too fine for pressing into pellets. This scrap is crushed and calcinated in air. The resulting solid is reduced by heating in hydrogen gas (from ammonia) and ground. The powder is then blended in with the fresh mixed-oxide feed (ORNL 1975).

All stages of the mixed-oxide fuel fabrication are designed to contain the potentially hazardous material to the maximum practical extent. Equipment is enclosed in glove boxes, which are closed chambers with a window glass front, with long-armed rubber gloves sealed into the box. Glove boxes are enclosed in an outer building that must be capable of withstanding maximum natural phenomena, such as earthquakes, hurricanes, tornadoes, and floods.

The air from each confinement area is exhausted through at least two high-efficiency particulate air (HEPA®) filters before being discharged. The exhaust air is continuously monitored for alpha-particle radiation and operations are to be stopped if radiation levels are unexpectedly high, usually long before they become unsafe.

The most important liquid wastes from the mixed-oxide fuel production facilities are those from the treatment of dirty scrap. Liquid wastes containing plutonium are normally evaporated. Then the vapor may be discharged with ventilation air, or it may be condensed and reused in the plant. Residues from the evaporators are solidified in cement (or other material) and disposed. Air containing radioactive waste gases, mainly nitrogen oxides, ammonia, and hydrogen fluoride, is scrubbed and filtered before discharge to the atmosphere (NRC 1976).

2.6. Reactor Operations

Inside a nuclear reactor, the nuclei of ^{235}U atoms are split (fission) and, in the process, release energy. This energy is used to heat the water and turn it into steam. The steam is used to drive a turbine connected to a generator that produces electricity. The fission of uranium is used as a source of heat in a nuclear power station in the same way that the burning of coal, gas, or oil is used as a source of heat in a thermal power plant.

2.6.1. Fission

Nuclear fission is the splitting of a larger atomic nucleus into two or more smaller nuclei. When heavy nuclei, such as those of uranium or plutonium, undergo fission, large quantities of energy are released. Fission and the neutron chain reaction are the foundation for the use of nuclear energy in power plants. Uranium-235 absorbs a neutron upon impact, resulting in an exited nucleus, which splits or fissions, and energy is released. The fragments of the broken nucleus, “fission products,” are radioactive. At least one of the neutrons formed by fission of a first uranium nucleus collides with another ^{235}U nucleus, causing a second fission that releases more neutrons, one of which collides with another uranium nucleus, causing a further fission.

2.6.2. Fissile, Fertile, and Fissionable Materials

Fissile materials are those that can undergo fission upon absorbing thermal (slow) neutrons. The three primary fissile materials are ^{233}U, ^{235}U, and ^{239}Pu. A fertile material is not itself fissile but can be converted into a fissile material by irradiation in a reactor. The two basic fertile materials are ^{238}U and ^{232}Th; these can be converted in a nuclear reactor into fissile ^{239}Pu and ^{233}U materials respectively. Fissionable material is commonly used as a synonym for fissile material, the meaning of this term has been extended to include material that can be fissioned by fast neutrons, such as ^{238}U.

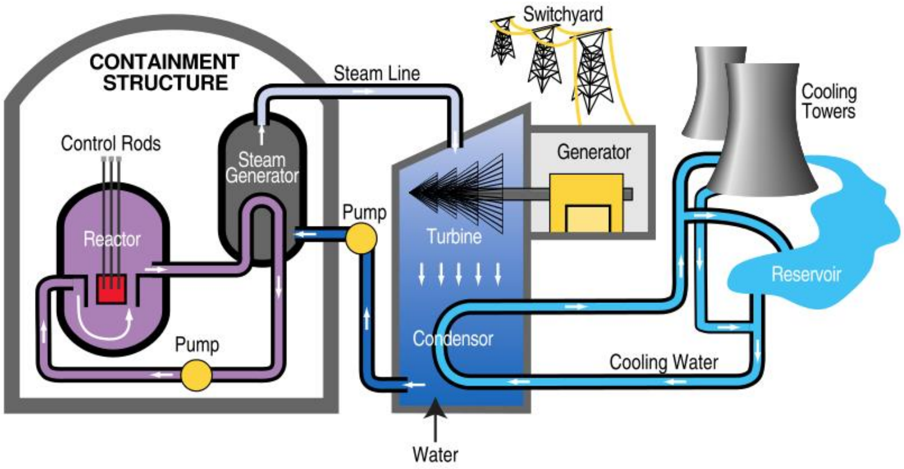
2.6.3. Nuclear Power Plants

Since nuclear power plants contain major sources of radiation within their systems, physical identification is important. The hyperbolic shape of their cooling towers is in many instances a characteristic feature of the nuclear power plants. Power plants can also have no distinctive cooling towers and use water from reservoirs in their cooling systems.

Plant systems and components that are sources of radiation exposure include:

- Main loop (primary), including major components.
- Reactor vessel.
- Reactor coolant.
- Reactor coolant purification system (including filters and demineralizers).
- Condensate purification system (boiling water reactor).
- Radioactive liquid waste processing systems (including tanks, filters, demineralizers, and evaporators).
- Spent reactor fuel.
- Radioactive gas waste processing systems (including tanks, compressors, charcoal bed absorbers, and filters).

All reactors rely on the same principles to produce electricity. The continuous fission process (chain reaction) maintained in the core releases energy in the form of heat. Coolant circulating through the reactor transfers this heat energy to a secondary cooling system that produces steam. This steam is used to drive the turbines that produce electricity. Typical reactor components include reactor pressure vessel, fuel, moderator control rods, coolant, steam generator, and containment. Figure 2.4 presents a schematic of a typical nuclear reactor.



Source: https://upload.wikimedia.org/wikipedia/commons/thumb/c/c3/PWR_nuclear_power_plant_diagram.svg/800px-PWR_nuclear_power_plant_diagram.svg.png

Figure 2.4. Schematic of a Typical Nuclear Reactor

2.6.3.1. Reactor Types

There are several types of reactors used for the production of electricity. The components and their orientation determine the various operating characteristics of each type of reactor. Certain designs are able to refuel “on-load,” that is, while the reactor is in operation, others must “shut down” to refuel. This becomes important in the process of identifying radiation levels during these types of operations. The type of fuel used and the amount being replaced will also vary with reactor type. Table 2.1 summarizes the different type of reactors in the world today (NRC 2019). This table also includes key information regarding the design of the reactors; that is, their type of fuel, moderator, and coolant.

This information can be used to help determine the appropriate course of action for evaluating sources of exposures, following adequate sampling protocol, performing needed decontamination, and deciding adequate response in the event of an accident or an unavoidable predicted exposure.

Table 2.1. Reactor Types Differentiated by the Combination of Fuel, Moderator, and Coolant

Reactor Design	Reactor Type	Fuel	Moderator	Coolant
LWR	PWR REP VVER	Enriched uranium	Light water	Pressurized water
	BWR	Enriched uranium	Light water	Boiling water
HWR	CANDU	Natural uranium	Heavy water	Pressurized heavy water
	Gentilly	Natural uranium	Heavy water	Boiling heavy water
	EL4, Bohunice	Natural uranium	Heavy water	Carbon dioxide gas
	Winfrith- SGHWR	Enriched uranium	Heavy water	Boiling water
	Fugen	Plutonium	Heavy water	Boiling water
GCR	UNGG Magnox	Natural uranium	Graphite	Carbon dioxide gas
	AGR	Enriched uranium	Graphite	Carbon dioxide gas
	HTGR	Enriched Uranium and Thorium	Graphite	Helium
LWGR	Beloyarsk	Enriched uranium	Graphite	Pressurized water
	RBMK	Enriched uranium	Graphite	Boiling water
	NPR, Hanford	Enriched uranium	Graphite	Light water
FBR	LMFBR FFTF	Enriched uranium or plutonium	none	Sodium
	Hallam	Enriched uranium	Graphite	Sodium
Other	OMR	Enriched uranium	Terphenyl	Terphenyl
	Arbus	Enriched uranium	Hydrogen carbide	Hydrogen carbide
	Training reactors	-	-	-
	Experimental reactors & others	-	-	-

Legend:
LWR = Light Water Reactor
PWR = Pressurized Water Reactor
BWR = Boiling Water Reactor
REP = “Reacteur Eau sous Pression” (French: “reactor pressurized water”)
VVER = “Vode Vodyanyye Energocheskiye Reaktor” (Russian: “water-water power reactors”)
HWR = Heavy Water Rector
CANDU = Canada Deuterium Uranium
EL4 = “Eau Lourde” (French: “heavy water”)
SGHWR = Steam Generating Heavy Water Reactor
GCR = Gas Cooled Reactor
UNGG = Uranium Natural Graphite Gas
AGR = Advanced Gas Reactor
HTGR = High Temperature Gas-Cooled Reactor
LWGR = Light Water Graphite Reactor
RBMK = “Reaktor Bolshoe Moshchnost’ Kipyacheniye” (Russian: “high power boiling water reactor”)
NPR = New Production Reactor
LMFBR = Liquid Metal Fast Breeder Reactor
FFTF = Fast Flux Test Facility
FBR = Fast Breeder Reactor
OMR = Organic Moderated Reactor

2.6.3.2. Radiation Sources from Nuclear Power Plants

The sources of radioactivity generated during the operation of a LWR may be spent fuel, fission products and neutron activation products, as illustrated in Table 2.2.

Table 2.2. Radiation Sources from a Nuclear Power Plant

Group source	Example radionuclides	Location in plant or process
Fuel	uranium, plutonium, fission products, activation products	core, spent fuel storage pool
Fission products	radionuclides such as those found in table 2.3	fuel, reactor effluents
Neutron activation products	Gases: ^{13}N, ^{16}N, ^{41}Ar Solids: ^{51}Cr, ^{54}Mg, ^{56}Mg, ^{58}Co, ^{60}Co, ^{59}Fe	systems, core components, reactor coolant system

The UO_2 fuel and its zirconium-alloy cladding should retain most fission products, including tritium generated in fission in light water reactors. However, gases and easily vaporized fission products, such as krypton, iodine, tritium, xenon, and some dissolved solid products can escape into the reactor water (Lamarsh 1983).

After a short period of time and because of radioactive decay, fission products constitute more than 300 radionuclides, all of which are radioactive (Lamarsh 1983). Many of these have a short half-life and can be ignored because they are formed in very small portions. Table 2.3 includes a list of the most important fission products, the type of radiation they emit and their half-lives. Although iodine is a solid at ordinary temperatures, it vaporizes readily so that part of the iodine in the fission products often appears together with the gases in the effluent from a reactor.

Tritium is the radioactive isotope of hydrogen and is produced because of fission. Tritium, although a fission product, can also be produced through other reactions. In LWRs, an important source of tritium is the interaction of neutrons of high energy with boron. Boron may be present in BWRs as a burnable poison (additive to the coolant to absorb excess neutrons and control criticality). In PWRs, boron may be dissolved (as boric acid) or it may be used in the control rods. Tritium can also result from the reaction of ^{6}Li with neutrons in some PWRs.

Table 2.3. List of Important Fission Products (Glasstone and Jordan 1980) (Eisenbud and Gesell 1997)

Radionuclide	Radiation	Half-life
Gases		
^{3}H	β	12.33 years
^{83m}Kr	γ	1.8 hours
^{85m}Kr	β, γ	4.5 hours
^{85}Kr	β, γ	10.7 years
^{87}Kr	β, γ	1.3 hours
^{88}Kr	β, γ	2.8 hours
^{133m}Xe	γ	2.2 days
^{133}Xe	β, γ	5.2 days
^{135m}Xe	γ	15.4 minutes
^{135}Xe	β, γ	9.1 hours
^{138}Xe	β, γ	14.1 minutes
Solids		
^{88}Rb	β	17.8 minutes
^{89}Sr	β, γ	50.6 days
^{90}Sr	β	28.74 years
^{90}Y	β	64.1 hours
^{91}Y	β, γ	58.5 days
^{129}Te	β, γ	1.2 hours
^{131m}Te	β, γ	30 hours
^{131}Te	β, γ	25.0 minutes
^{133}Te	β	12.4 minutes
^{129}I	β, γ	1.6E7 years
^{131}I	β, γ	8.0 days
^{133}I	β, γ	20.8 hours
^{135}I	β, γ	6.6 hours
^{134}Cs	β, γ	2.1 years
^{136}Cs	β, γ	13.2 days
^{137}Cs	β, γ	30.17 years
^{138}Cs	β, γ	32.2 minutes
^{140}Ba	β, γ	12.8 days
^{140}La	β, γ	1.68 days
^{144}Ce	β, γ	284.3 days
^{144}Pr	β, γ	17.3 minutes
^{147}Pm	β	2.62 years
^{151}Sm	β, γ	90 years

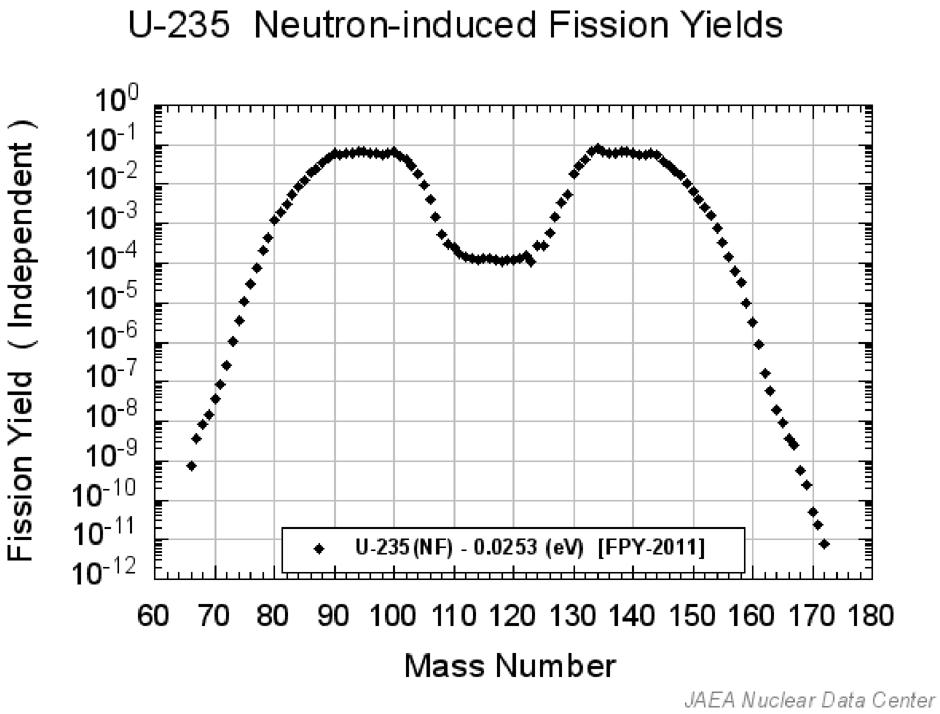


Figure 2.5. Fission Product Yield Curve, Thermal Neutron Fission of ^{235}U (Japan Atomic Energy Agency 2013)

Neutron activation products are formed in the reactor coolant by interaction of neutrons with water molecules (oxygen nuclei), oxygen, nitrogen, and argon dissolved in air. Tritium that is formed in the water from deuterium, boron, or lithium is also considered an activation product. The most important activation products are those arising from neutron reactions with various elements (such as iron, chromium, nickel, cobalt, and manganese) that enter the water because of corrosion and erosion of steel and alloys found in the reactor vessel, pumps, piping, valves, and steam generator. Table 2.4 identifies the most significant activation products.

Table 2.4. List of Most Important Activation Products

Activation Product	Activity	Half-life
Gases		
^{13}N	β	10 minutes
^{16}N	β, γ	7.13 seconds
^{41}Ar	β, γ	1.8 hours
Solids		
^{51}Cr	β, γ	27.7 days
^{54}Mn	γ	312.7 days
^{56}Mn	β, γ	2.6 hours
^{58}Co	β, γ	70.8 days
^{60}Co	β, γ	5.3 years
^{65}Zn	β, γ	244.4 days
^{59}Fe	β, γ	44.6 days

Activation products are also produced by the neutron irradiation of nonfuel materials. For example, tritium can be formed from the irradiation of hydrogen in the air and water. Other isotopes that can be formed this way are ^{14}C, ^{16}N, ^{17}N, ^{19}O, and ^{41}Ar. Sodium activation results in the production of isotopes ^{24}Na, ^{22}Na, and ^{86}Rb. Other alloys are activated and produce ^{28}Al, ^{51}Cr, ^{54}Mn, ^{56}Mn, ^{55}Fe, ^{59}Fe, ^{58}Co, ^{60}Co, ^{64}Cu, ^{65}Zn, ^{95}Zr, ^{110m}Ag, ^{182}Ta, and ^{187}W.

The presence of radioactive materials in the reactor coolant system (RCS) is a result of neutron activation of impurities, chemicals and the water contained in the system, and from the leakage due to defects in the reactor fuel rods. Although fuel rods are sealed and designed to contain fission products, minor defects develop and some fission products leak from the fuel into the reactor coolant system. The radioactive material is transferred from the fuel to other parts of the plant via RCS, reactor coolant cleanup systems, heat exchangers, pumps and vents, leaks and drains from these systems.

A percentage of the reactor coolant is continuously taken from the RCS for removal or cleanup of radioactive material. The cleanup systems are a source of radiation exposure because they contain radioactive water. Additional transport paths for radioactive materials are found in the liquid and gaseous waste disposal systems and subsystems of the cleanup system.

As water in the reactor coolant, reactor coolant cleanup and waste disposal systems flows through heat exchangers, they become a source of radiation exposure. Vents and drains from these systems transport radioactive material to other areas of the plant, as does unplanned leaks in system lines and components.

Activated corrosion products (crud) and fission products are often deposited in low-flow areas of systems containing radioactive liquids. The following examples of low-flow areas include: flanged dead legs, valves, bends in pipes (elbows), and so forth. As the radioactivity in these crud traps accumulates with time, the exposure rates increase resulting in hot spots.

Source: https://www.gettyimages.com/detail/photo/close-up-of-red-valves-in-industry-royalty-free-image/643835805?adppopup=true

Figure 2.6. Example of a Low-Flow Area

Traces of UO_2 may remain on the outside surface after fabrication of fuel elements. This is referred to as “tramp uranium” (Glasstone and Jordan 1980). Fission products (both gaseous and solid) from the fission of ^{235}U present in the reactor are released into the surrounding water. The amount of tramp uranium is usually quite small in amount, but it constitutes a possible source of radioactivity in the liquid effluent from nuclear power plants.

Table 2.5 includes the principal radiation exposure pathways from nuclear power plant effluents. Because of their relatively large yield in uranium fission and known affinity to be deposited in the thyroid (critical organ), ^{131}I and ^{133}I are very important sources of exposure. Cesium-133 and ^{137}Cs are radioisotopes of cesium of most importance and are also produced in significant amounts in fission. Cesium becomes uniformly distributed throughout the body and exposes all organs to beta-gamma radiation. Cesium can enter the body by drinking water or milk, or by eating fish from the general vicinity of the liquid effluent discharged from the plant. The internal (lung) dose from inhalation of radioactive isotopes of noble gases, which may be found as part of airborne effluents, is very small. If adequate holdup is provided before release to the atmosphere, exposure to short-lived noble gases, such as ^{133}Xe and ^{88}Kr can be minimized during normal operations. However, long-lived ^{85}Kr may cause significant exposure if there is atmospheric accumulation.

Gaseous and liquid effluents contain tritium, which produces small radiation doses. However, tritium can accumulate in the environment, as ^{85}Kr does. The whole body dose equivalent from tritium intake would depend on the amount deposited in the body, which can be directly related to its concentration in the food (including milk) and water consumed.

Table 2.5. Radiation Exposure Pathways from Nuclear Plants

Radiation from:	Effluent	Exposure Pathway	Critical Organ
Iodine isotopes	Airborne	Ground deposition (external)	Whole body
		Air inhalation	Thyroid
		Grass → cow → milk	Thyroid
		Leafy vegetables	Thyroid
	Liquid	Drinking water	Thyroid
		Fish (and shellfish consumption)	Thyroid
Tritium	Airborne	Submersion (external)	Skin
		Air inhalation	Whole body
	Liquid	Drinking water	Whole body
		Food consumption	Whole body
Cesium isotopes	Airborne	Ground deposition (external)	Whole body
		Grass → cow → milk	Whole body
		Grass → cow → meat	Whole body
		Inhalation	Whole body
	Liquid	Sediments (external)	Whole body
		Drinking water	Whole body
		Fish consumption	Whole body
Isotopes of metals (iron, cobalt, nickel, zinc, manganese)	Liquid	Drinking water	GI tract
		Fish consumption	GI track
Direct radiation from plant		External	Whole body

2.7. Spent Fuel and Storage

The concentration of fission fragments in a fuel bundle will increase with time to the point where it is no longer practical to continue to use the fuel. At this point, the spent fuel is removed from the reactor. When removed from the reactor, fuel bundles emit radiation, primarily from the fission fragments, and heat. Spent fuel is unloaded into a storage facility, immediately adjacent to the reactor, to allow the radiation levels and the quantity of heat being released to decrease. These facilities are large pools of water, which act as both shields against the radiation and absorbers of the heat released. The Cherenkov Effect can be observed in a spent fuel storage pool; high-energy electrons, traveling faster than light in water, emit a brilliant blue illumination as they are slowed down.

During the cooling period, partial decay of the various radionuclides occurs. These radionuclides include fission products, isotopes of heavy elements and activation products, as the ones mentioned earlier. The most important consequences of cooling are the following:

1) Fission products of short or moderately short half-life decay almost completely;
2) The overall beta and gamma activities are decreased to a level at which radiological decomposition of the subsequently used reprocessing agent would be tolerable; and
3) Certain undesirable heavy isotopes decay into elements, which can be separated from desired products (Glasstone and Sesonske 1981).

Spent fuel is generally held in the storage pools for a minimum of about 5 months. A minimum cooling period of 150 days is generally required and commonly used as a point of reference in light water reactors. The main objective of the 150-day cooling period is to allow for substantial decay of volatile fission products that can be released to the environment. Iodine is volatile and release to the environment must be minimized. After the 150 day of cooling, the major contributors to the radioactivity of spent fuel are listed in Table 2.6. The values in this table are in curies and becquerels per metric ton (1,000 kilograms (kg)) of uranium. The uranium is assumed to be initially free of plutonium when charged to the reactor. The values in Table 2.6 were calculated for a hypothetical LWR having a thermal power of 3,300 megawatts and a specific fuel burnup of 2.85E12 Joules (2.85 TeraJoules, thermal) per kg of uranium in the original fuel. Other operating conditions will derive different activities; however, those in the table are fairly typical.

Table 2.6. Major Contributors of Radioactivity from Spent Fuel (LWR fuel) after 150 Days Cooling Period (Glasstone and Sesonske 1981)

Radionuclide	**Radiation**	**Half-life**	**Activity**	
			Bq/1000 kg U	Ci/1000 kg U
Fission Products				
^{89}Sr	β	50.6 days	3.6E15	9.6E04
^{90}Sr	β	28.74 years	2.8E15	7.7E04
^{95}Zr	β, γ	64.0 days	1.0E16	2.8E05
^{95}Nb	β, γ	35.1 days	1.9E16	5.2E05
^{106}Ru	β	373.59 days	1.5E16	4.1E05
^{134}Cs	β, γ	2.1 years	7.7E15	2.1E05
^{137}Cs	β, γ	30.17 years	4.1E15	1.1E05
^{144}Ce	β, γ	284.3 days	2.8E16	7.7E05
^{147}Pm	β	2.62 years	3.7E15	9.9E04
Heavy-elements Isotopes				
^{238}Pu	α, γ	87.8 years	1.1E13	2.8E02
^{239}Pu	α, γ	2.41E4 years	1.2E13	3.3E02
^{240}Pu	α, γ	6,569 years	1.8E13	4.8E02
^{241}Pu	α, β ,γ	14.35 years	4.1E15	1.1E05
^{242}Pu	α, γ	3.76E5 years	5.0E10	1.36
^{241}Am	α, γ	432.2 years	7.4E12	2.0E02
^{243}Am	α, γ	7,380 years	6.4E11	17.4
^{241}Cm	α, γ, SF*	32.8 days	5.5E14	1.5E04
^{244}Cm	α, γ, SF*	18.1 years	9.3E13	2.5E03

Notes: * Spontaneous fission (SF). These radionuclides go through significant spontaneous fission, which is accompanied by neutron emission.

For a cooling period of 150 days or more, a few fission products—that is, strontium, zirconium, niobium, ruthenium, cesium, and some rare earth elements—are responsible for nearly the entire radioactivity. These are the most important elements from which U and Pu must be separated in spent fuel reprocessing. Ultimately, spent fuel must either be reprocessed or sent for permanent disposal.

2.8. Reprocessing

Spent fuel is about 95% ^{238}U but it also contains ^{235}U that has not fissioned, plutonium and fission products, which are highly radioactive. In a reprocessing facility the spent fuel is separated into its three components: uranium, plutonium, and waste containing fission products. The most common process used is called PUREX (plutonium and uranium recovery by extraction). This process uses liquid solvent extraction principles coupled with oxidationreduction chemical reactions to separate the various constituents of the spent fuel chemically. Generally, reprocessing is done by cutting fuel assemblies into pieces, dissolving the contents of the fuel rods with nitric acid, and applying a solvent extraction method. This generates three principal components: uranium, plutonium, and fission products.

Large quantities of fission products are produced during reprocessing and must be managed to avoid environmental contamination, which may occur during normal operations or because of an accident. In fission, ^{129}I (half-life of 1.6E7 y) is produced with a yield of 1% and, therefore, it is present in large quantities in the reprocessing waste and it may accumulate in the environment. The release of this gas can cause an increase to the thyroid dose to the general population (Eisenbud and Gesell 1997).

Other radioactive gaseous releases from nuclear fuel-reprocessing plants include ^{85}Kr and ^{3}H. The dose from these gases to individuals is expected to be small but they can accumulate in the environment and expose large numbers of people. Krypton does not participate in the metabolic process and its principal dose contribution is from external contamination. Tritium gas is combined with oxygen to produce tritium oxide. If tritium enters the body, over-hydration is recommended to minimize the dose by increasing its biological elimination. Liquid tritium can be disseminated in the environment as water and enter the hydrological cycle.

Nuclear power reactors shut down for refueling roughly once a year. About one-third (in a PWR) or a fourth (in a BWR) of the fuel is removed and, after some rearrangement, is replaced by fresh fuel. The spent fuel rods contain most of the ^{238}U and roughly one-third of the ^{235}U originally present, along with all the fission products formed during operations (apart from the small proportion that may have escaped through cladding defects). The spent fuel also contains ^{239}Pu, resulting from the capture of neutrons by ^{238}U, and smaller amounts of other isotopes of plutonium and of the transuranic elements neptunium, americium, and curium.

The fuel reprocessing operations are designed to remove the highly radioactive fission products and unwanted transuranic elements, and to separate the plutonium from the uranium. After conversion to uranium hexafluoride, the uranium can be re-enriched in ^{235}U to make it suitable for use as fresh reactor fuel. The plutonium could be used as a partial replacement for ^{235}U in a LWR, or as the fuel in a fast breeder reactor (ORNL 1975). The plutonium can also be used in the fabrication of nuclear weapons.

2.9. Wastes

The radiation waste systems are those used for treatment of the various radioactive liquids and gases prior to discharge to the environment. The function of these systems is to reduce the radioactivity levels in the plant effluents so they are below the limits specified by regulation. Appendix C includes the classification of radioactive waste by current regulatory agencies in the U.S. This chapter includes a description of the liquid and gas solid waste found in LWRs. Table 2.7 includes examples of radioactive wastes from the nuclear fuel cycle and their estimated activity (Some of the waste is based on fuel that has been exposed 20,000 megawatt-days per metric ton (MWd/ton) of U and other waste based on fuel that has been further cooled for about 120 days) (Introduction to Health Physics 1996).

Table 2.7. Examples of Wastes from the Nuclear Fuel Cycle

Cycle Process	Type of Waste by its physical state	Principal Radionuclides and contents	Radioactivity Level (approximate) Bq/ton U [Ci/ton U]
Mining and Milling	Gaseous	^{210}Po, ^{214}Bi, ^{214}Po, ^{218}Po, ^{222}Rn	4E6 – 4E7 [1E-4 – 1E-3]
	Liquid and Solid	U, ^{226}Ra, ^{230}Th, ^{210}Pb	2E10 – 4E10 [0.5 - 1]
Conversion and Enrichment	Liquid	^{238}U, ^{234}Th, ^{234}Pa, ^{226}Ra	4E6 – 4E7 [1E-4 – 1E-3]
Fuel Fabrication	Liquid and Solid	U, Pu, Th	4E6 – 4E7 [1E-4 – 1E-3]
Reactor Operations	Gaseous	^{13}N, ^{41}Ar, ^{89}Kr, ^{87}Kr, ^{135}Xe, ^{138}Xe	4E11 - 4E12 [10-100]
	Liquid and Solid	^{58}Co, ^{60}Co, ^{59}Fe, ^{51}Cr, ^{3}H	2E12 – 4E12 [50 - 100]
Waste Reprocessing	Gaseous	^{85}Kr, ^{133}Xe, ^{129}I, ^{131}I, ^{3}H	26E13 [7E3]
	Liquid and Solid	Fission Products Pu, Am, Cm	22E16 [6E6]

2.10. High Level Waste Reprocessing

Table 2.8 lists some of the most significant solid reprocessing high-level-waste nuclides (Johnson 2012). These are usually produced from reactors (spent fuel), reprocessing activities, weapon production, and research activities. High-level wastes (HLW) are reprocessed in the same fashion as during the reprocessing described above by solvent extraction. Table 2.9 includes the typical composition of the liquid HLW from a LWR spent fuel.

Table 2.8. Radionuclides found in High Level Solid Radioactive Wastes

Radionuclide	Radiation	Half-life (years)
Fission Products		
Strontium-90	β	28.74
Technetium-99	β	2.1E5
Cesium-137	β, γ	30.17
Transuranics		
Plutonium-238	α	87.8
Plutonium-239	α	2.41E4
Plutonium-240	α, neutrons*	6.569E3
Americium-241	α	432.2
Americium-243	α	7.38E3
Curium-244	α, neutrons*	18.1

Note: *neutrons arise from spontaneous fissions.

Table 2.9. Typical Composition of Liquid HLW from LWR Fuel (Glasstone and Sesonske 1981)

Waste	Amount (kg/1000 kg fuel)
Reprocessing and Corrosion	
Hydrogen (free acid)	0.40
Nitrate	65.8
Phosphate	0.9
Iron	1.1
Nickel	0.1
Chromium	0.2
Fission Products (total in solution)	28.8
Actinides	
Uranium	4.8
Plutonium	0.04
Neptunium	0.76
Americium	0.14
Curium	0.04
Total	103

Treating the liquid wastes in various ways has developed several forms of high level reprocessing wastes. The two most common types of reprocessing are drying and calcination, and vitrification.

2.11. Disposal

There are three practices of radioactive waste disposal, which include: disperse and dilute, concentrate and contain, and delay and decay. The ALARA (as low as reasonably achievable) principle influences the development of waste disposal plans.

Low-level radioactive waste is produced by users of radioactive materials, including hospitals, research laboratories, universities, manufacturers, and nuclear power plants. Nuclear power plants produce most of the volume, and most of the radioactivity, of low-level radioactive waste.

All low-level waste is solid. It consists of common everyday items such as protective clothing, gloves, plastic laboratory supplies, filters, machine parts, and tools that have encountered radioactive materials. It does not include used fuel from nuclear power plants. The level of radioactivity in almost all low-level waste decays to background levels within weeks, months, or years. A small percentage of this waste stays radioactive for about 500 years or longer.

Both nuclear power plants and reprocessing plants produce low and medium radioactive waste that is encapsulated in asphalt or concrete and placed in metal or concrete drums, depending on the level of radioactivity. The following figure is an example of disposal of low and medium radioactive waste. There are three barriers to prevent release of radioactivity: the waste drums, the concrete pad, and the clay overburden. A rainwater recovery system can be used to collect and monitor runoff.

Source: https://www.flickr.com/photos/simplyinfo/32597270477/in/photolist-qWSWvZ-qX2c44-qWSWyV-qWSWxn-ffYJc2-q1fqvB-qWSWvi-qAg2rb-q4jKYx-qAg2eY-qWSWcx-nKXNXa-qX2c9e-nKXNde-qAg2b1-q1fqup-qAmCXk-qX2cfg-7iTxjt-nMX8zS-2e3uuoT-Ti9Nef-REvwQM-cABkN5-qWSWoK-dUpGh2-qAg2rG-dUviJL-7dsh1T-fozook-q4bKwu-qX2cfM-pVWF3T-qU5SSS-jDNWRa-qAgqmP-qAgjQP-qQqBdo-hunRYd-cABiTY-qSHCpV-cABhZf-cABh4o-BzM1Vp-2g5atxs-hmgyYR-Gen135-hmgyZ2-5J1vKK-Mpw5P4

Figure 2.7. Radioactive Waste Drums

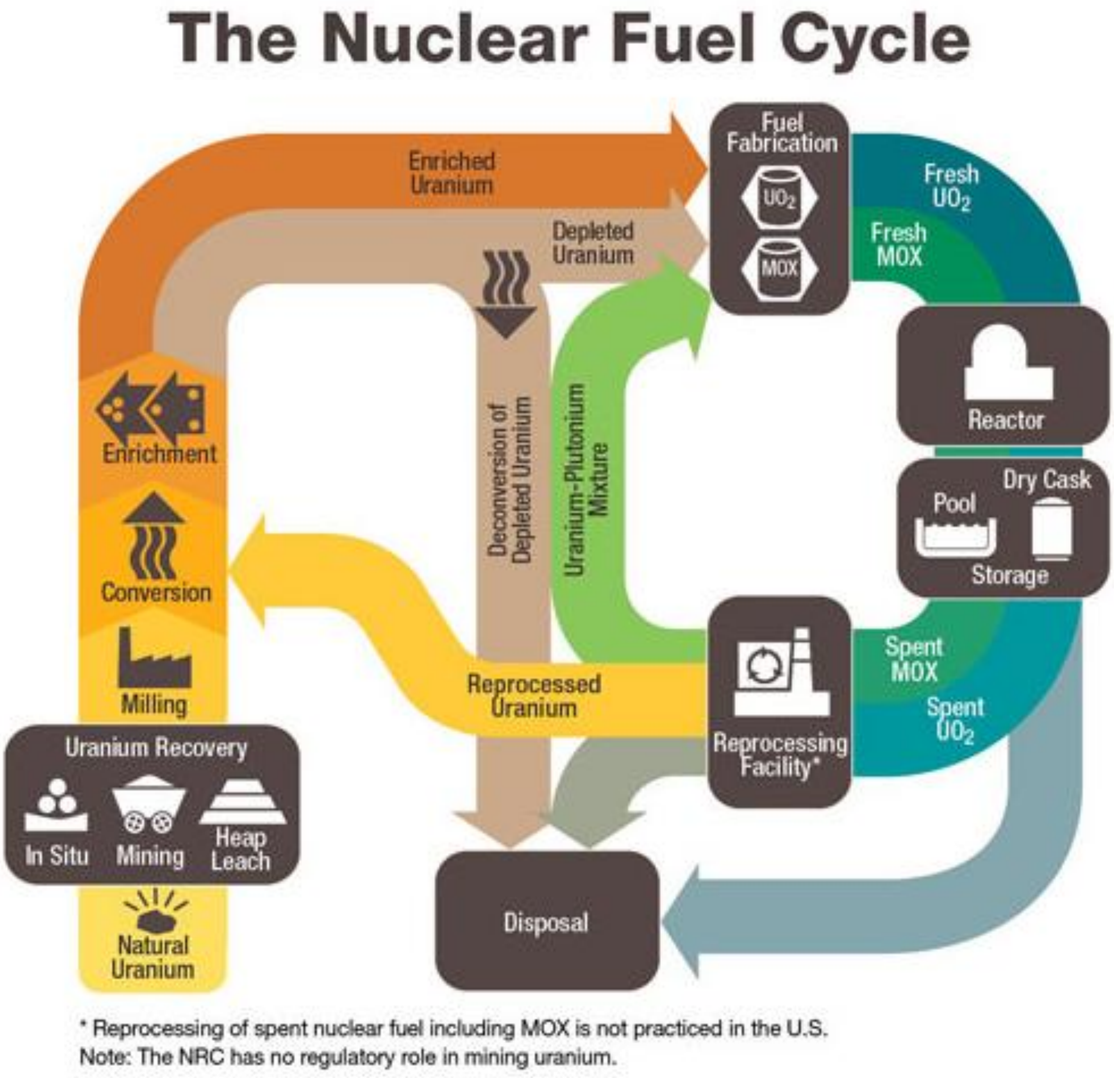
2.12. Summary of Radiation Sources from the Nuclear Fuel Cycle

Table 2.10 summarizes the sources addressed in this chapter throughout the entire fuel cycle.

Table 2.10. Summary of Radiation Sources from the Nuclear Fuel Cycle

Process	Radionuclides	Radiation	Longest half-life	Approximate radioactivity level in Bq/ton U [Ci/ton U]
Mining and Milling	^{235}U and its daughters (^{231}Th, ^{231}Pa, ^{227}Ac, ^{227}Th, ^{223}Ra, ^{219}Rn, ^{215}Po, ^{211}Pb, ^{211}Bi, ^{207}Tl)	α, β, γ	~1 E8 y	Gases ~1E7 [1E-3] Liquids and solids ~1E10 [1]
	^{238}U and its daughters (^{234}Th, ^{234}Pa, ^{234}U, ^{230}Th, ^{226}Ra, ^{222}Rn and its daughters)	α, β, γ	~1E9 y	
	^{222}Rn and its daughters (^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po, ^{210}Pb, ^{210}Bi, ^{210}Po)	α, β, γ	21 y	
Conversion	Same radionuclides as above. Radioisotopes are found in the conversion process and in the low-level waste.	α, β, γ	1E9 y	Gases ~1E7 [1E-3] Liquids and solids ~1E7 [1E-3]
Enrichment	Same radionuclides as above. Two main concerns are the enriched product containing ^{235}U and the depleted uranium (mostly ^{238}U) waste	α, β, γ	1E9 y	Gases ~1E7 [1E-3] Liquids and solids ~1E7 [1E-3]

Process	**Radionuclides**	**Radiation**	**Longest half-life**	**Approximate radioactivity level in Bq/ton U [Ci/ton U]**
Fuel Fabrication	Same radionuclides as above in low level radioactive waste (liquid and gas waste)	α, β, γ	1E9 y	Gases ~1E7 [1E-3] Liquids and solids ~1E7 [1E-3]
	Pu isotopes from the MOX fuel fabrication process, liquid waste and gasses	α, β, γ, ν	1E9 y	
Reactor Operations	Same radionuclides as above plus: ^{239}U, ^{240}U, ^{239}Np, ^{240}Np, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{243}Pu, ^{241}Am, ^{243}Am	α, β, γ, ν	1E9 y	Gases ~1E12 [100] Liquids and solids ~1E12 [100]
	Fuel (core and spent fuel pool)			
	Same as above and mainly U and Pu isotopes, plus fission products and activation products	α, β, γ, ν	1E9 y	
	Fission products (in fuel and reactor effluents)			
	Gases: ^{3}H, ^{83m}Kr, ^{85m}Kr, ^{85}Kr, ^{87}Kr, ^{88}Kr, ^{133m}Xe, ^{133}Xe, ^{135m}Xe, ^{135}Xe, ^{138}Xe	β, γ	12.3 y	
	Solids: ^{88}Rb, ^{89}Sr, ^{90}Sr, ^{90}Y, ^{91}Y, ^{95}Zr, ^{95}Nb, ^{106}Ru, ^{129}Te, ^{131m}Te, ^{131}Te, ^{133}Te, ^{131}I, ^{133}I, ^{135}I, ^{134}Cs, ^{136}Cs, ^{137}Cs, ^{138}Cs, ^{140}Ba, ^{140}La, ^{144}Ce, ^{144}Pr	β, γ	30 y	
	Neutron activation products (in systems, core components, reactor coolant system)			
	Gases: ^{13}N, ^{16}N, ^{41}Ar	β, γ	2 h	
	Solids: ^{51}Cr, ^{54}Mg, ^{56}Mg, ^{58}Co, ^{60}Co, ^{59}Fe	β, γ	5.3 y	
Waste / Reprocessing	Most of radionuclides with longer half-lives	α, β, γ, ν	1E9 y	Gases ~1E14 [1E3] Liquids and solids ~1E17 [1E6]



* Reprocessing of spent nuclear fuel including MOX is not practiced in the U.S.
Note: The NRC has no regulatory role in mining uranium.

Source: http://www.nrc.gov/images/materials/fuel-cycle-fac/nuclear-fuel-cycle-02.jpg

Figure 2.8. The Nuclear Fuel Cycle

CHAPTER 3. BIOMEDICAL SOURCES

Biomedical sources of radiation are readily available at hospitals and some laboratories, which could present an exposure hazard. Medical facilities may use large sources, which are made safe with appropriate shielding. During hostile conditions such as a battle or an action of sabotage, the shielding safeguarding these sources may be breached and environmental release or exposure to personnel may occur. Force Health Protection leaders should incorporate these hazards into mission analysis.

3.1. General Sources of Exposure from the Medical Uses of Radiation

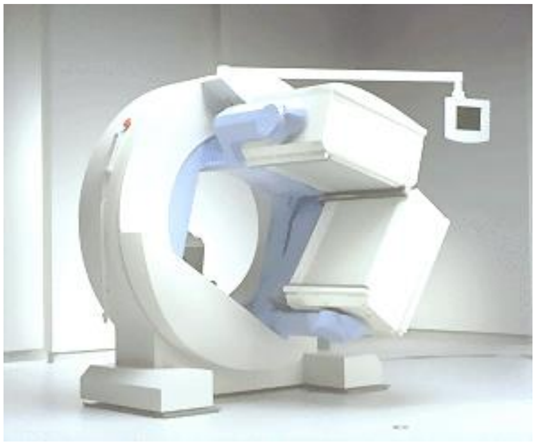
Radionuclides used in medicine are sealed or unsealed sources. One can find unsealed sources in clinical laboratories for analyzing blood samples, in the research laboratories for in vitro and animal studies, and in the nuclear medicine department for both diagnosis and therapy. Unsealed sources for therapeutic uses may also be found in the departments of endocrinology or radiation therapy.

Medical uses of radiation are roughly broken into two areas: diagnosis and therapy. Diagnosis includes routine x-rays, fluoroscopic examinations, computed tomography exams, and exams performed in nuclear medicine. Therapy is primarily the treatment of cancer. Therapy includes radiation from radiation-producing equipment, such as linear accelerators, radioisotope-generating machines, and brachytherapy sources. This TG will focus on the radioactive material potentially found in the medical environment.

3.2. Sources in Nuclear Medicine

Nuclear medicine uses radiation in order to provide information about a person's anatomy and the functioning of specific organs. The positioning of a radiation source within the body makes the fundamental difference between nuclear medicine imaging and other diagnostic techniques.

Tracers are used in nuclear medicine in the form of radiopharmaceuticals, which are attracted to specific organs, bones, or tissues. Radiopharmaceuticals introduced into the body produce radiation emissions. A special type of camera, a gamma, positron emission tomography (PET) camera, or a single photon emission computed tomography (SPECT) camera, is used to transform these emissions into images and data, which provide information about the area of the body being imaged. Gamma imaging provides a view of the position and concentration of the radioisotope within the body. Organ malfunction can be indicated if the isotope is either partially taken up in the organ (cold spot), or taken up in excess (hot spot). If a series of images is taken over a period of time, an unusual pattern or rate of isotope movement could indicate malfunction in the organ (Sorenson 1987). The gamma camera is not a source of radiation itself, unless it is contaminated with a radiopharmaceutical. Figures 3.1, 3.2, 3.3, and 3.4 are images of different nuclear imaging cameras that may be found in a hospital.



Dual head Gamma Camera: http://www.istockphoto.com/photo/gamma-camera-gm186831409-17106701?st=1bbdd16

Figure 3.1. Gamma Camera with Dual Head System (left)

Orbiter SPECT gamma camera: Courtesy of Walter Reed National Military Medical Center
Diacam gamma camera: https://openi.nlm.nih.gov/detailedresult.php?img=PMC4145160_WJNM-12-94-g002&query=&req=4&npos=-1

Figure 3.2 and Figure 3.3. An "Orbiter" SPECT Gamma Camera (left) and a Diacam Gamma Camera (right)

Pet scan: http://www.istockphoto.com/photo/man-having-a-medical-examination-gm174988659-22547927?st=a9eafe7

Figure 3.4. A PET Scanner Unit

By putting a radioactive isotope in the body, its path through the body can be tracked by an external monitor. If the radioisotope mimics a particular chemical, one can see exactly where that chemical goes, at what rate, and where in the body it accumulates. For this reason, there are large numbers of specially developed isotopes for specific diagnostic imaging tasks.

Radioisotopes are also used in cancer treatment. In such treatment, the radiation is used selectively to irradiate and kill cancerous cells and tumors. An even more selective process involves sending-in masked isotopes to lodge in a cancerous cell to kill it internally.

Nuclear medicine generates some wastes, both in the process of making radioactive isotopes and in treating patients. That waste comes in both high and low level radioactive forms. Therefore, a Soldier should be aware of the possible presence of such waste when entering areas linked to nuclear medicine procedures.

There are many choices of radioisotopes for performing human studies in nuclear medicine. Table 3.1 lists these isotopes and their half-life, type of radiation, and application in the medical field. From this table ^{99m}Tc is the most commonly used in nuclear medicine, followed by ^{201}Tl, ^{131}I, ^{125}I, ^{67}Ga, ^{111}In, ^{123}I, ^{133}Xe, and ^{127}Xe. Table 4.2 also includes radioisotopes used in radiation therapy procedures, quality control, and biomedical research.

Table 3.1. Summary of Biomedical Radiation Sources and Most Commonly Used Radionuclides in Nuclear Medicine, Radiation Therapy, and Biomedical Research

Source	Radiations	Half-life	Application
X-rays	γ	n/a	X-ray equipment, CT, fluoroscopy, linear accelerator (Not a hazard, unless functional)
Nuclear Medicine equipment	All	n/a	Nuclear medicine diagnostic equipment, such as Gamma Cameras
Isotopic generators	All	n/a	Generators of radioisotopes to be used in nuclear medicine as radiopharmaceuticals; for example, the ^{99}Mo-^{99m}Tc generator
Therapy Units	γ	n/a	Radiation therapy units, such as ^{60}Co or ^{137}Cs therapy units.
Brachytherapy Equipment	All	n/a	Equipment used in the application of brachytherapy
^{198}Au	$\beta-, \gamma$	2.7 d	Brachytherapy
^{18}F	$\beta+, \gamma$	1.8 h	PET studies for brain physiology and pathology, for localizing epileptic focus, psychiatry and neuropharmacology studies
^{67}Ga	γ	79.2 h	Tumor imaging and localization of inflammatory lesions (infections)
^{123}I	$\beta+, \gamma$	13.1 h	Diagnosis of thyroid function, brain, kidney and myocardial imaging
^{125}I	γ	60.1 d	Glomerular filtration rate of kidneys, deep vein thrombosis in the leg, radioimmunoassays, as an x-ray source for bone density measurements, brachytherapy and biomedical research
^{131}I	$\beta-, \gamma$	8.0 d	Thyroid functional imaging, thyroid therapy, liver function, renal (kidney) blood flow and urinary tract obstruction studies, biomedical research
^{111}In	γ	2.80 d	Brain studies, infection and colon transit studies
^{99}Mo	$\beta-, \gamma$	67.2 h	Generation of technetium 99m

Source	Radiations	Half-life	Application
^{32}P	β–	14.26 d	Treatment of polycythemia rubra vera (excess red blood cells)
^{226}Ra	α, (Rn x rays)	1600 y	Brachytherapy, target isotope to make ^{227}Ac, ^{228}Th, ^{229}Th
^{99m}Tc	γ	6.0 h	Most commonly used radionuclide in nuclear medicine, used in scintigraphy (imaging of brain, thyroid, lungs, liver, spleen, kidneys, gall bladder, skeleton, blood pool, bone marrow, salivary and lachrymal glands, heart blood pool, others.
^{201}Tl	γ	72 h	Myocardial perfusion imaging, for diagnosis and location of myocardial infarction (heart muscle death)
^{192}Ir	β–, γ	74.0 d	PET studies
^{127}Xe	γ	36.4 d	Pulmonary ventilation studies
^{133}Xe	β–, γ	5.2 d	Pulmonary ventilation studies, brain SPECT

3.2.1. Reactor-produced Isotopes

Isotopes used in medicine can be byproducts of the fission reaction of ^{235}U. These byproducts, including ^{133}Xe, ^{99}Mo, and ^{131}I, are produced in in nuclear research reactors. The nuclear power industry considers these byproducts waste; however, once purified adequately they become suitable for human use. Due to supply issues and proliferation concerns, more ^{99}Mo is instead being generated using particle accelerators (Galea 2013).

3.2.2. Generator/Accelerator-produced Isotopes

Generators are used to produce radioactive isotopes such as ^{68}Ga, ^{81m}Kr, ^{82}Rb, ^{99m}Tc, and ^{113m}In. For medical applications however, the workhorse isotope is ^{99m}Tc. Its supply is dependent on the production of its "parent," the reactor produced isotope ^{99}Mo. Technetium-99m is desired due to its ideal imaging energy and physical half-life as well as the ability to bind to so many compounds. Accelerators and generators are covered in more detail in Appendix B.

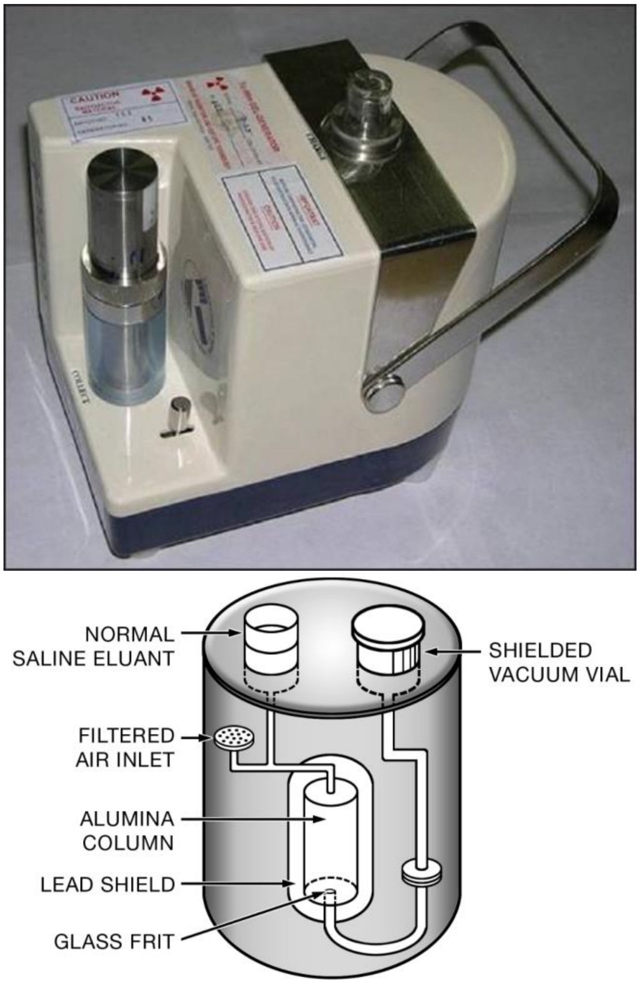
3.2.3. Radioisotope Generators

A generator is a self-contained system housing a parent/daughter mixture in equilibrium, which is designed to yield the daughter for some purpose after separating it from the parent (Sorenson 1987). The principal utility is to produce certain radioisotopes (on-site) which, because of their short half-lives, cannot be shipped by commercial sources. To be useful, the parent's half-life must be long compared to the travel time required to transport the generator to the recipient. Commercially prepared generators are sterilized, well shielded and largely automated in operation. The following table includes some of the common radionuclide generators used in nuclear medicine.

Table 3.2. Common Radionuclide Generators used in Nuclear Medicine

Daughter	Decay Mode	Half-life	Parent	Half-life
^{68}Ga	β+, EC	66 min	^{68}Ge	270.82 d
^{82}Rb	β+, EC	1.3 min	^{82}Sr	25.55 d
^{87m}Sr	IT	2.8 h	^{87}Y	79.8 h
^{99m}Tc	IT	6 h	^{99}Mo	65.94 h
^{113m}In	IT	102 min	^{113}Sn	115.09 d

The most important generator is the ^{99}Mo - ^{99m}Tc system because of the widespread use of ^{99m}Tc for radionuclide imaging. Technetium-99m emits gamma rays (140 keV) that are very favorable for use with a gamma camera. It has a reasonable half-life (6 hours), delivers a relatively low radiation dose per emitted gamma ray, and can be used to label a wide variety of imaging pharmaceuticals. Figure 3.5 is a picture of a ^{99}Mo - ^{99m}Tc generator. Of the available ^{99m}Tc activity, 75–85% is typically extracted in a single elution. Although the activity of ^{99m}Tc builds up after an elution and reaches maximum activity in about 24 hours, usable quantities are available in 3–6 hours. Generators are typically used for about 1 week and then discarded because of the natural decay of the ^{99}Mo (Sorenson 1987). Figure 3.6 shows the inside of a typical ^{99}Mo - ^{99m}Tc generator.



Sources: Figure 3.5: https://openi.nlm.nih.gov/detailedresult.php?img=PMC3800314_IJNM-28-70-g001&query=geltech&it=xg&req=4&npos=2
Figure 3.6: U.S. Army Public Health Center

Figures 3.5 and Figure 3.6. ^{99}Mo-^{99m}Tc Generator

3.3. Radiopharmaceuticals

Radiopharmaceuticals are radioactive drugs used for the purpose of diagnosis or therapy. They typically elicit no physiological response from the patient. The design of these compounds is based solely upon physiological function of the target organ. Unlike radiographic procedures, which depend almost entirely upon tissue density differences, external imaging of radiopharmaceuticals is essentially independent of the density of the target organ.

Radiopharmaceuticals can be categorized in the following manner: ready-to-use, instant kits for preparation of ^{99m}Tc products, kits requiring heating, and products requiring significant manipulation. Examples of each of these categories are listed in Table 3.3.

Table 3.3. Types of Radiopharmaceuticals

Pharmaceutical type	Example
Ready-To-Use	^{123}I capsules ^{131}I hippuran ^{67}Ga citrate ^{201}Tl chloride ^{133}Xe gas ^{99m}Tc pertechnetate
Instant Tc-99m kits	Disofenin DTPA GH HDP MDP mebrofenin MIAA MAA PYP
Tc-99m Kits requiring heating	MAG3 sestamibi sulfur colloid teboroxime
Products requiring significant manipulation	Cr-RBC's ^{99m}Tc RBC's ^{99m}Tc WBC's ^{111}In WBC's, ^{111}In Platelets ^{133}Xe in saline ^{123}I MIBG certain IND's

Legend:

DMO = dimethyloxazolidinedione
DTPA = diethylenetriaminopentaacetate
EDTA = ethylenediaminetetraacetate
GH = glucoheptonate
HDP = hydroxymethylenediphosphonate
HIDA = hepatobilary iminodiacetate
HIPDM = hydroxyliodobenzylpropanediamine
HAS = human serum albumin
IMP = iodoamphetamine
IND = investigational new drug
MAA = macroaggregated albumin
MAG3 = mercaptoacetyltriglycine
MIBG = metaiodobenzylguanidine
MDP = methylenediphosphonate
MIAA = microaggregated albumin
PYP = pyrophosphate
QNB = quinuclidinyl bezilate
RBC = red blood cells
WBC = white blood cells

3.4. Radiation Therapy

Radiation therapy departments offer treatment to patients for cancer or certain benign conditions. The type of energy of the radiation used depends on the location of the cancer. The most common types of therapy equipment are cobalt teletherapy equipment and linear accelerators. The later, when operated above 10 MeV, are capable of producing neutrons in addition to high-energy electromagnetic radiation.

Rapidly dividing cells are particularly sensitive to damage by radiation. For this reason, control or eliminate some cancerous growths by irradiating the area containing the growth. This irradiation can occur by using an external beam, for example a beam from a radioactive ^{60}Co source or from linear accelerators. Other cancers are treated with sealed radioactive sources placed directly in tissue, in a body cavity, or on body surfaces called brachytherapy.

3.4.1. Therapeutic Radioisotopes

Contamination with a radioisotope used in radiation therapy may have higher detrimental effects than those used in diagnosis. This is because therapeutic radiopharmaceuticals are designed to destroy tumor cells and are used in sufficient amounts and concentrations for this purpose. Consequently, accidental exposure/contamination is of concern. Table 3.2 includes commonly used radioisotopes.

For some medical conditions, it is useful to destroy or weaken malfunctioning cells using radiation. The radioisotope that generates the radiation can be localized in the required organ in the same way it is used for diagnosis. That is, through a radioactive element following its usual biological path, or through the element being attached to a suitable biological compound. In most cases, beta radiation causes the destruction of the damaged cells. Iodine-131 and ^{32}P are examples of two radioisotopes used for therapy. Iodine-131 is used to treat the thyroid for cancers and other abnormal conditions such as hyperthyroidism (over-active thyroid). Phosphorous-32 is used to control the excess of red blood cells produced in the bone marrow from a disease called Polycythemia Vera (Quimby 1970).

3.4.2. Radiation Therapy machines Using Radionuclides

Radionuclides such as ^{226}Ra, ^{137}Cs, and ^{60}Co have been used as sources of gamma rays for teletherapy (a general term applied to external beam treatments in which the source of radiation is at a large distance from the patients). The radionuclides emit gamma rays as they undergo radioactive disintegration. Cobalt-60 has proved to be the most suitable and most commonly used source for external beam radiotherapy. Take caution when handling teletherapy units because sources in these units may not be in the shielded position and may be a serious radiological hazard.

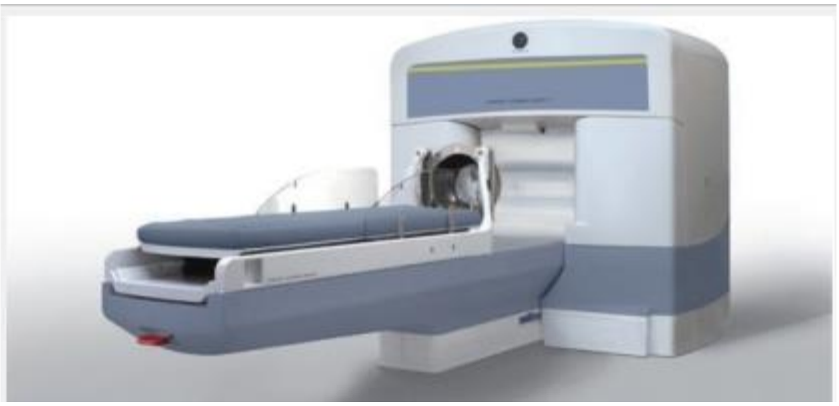
3.4.2.1. The Cobalt-60 Unit

The ^{60}Co source, usually in the form of a solid cylinder, discs, or pallets, is contained inside a stainless-steel capsule and sealed by welding. This capsule is placed into another steel capsule, which is again sealed by welding. The double-welded seal is necessary to prevent any leakage of the radioactive material (Quimby 1970). A typical teletherapy ^{60}Co source is a cylinder of diameter ranging from 1.0 to 2.0 cm and is positioned in the cobalt unit with its circular end facing the patient. The source head houses the source and it is built of steel filled with lead for shielding purposes and a device for bringing the source in front of an opening in from which the useful beam emerges.

3.4.2.2. The Gamma Knife®

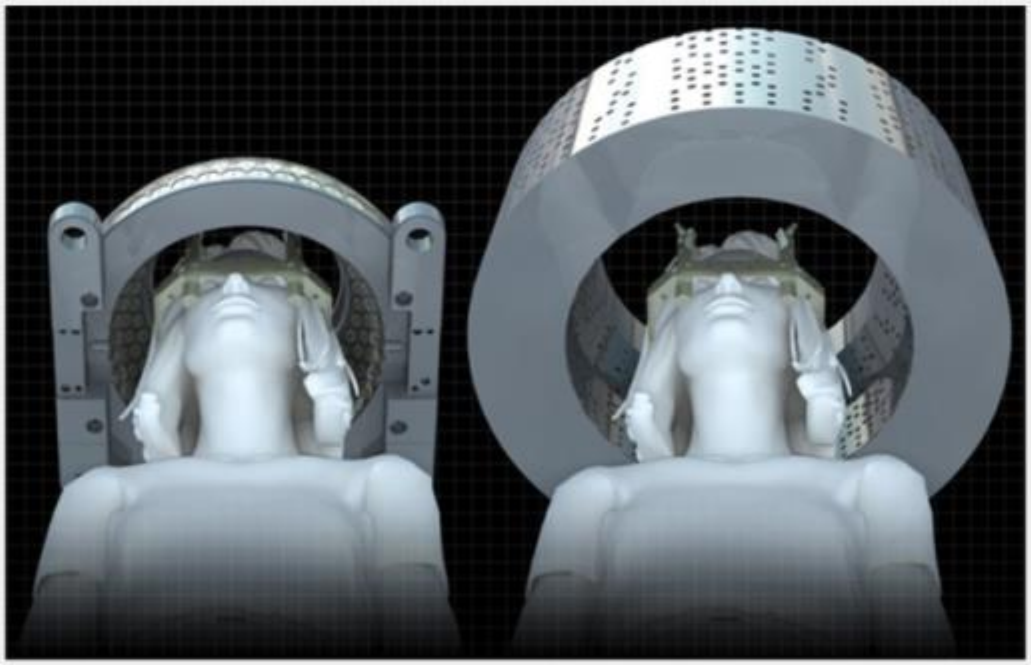
The Gamma Knife delivers a single, high dose of ionizing radiation by exactly pinpointing the target. It does so by sending beams from 201 ^{60}Co sources through a device known as the collimator helmet. Each of the 201 radiation sources is composed of ^{60}Co pellets, which are contained in double stainless steel capsules with welded closures. Only at the point where all 201 beams converge at a single, finely focused point is enough radiation delivered to treat the diseased tissue while nearby healthy tissue is spared (Elekta 2019). The Gamma Knife has been successfully applied to various conditions, such as brain tumors, arteriovenous malformations, and functional disorders. Figures 3.7 and 3.8 are pictures of a gamma knife unit and its helmet, which houses the ^{60}Co.

The gamma knife can present a radiological hazard if shielding mechanisms fail or if the source unit is part of an explosion or fire. Deadly consequences are expected if a Soldier is exposed in such a scenario; therefore, it is important to keep in mind the possible presence of this type of equipment.



https://openi.nlm.nih.gov/detailedresult.php?img=2871531_IJPED2010-870921.008&query=sedation+and+anesthesia+options&it=xg&req=4&npos=8

Figure 3.7. Gamma Knife Unit (Khan 1984)



Source: https://openi.nlm.nih.gov/detailedresult.php?img=4229922_rru05701&query=gamma+knife+helmet&it=xg&req=4&npos=1

Figure 3.8. Close View of a Gamma Knife Helmet

3.4.3. Brachytherapy

Brachytherapy is a method of treatment in which sealed radioactive sources are used to deliver radiation at short distance by interstitial (temporary or permanent implants), intracavitary or surface application. In interstitial therapy, the radioactive material is in the form of needles, wires, or seeds, which can be inserted into the tissue. Interstitial implants can be temporary or permanent implants. In a temporary implant, the sources are removed after the desired dose has been delivered. Examples are radium needles, iridium (^{192}Ir) wires, or iridium seeds. Permanent implants are sources of shorter half-lives that remain in the implanted tissues permanently. Two examples of these sources are ^{198}Au and ^{125}I seeds.

Intracavitary brachytherapy is mostly used for cancers of the uterine cervix, uterine body, and vagina. Applicators are designed to hold the sources in a fixed configuration. A cervix applicator basically consists of a central tube, called the tandem, and lateral capsules or “ovoids.” Spacers separate the ovoids from each other. In a Fletcher-Suit applicator set, the tandem and the ovoids are made of stainless steel and then secured to hollow handles to permit after loading of the source (Khan 1984).

With brachytherapy, a high radiation dose can be delivered locally to the tumor with rapid dose fall-off in the surrounding normal tissue. In the past, brachytherapy was carried out mostly with radium and radon sources. Currently, use of artificially produced radionuclides, such as ^{137}Cs, ^{192}Ir, ^{198}Au, and ^{125}I is more predominant (Meisberger 1968). Table 3.4 lists the most commonly used sources for brachytherapy with their relevant physical properties.

Table 3.4. Most Common Radionuclides used in Brachytherapy (Hilaris 1975)

Radionuclide	Half-life	HVL (mm lead)	Exposure rate constant (mSv m^2)/(hr MBq)	Exposure rate constant (rem m^2)/(hr Ci)
^{60}Co	5.3 years	11.0	3.703E-4	1.371
^{103}Pd	17.0 days	0.008	6.219E-5	0.2303
^{125}I	60.1 days	0.025	7.432E-5	0.2753
^{137}Cs	30.17 years	5.5	1.032E-4	0.3822
^{192}Ir	74.0 days	2.5	1.599E-4	0.5922
^{198}Au	2.7 days	2.5	7.882E-5	0.2919
^{222}Rn	3.8 days	8.0	7.390E-8*	0.0002737*
^{226}Ra	1600 years	8.0	3.274E-6*	0.01213*

Note: *In equilibrium with daughter products.

CHAPTER 4. ARMY COMMODITIES AND FOREIGN MATERIAL SOURCES

This chapter identifies radiological sources found in Army commodities. The summary tables in this chapter include radionuclides found in commodities and their general characteristics. These tables can be used to quickly identify sources of ionizing radiation and assess the potential hazard.

Table 4.1 indicates radioactive commodities found in the U.S. Army as well as some foreign sources. Further information on specific items of interest may be found in Technical Bulletin (TB) 43-0116, Identification of Radioactive Items in the Army, as well as NGIC 1162-325-98, Identification Guide for Radioactive Sources in Foreign Materiel (For Official Use Only). The TB includes item national stock numbers (NSNs), end-item NSNs, specific isotopes, activity present, and the inventory control point (in most cases, this number indicates the license holder for that commodity). The document that identifies radiation sources in foreign material contains the description, location, and specific physical characteristics of these radioactive sources, in addition to numerous photographs.

Table 4.1. Army Radioactive Commodities, Major Radiation Energies, and Main Progeny

Isotope	Half-life	Major Radiation	Main Progeny	Half-life	Major Radiation	Use of Materiel
^{3}H	12.33 years	β^-	^{3}He	stable	N/A	Meter faces, dials, compasses, watches, collimators, telescopes, fire control devices, rifle sights, radioluminous devices
^{14}C	5730 years	β^-	^{14}N	stable	N/A	Calibration, check sources
^{60}Co	5.3 years	β^-	^{60}Nι	stable	N/A	Wave tube, spark gap, surge arr., omni wave, calibration source, rad calib
^{63}Ni	100.1 years	β^-	^{63}Cu	stable	N/A	CAM, expl. Detonator
^{85}Kr	10.7 years	β^-, γ	^{85}Rb	stable	N/A	Exciter, spark gap, omni wave, check source
^{90}Sr	28.74 years	β^-	^{90}Y	64.1 h	β^-	Rad calibration source, marker, det. Unit
^{90}Y	64.1 hours	β^-	^{90}Zr	stable	N/A	Ice detector (foreign)
^{131}I	8.0 days	β^-, γ	^{131}Xe	stable	N/A	Radiation source
^{137}Cs	30.17 years	β^-	^{137m}Ba	2.60 m	γ	Spark igniter, density probe, calibration source
^{133}Ba	10.5 years	γ	^{133m}Ba	38.9 h	γ	Radiation source
^{147}Pm	2.62 years	β^-	^{147}Sm	1.1E11 y	α	Luminous dials, sights
^{204}Tl	3.8 years	β^-	$^{204}\Pi\beta$	1.4E17 y	α	Depth gauge
^{210}Pb	22.3 years	β^-	^{210}Bi	5.013 d	β^-	Arrestor
^{210}Bi	5.013 days	β^-	^{210}Po	138 d	α	Radiation source
^{226}Ra	1600 years	α	^{222}Rn	3.8 d	α	Toggle switches, knobs, meters, watches, luminous dials, sights
^{232}Th	1.4E10 years	α	^{228}Ra	5.75 y	β^-	Thermal optics, combustor (M1 tank), check source
^{234}Pa	6.7 hours	β^-	^{234}U	2.44E5 y	α	Radiation source
^{235}U (1)	7.04E8 years	α, γ	^{231}Th	1.1 d	β^-, γ	DU component
^{238}U (2)	4.47E9 years	α	^{234}Th	24.1 d	β^-	Radiation source
DU*	-	α {see below}	-	-	α, and weak x-ray and beta from daughters	AP munitions, armor, radiation shields, aircraft counter weights
^{239}Pu	2.41E4 years	α (x ray from U)	-	-		Rad calibration source
^{241}Am	432.2 years	α, γ	^{237}Nπ	2.1E6 y	α, γ	density and moisture tester, chem. Detector
Am/Be						Radiation source (neutrons)

Notes: *Depleted uranium (DU) is the material remaining after the uranium enrichment process is used to produce nuclear fuel and weapons grade material. DU is defined as uranium metal containing less than 0.3% ^{235}U, and trace amounts of ^{234}U and ^{236}U, the remainder being ^{238}U. Typical DU used by the Department of Defense (DOD) is 99.8% ^{238}U, by weight.

All radioactive commodities in use by the U.S. Armed Forces are appropriately labeled as such. Caution should be used with Foreign military commodities as they are not always so labeled. Foreign military commodities of the same general types should be assumed radioactive (for example, self-luminous dials, and sights).

4.1. Main Sources in Army Commodities

This section includes examples of radioactive sources in Army commodities. The following are included to illustrate the most common radioactive materials among commodities: ^{3}H, ^{63}Ni, ^{137}Cs, ^{147}Pm, ^{226}Ra, ^{232}Th, DU, and ^{241}Am.

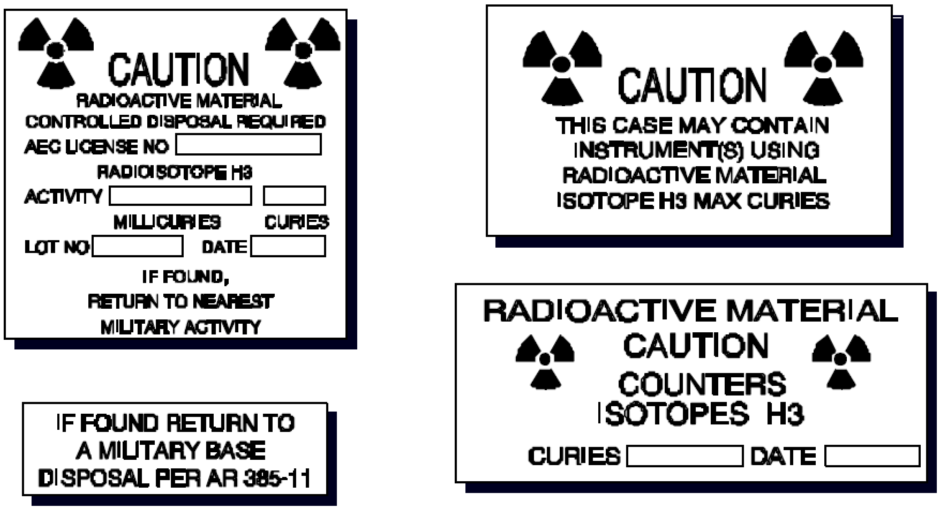
4.1.1. Tritium (^{3}H)

Tritium used in military applications is contained in a Pyrex® glass tube, which has been lined with a phosphor. The interaction between the phosphor and the beta particles from tritium gas produces visible light. The amount of tritium used in manufacturing a source is determined by the size and intensity of the light source. Small amounts of tritium are required for watches, compasses, and other small items that are viewed only a few inches away. Fire control devices used with mortars, howitzers, and tanks use tritium sources to illuminate them in low light conditions. A single howitzer can have 10 or more fire control devices, each of which can contain several tritium light sources. The fire control devices that contain the most tritium are collimators and aiming lights. These items must be visible from a distance of several meters (m). In all cases, the equipment and its carrying case should have warning labels attached to it (DA 1997).

Tritium is a low energy beta emitter that cannot penetrate the intact Pyrex tube. However, if the tube is broken, the tritium gas will dissipate, and outer surfaces of the device and surfaces in the near vicinity of the break may become contaminated. Because of the weak beta radiation, the ordinary Geiger-Mueller counter does not readily measure tritium and it may require wipe testing to determine the level of contamination.

Tritium, in its gaseous state dissipates quickly into the atmosphere; therefore, the skin does not significantly absorb it. The hazardous nature of tritium is due to its ability to combine with other materials. Tritium gas, when combined with water, forms water vapor that is readily absorbed by the body (tritium oxide). In addition, tritium that has plated out on a surface or combined chemically with solid materials may be a contact hazard.

Figure 4.1 includes typical warning plates that are used to label devices and equipment that contains radioactive material. Some of these plates are unique to tritium. Equipment that contains tritium and their carrying cases should always have this type of warning label. Table 4.2 includes a list of devices that contain tritium. The following pictures are illustrations of these devices.



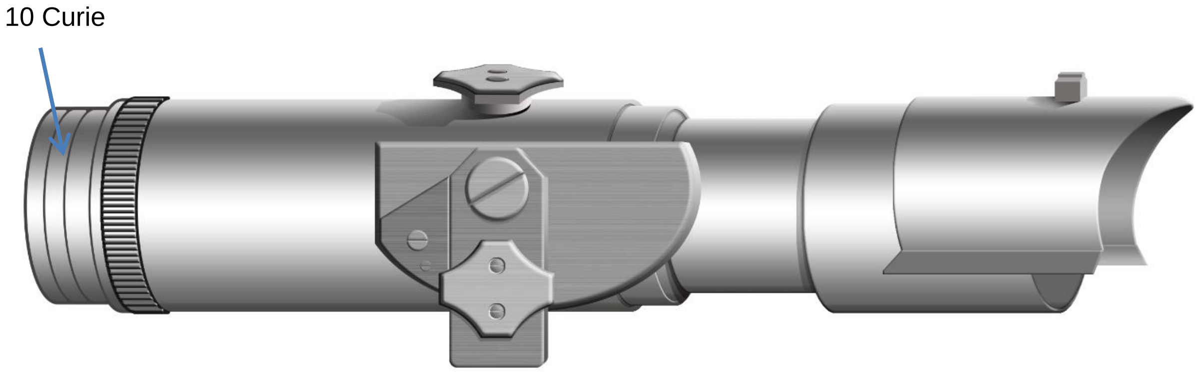
Source: U.S. Army Communications-Electronics Command (CECOM) Technical Report (TR) 94-11: Radiation Safety Information Safe Handling of Tritium Sources in Radioluminescent Devices, CECOM

Figure 4.1. Typical Radioactive Material Data Plates

Table 4.2. List of Some Army Devices Containing Tritium and Corresponding Activity (DA 2019)

Equipment	Device	Description	Activity in Bq	Activity in Ci
M1 Series Tank	MRS	Muzzle Reference Sensor	3.70E+11	10.0
	M1A2	Gunner’s Quadrant	2.78E+09	0.075
M119A1 Howitzer	M137A1	Panoramic Telescope	1.89E+11	5.1
	M187	Telescope Mount & Quadrant	9.81E+10	2.65
	M90A2	Straight Telescope	5.92E+10	1.6
	M140	Alignment Device	1.11E+11	3.0
	M1A1	Collimator	3.70E+11	10.0
	M1A2	Gunner's Quadrant	2.78E+09	0.075
M102 Howitzer	M113A1	Panoramic Telescope	1.48E+11	4.0
	M134A1	Telescope Mount	5.55E+09	0.15
	M114A1	Elbow Telescope	2.07E+11	5.6
	M14A1	Fire Control Quadrant	7.96E+10	2.15
	M140	Alignment Device	1.11E+11	3.0
	M1A1	Collimator	3.70E+11	10.0
	M1A2	Gunner's Quadrant	2.78E+09	0.075
M198 Howitzer	M137	Panoramic Telescope	1.89E+11	5.1
	M171	Telescope Mount	5.55E+09	0.15
	M17	Fire Control Quadrant	6.94E+10	1.875
	M18	Fire Control Quadrant	7.22E+10	1.95

Equipment	Device	Description	Activity in Bq	Activity in Ci
	M139	Alignment Device	1.11E+11	3.0
	M1A1	Collimator	3.70E+11	10.0
	M1A2	Gunner's Quadrant	2.78E+09	0.075
M110 & M109 Series Self-Propelled Howitzer	M140	Alignment Device	1.11E+11	3.0
	M1A1	Collimator	3.70E+11	10.0
	M1A2	Gunner's Quadrant	2.78E+09	0.075
M224 Mortar	M58 & M59	Aiming Post Light	3.33E+11	9.0
	M64A1	Sight Unit w/ M9 Elbow Telescope	2.48E+11	6.69
	M224	Range Indicator	1.18E+11	3.2
	M1A2	Gunner's Quadrant	2.78E+09	0.075
M252 Mortar	M58 & M59	Aiming Post Light	3.33E+11	9.0
	M64A1	Sight Unit w/ M9 Elbow Telescope	2.48E+11	6.69
	M1A2	Gunner's Quadrant	2.78E+09	0.075
M120 Mortar	M58 & M59	Aiming Post Light	3.33E+11	9.0
	M67A1	Sight Unit w/ M9 Elbow Telescope	2.14E+11	5.79
	M1A2	Gunner's Quadrant	2.78E+09	0.075
M16A1 Rifle	Front Sight Post		3.33E+08	0.009
M11 Pistol, 9MM	Front Sight Post		6.66E+08	0.018
	Rear sight Assembly (2 light sources w/ 0.018 Ci each)		1.33E+09	0.036

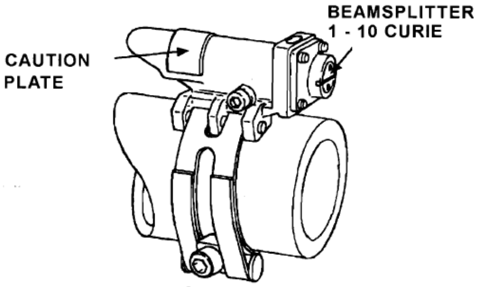


Source: U.S. Army Public Health Center

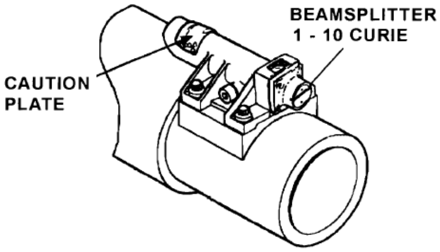
Figure 4.2. The M1A1 Collimator (total activity = 10 Ci)

Figure 4.3 shows the infinite collimator found in all M1 series tanks with its respective NSN numbers. The Muzzle Reference Sensor (MRS) is located on the end of the main gun tube of all M1 series tanks and has a beam-splitter assembly, which contains a 10 Ci tritium light source. This light source is completely contained within the beam-splitter and poses no external radiation hazard unless the Pyrex vial is broken. If there is no apparent illumination when viewed in subdued light, the source may be leaking. The entire MRS should be double bagged if the beam-splitter is still mounted. To avoid or minimize contamination, it is recommended not to remove the beam-splitter assembly from the MRS if there is no illumination.

Figures 4.3 to 4.23 show several Army commodities that contain radioactive material.



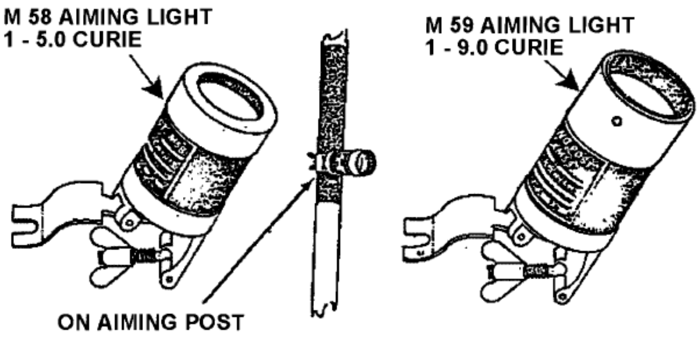
105 MM MAIN GUN, M1 AND IPM1 TANK



120 MM MAIN GUN, M1A1 AND M1A2 TANK

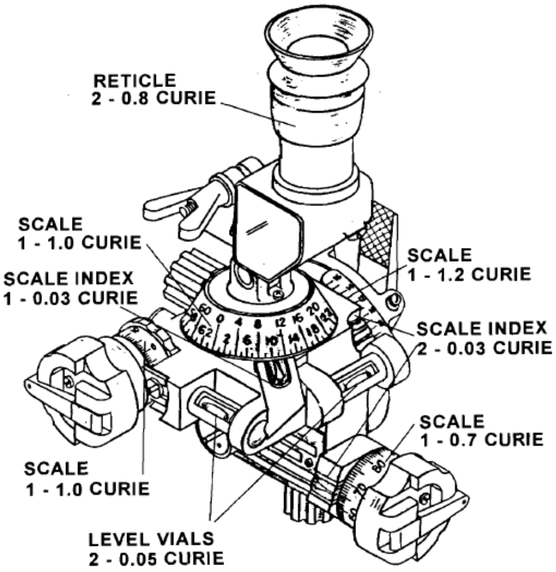
Source: CECOM TR 94-11: Radiation Safety Information Safe Handling of Tritium Sources in Radioluminescent Devices, CECOM

Figure 4.3. The Infinity Collimator MRS for M1 Series Tanks and Beam-splitter (The beam-splitter is the same for all three MRSs, with total activity of 10 Ci)



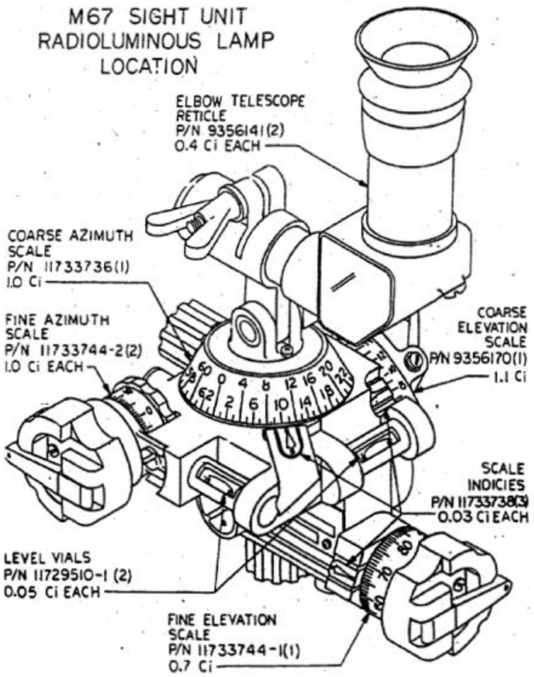
Source: CECOM TR 94-11: Radiation Safety Information Safe Handling of Tritium Sources in Radioluminescent Devices, CECOM

Figure 4.4. The M58 and M59 Aiming Post Lights [M58 Contains a 5.0 Curie Tritium Source (RED) and M59 Contains a 9.0 Ci Tritium Source (Green)]



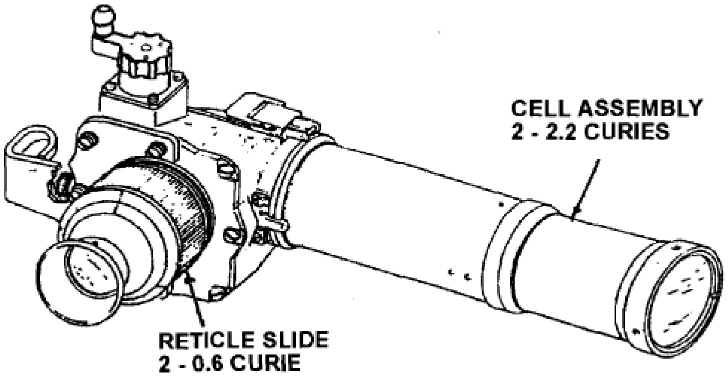
Source: CECOM TR 94-11: Radiation Safety Information Safe Handling of Tritium Sources in Radioluminescent Devices, CECOM

Figure 4.5. M64A1 Sight Unit w/ M9 Elbow Telescope (total activity = 6.69 Ci)



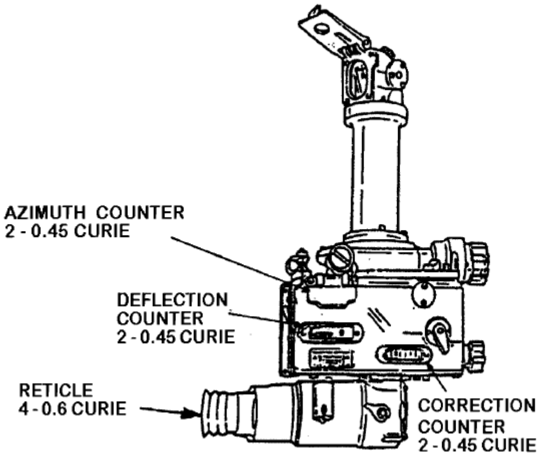
Source: Registry of Radioactive Sealed Sources and Devices; Safety Evaluation of a Sealed Source, Department of the Army Tank-Automotive and Armaments Command (TACOM)

Figure 4.6. The M67 Sight Unit (total activity = 5.79 Ci)



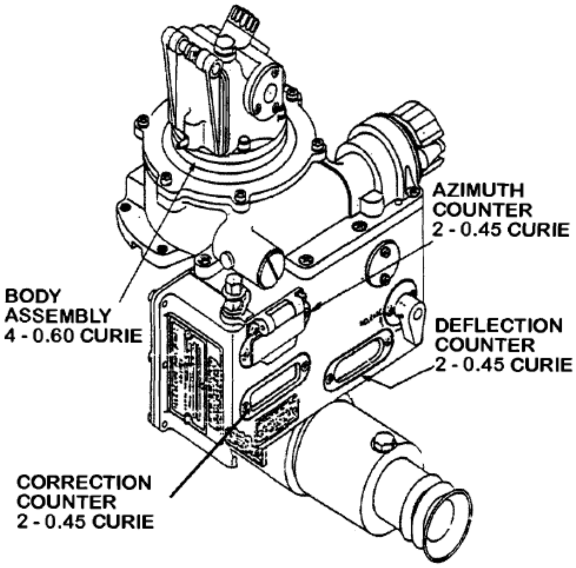
Source: CECOM TR 94-11: Radiation Safety Information Safe Handling of Tritium Sources in Radioluminescent Devices, CECOM

Figure 4.7. The M114A1 Elbow Telescope (total activity = 5.6 Ci)



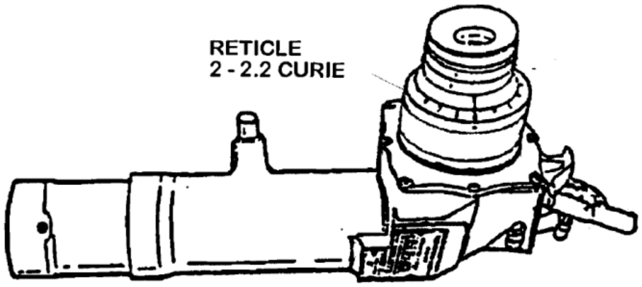
Source: CECOM TR 94-11: Radiation Safety Information Safe Handling of Tritium Sources in Radioluminescent Devices, CECOM

Figure 4.8. The M137 Panoramic Telescope (total activity = 5.1 Ci)



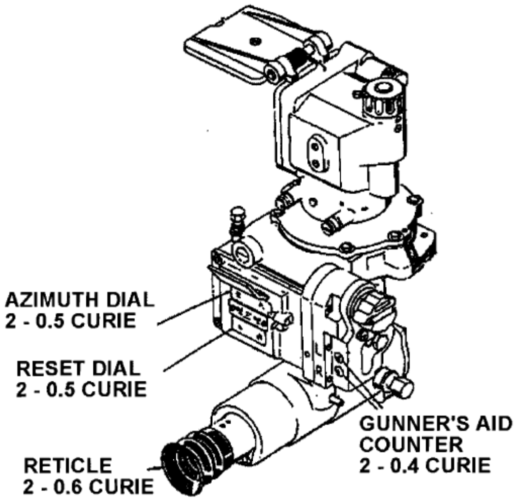
Source: CECOM TR 94-11: Radiation Safety Information Safe Handling of Tritium Sources in Radioluminescent Devices, CECOM

Figure 4.9. The M137A1 Panoramic Telescope (total activity = 5.1 Ci)



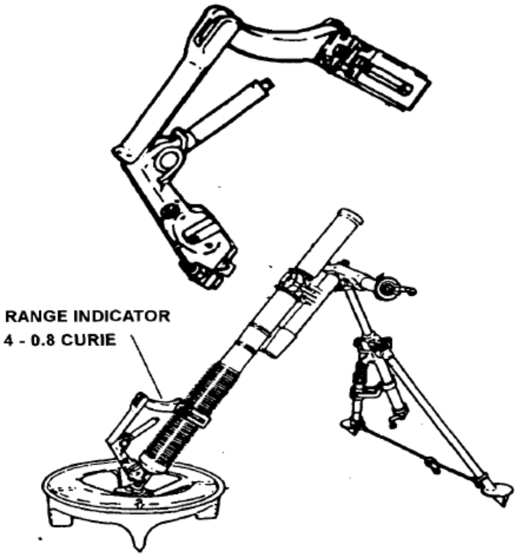
Source: CECOM TR 94-11: Radiation Safety Information Safe Handling of Tritium Sources in Radioluminescent Devices, CECOM

Figure 4.10. The M138 Elbow Telescope (total activity = 4.4 Ci)



Source: CECOM TR 94-11: Radiation Safety Information Safe Handling of Tritium Sources in Radioluminescent Devices, CECOM

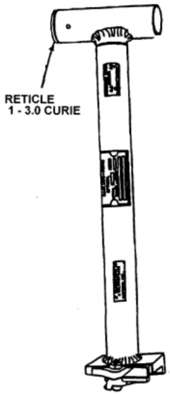
Figure 4.11. The M113A1 Panoramic Telescope (total activity = 4.6 Ci)



Source: CECOM TR 94-11: Radiation Safety Information Safe Handling of Tritium Sources in Radioluminescent Devices, CECOM

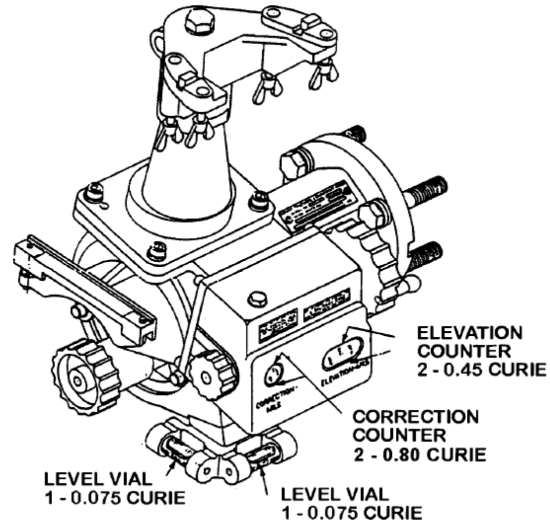
Figure 4.12. The M224 Mortar, 60mm, Range Indicator (total activity = 3.23 Ci)

The alignment device contains a light source, which has 3.0 Ci of tritium. The device is used to align the sights with the gun tube. It is considered support equipment for the howitzer and is not mounted except while performing alignment procedures.



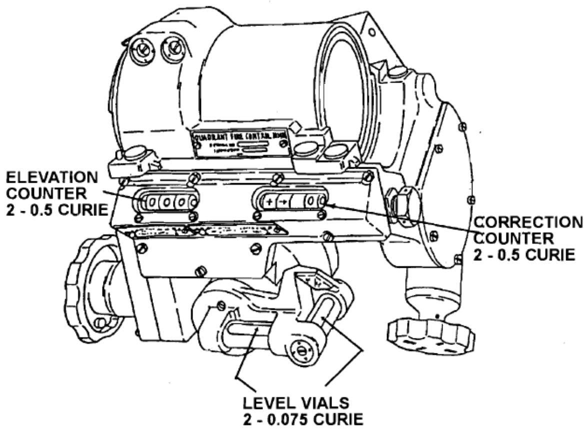
Source: CECOM TR 94-11: Radiation Safety Information Safe Handling of Tritium Sources in Radioluminescent Devices, CECOM

Figure 4.13. The M139/M140 Alignment Device (light source contains 3.0 Ci of tritium)



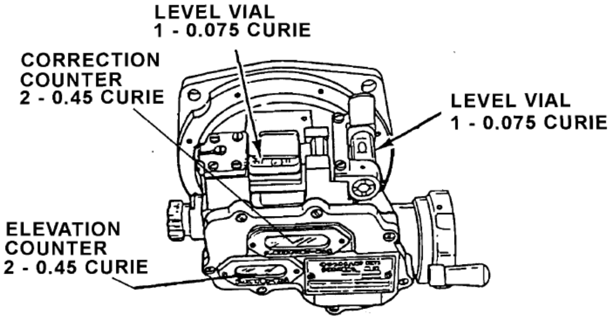
Source: CECOM TR 94-11: Radiation Safety Information Safe Handling of Tritium Sources in Radioluminescent Devices, CECOM

Figure 4.14. The M187 Telescope Mount and Quadrant (total activity = 2.65 Ci)



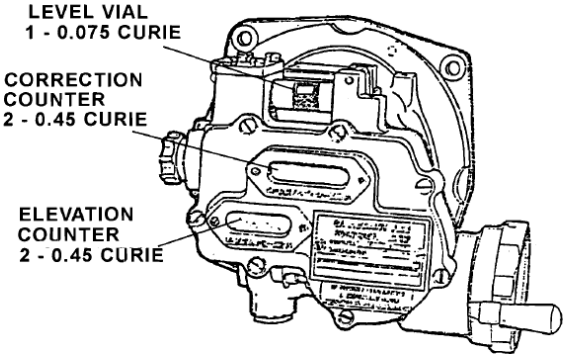
Source: CECOM TR 94-11: Radiation Safety Information Safe Handling of Tritium Sources in Radioluminescent Devices, CECOM

Figure 4.15. The M14A1 Fire Control Quadrant (total activity = 2.15 Ci)



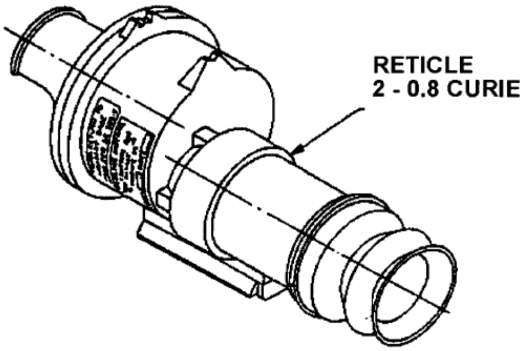
Source: CECOM TR 94-11: Radiation Safety Information Safe Handling of Tritium Sources in Radioluminescent Devices, CECOM

Figure 4.16. The M18 Fire Control Quadrant (total activity = 1.95 Ci)



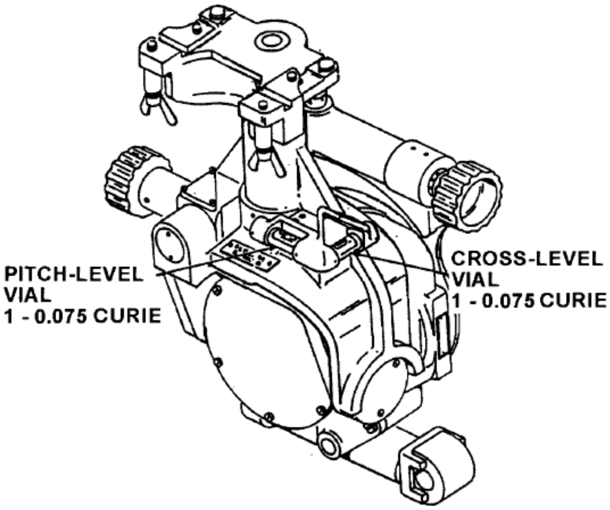
Source: CECOM TR 94-11: Radiation Safety Information Safe Handling of Tritium Sources in Radioluminescent Devices, CECOM

Figure 4.17. The M17 Fire Control Quadrant (total activity = 1.875 Ci)



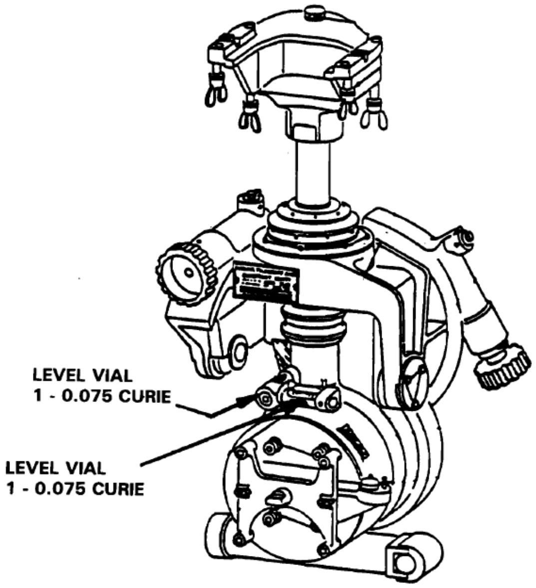
Source: CECOM TR 94-11: Radiation Safety Information Safe Handling of Tritium Sources in Radioluminescent Devices, CECOM

Figure 4.18. The M90A2 Straight Telescope (total activity = 1.6 Ci)



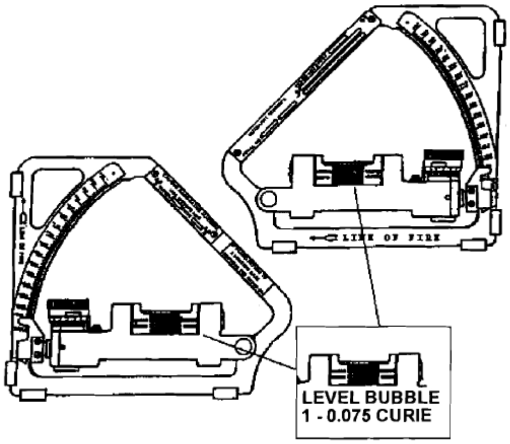
Source: CECOM TR 94-11: Radiation Safety Information Safe Handling of Tritium Sources in Radioluminescent Devices, CECOM

Figure 4.19. The M134A1 Telescope Mount (total activity = 0.15 Ci)



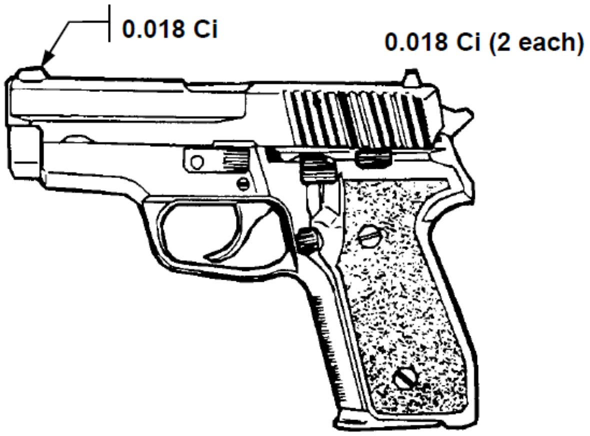
Source: CECOM TR 94-11: Radiation Safety Information Safe Handling of Tritium Sources in Radioluminescent Devices, CECOM

Figure 4.20. The M171 Telescope Mount (total activity = 0.15 Ci)



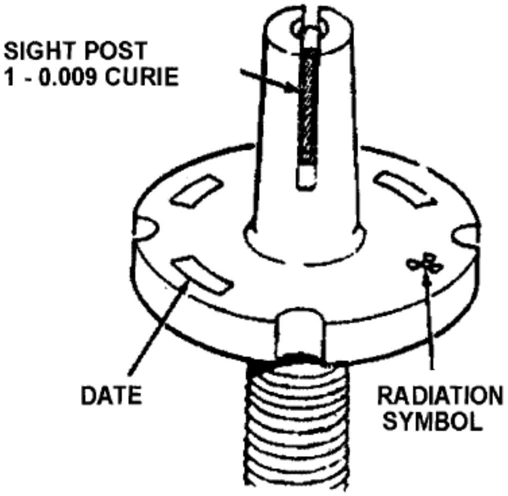
Source: CECOM TR 94-11: Radiation Safety Information Safe Handling of Tritium Sources in Radioluminescent Devices, CECOM

Figure 4.21. The M1A2 Gunner’s Quadrant (total activity = 0.075 Ci)



Source: TB 43-0197, Instructions for Safe Handling, Maintenance, Storage and Disposal of Radioactive Items, Headquarters Department of the Army (HQ/DA)

Figure 4.22. The M11 Pistol, 9mm - DARA 12-93-01 (total activity = 0.054)

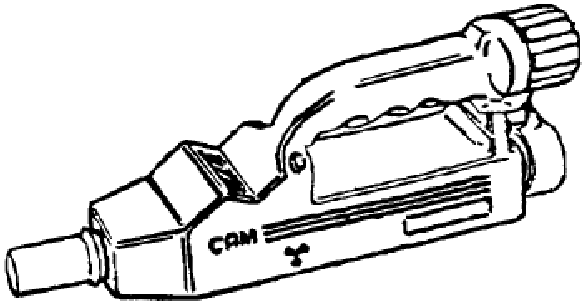


Source: CECOM TR 94-11: Radiation Safety Information Safe Handling of Tritium Sources in Radioluminescent Devices, CECOM

Figure 4.23. The M16A1 Rifle Front Sight Post (No longer in use) (total activity = 0.009 Ci)

4.1.2. Nickel-63 (^{63}Ni)

Nickel-63 is a pure beta emitter (it does not emit any gamma rays) with a radiological half-life of 92 years. The beta energy of ^{63}Ni is too low to penetrate the dead layer of skin. Efforts should be taken to prevent ingestion, inhalation, or absorption through broken skin. The Chemical Agent Monitor (CAM) and Improved Chemical Agent Monitor (ICAM) both use this isotope. The ^{63}Ni is used to ionize air molecules as they pass through the detector. The drift tube module consists of 10 mCi of ^{63}Ni plated on a brass foil cylinder inside a Teflon® housing that is installed in a larger aluminum alloy cylinder. Figure 4.24 shows the CAM.



Source: TB 43-0197, Instructions for Safe Handling, Maintenance, Storage, and Disposal of Radioactive Items, HQ/DA

Figure 4.24. CAM/ICAM

4.1.3. Cesium-137 (^{137}Cs)

Cesium-137 emits a negative beta particle and becomes ^{137}Ba, which in turn decays by emitting gamma rays of a single energy (0.662 MeV). The fixed spectrum emission requires less shielding than other radionuclides and is ideal for soil density determination. The density and moisture tester (Campbell Pacific Model MC-1), which is used by the Army, has a 10 mCi ^{137}Cs source located in a probe tip used to determine the density of the soil at a construction site. This source is double encapsulated in stainless-steel. The betas from ^{137}Cs are shielded by the stainless-steel.

Figure 4.25 illustrates the functioning of the MC-1 density tester. The detector in the tester measures the amount of radiation that penetrates the soil. Dense soil will block more of the radiation than lighter soil. The measurement taken by the detector is displayed electronically as an indication of the soil density.

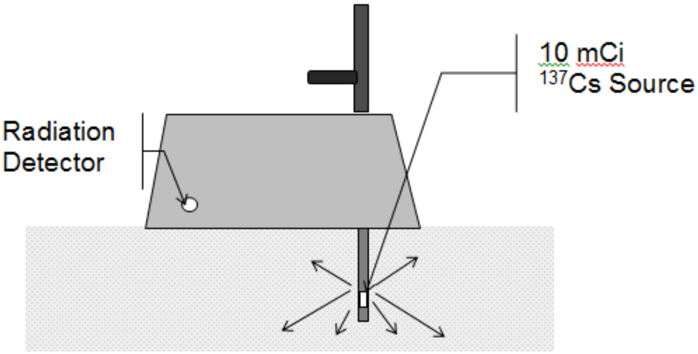
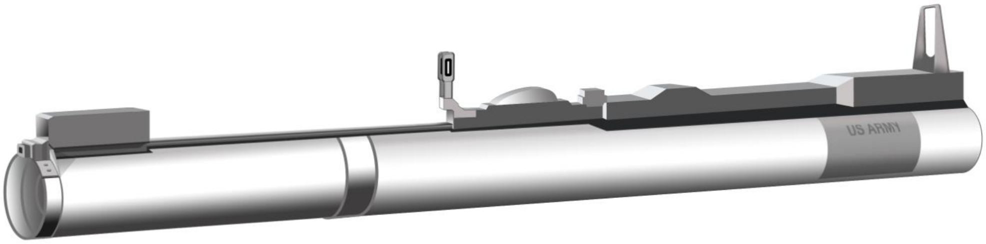


Figure 4.25. Illustration of the Density and Moisture Tester

4.1.4. Promethium-147 (^{147}Pm)

Promethium-147 has a half-life of 2.6 years and is a beta particle emitter used in luminous paints. This element is in the M72 series, 66-mm, Light Antitank Weapon (LAW). For 20 years the LAW was manufactured with ^{147}Pm. Promethium-147 is located in just two spots that are at the 100 and 150 range markers on the sight (these items are obsolete and should be disposed as radioactive waste). In the early 1980s, the “E” version of the LAW changed the sight to an adjustable rifle type there by eliminating the need for ^{147}Pm. However, the older models remain in use for training and in storage, and therefore are identified in this technical guide. Figure 4.26 illustrates a LAW.



Source: U.S. Army Public Health Center

Figure 4.26. Light Antitank Weapon

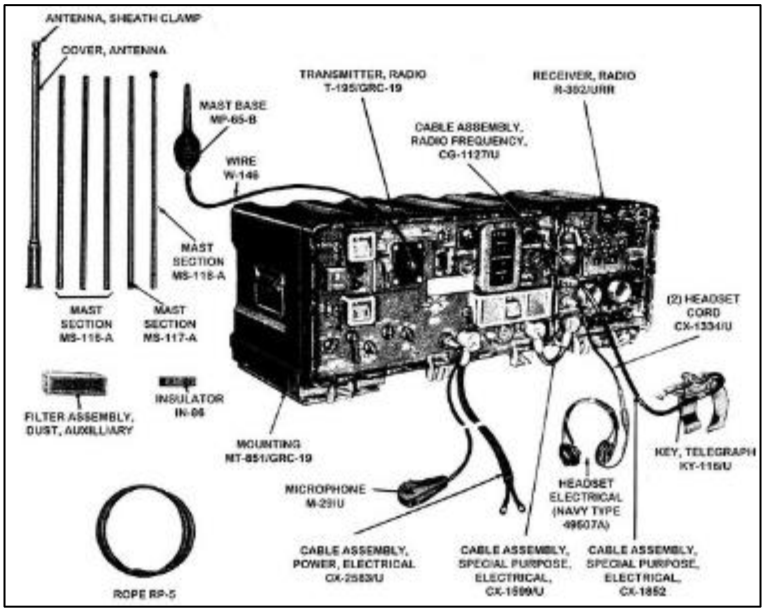
4.1.5. Radium-226 (^{226}Ra)

Radium-226 is primarily an alpha emitter, but it also emits some low energy beta and gamma radiation. Radium-226 was used on the faces and pointers of dials and gauges of instrument panels in tactical and combat vehicles. These items are no longer in DOD storage depots and have not been procured since 1969. Nonradioactive replacements are available in the supply system for all of the radioactive items.

According to Department of the Army Radiation Authorization (DARA) A21-12-04 and TB 43-0216 all fielded TACOM managed vehicles containing radioactive dials and gauges will have the instrument panel labeled “*CAUTION RADIOACTIVE. THE GAUGES IN THIS VEHICLE MAY CONTAIN RADIUM-226. REMOVE RADIOACTIVE GAUGES PRIOR TO EXCESS OR DISPOSAL OF THIS VEHICLE IAW AR 385-11, and Technical Manual (TM) 3-261. REFER TO TB43-0216 FOR ADDITIONAL GUIDANCE.*” Gauges removed from pre-1970 vehicles should be reported immediately to the garrison/installation radiation safety officer or APHC for further evaluation.

The easiest way to tell whether an unmarked dial or gauge contains radium or some other radioactive material is to check with a Radioactivity, Detection, Indication, and Computation (RADIAC) meter. This meter will easily detect the gamma emissions from radium but fielded RADIAC instruments will not be able to detect tritium. When looking at the gauge, if one sees a “-2” in the part number, it is probably not radium, but if there is a “-1” in the part number, it is probably a radium gauge (DA 1997).

Radium dials and radium marks on toggle switches may also be found in some radios, such as the AN/GRC-19 (Figure 4.27), the VRC-46 and the GRC-106.



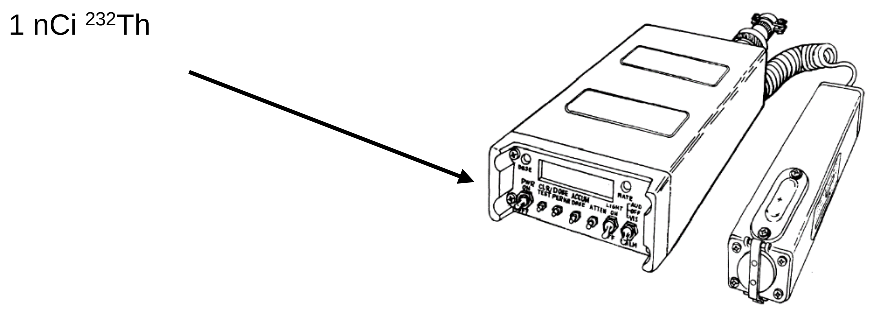
Source: https://www.flickr.com/photos/byteboy/10303422686/in/photolist-gGtJAJ

Figure 4.27. AN/GRC-19

4.1.6. Thorium-232 (^{232}Th)

Thorium-232 is an alpha emitter naturally produced radioisotope of thorium. When thorium is heated in air, it glows with a white light. For this reason, one of the major uses of thorium has been the Welsbach lantern mantle used in portable gas lanterns.

The AN/VDR-2 RADIAC set uses a 1 nanocurie (nCi) ^{232}Th source. The check sources of the AN/PDR-54 and the AN/PDR-77 RADIAC sets contain 0.1 microcuries (μCi) of ^{232}Th (Figure 4.28).



Source: TM 11-6665-251-20, Organization Maintenance Manual, Radiac Set AN/VDR-2, HQ/DA

Figure 4.28. Source found in RADIAC Instrumentation

Thermal optics have a multi-layer infrared anti-reflective coating that contains ^{232}Th as a fluoride compound (thorium tetrafluroride). This hard coating is covered with a protective layer of a nonradioactive compound, which prevents direct contact with the thorium surface. Care should be taken in the handling of these optical components to avoid inhalation and/or ingestion of any particles inadvertently chipped or scratched.

4.1.7. Depleted Uranium

Natural uranium is predominantly ^{238}U by weight, but also contains isotopes ^{234}U and ^{235}U. The Department of Energy (DOE) runs natural uranium through its enrichment facilities to obtain uranium with higher ^{235}U content (enriched uranium). The enriched uranium is put into nuclear reactors and nuclear weapons. The waste product of the enrichment process is uranium that has a lower content of ^{235}U and it is known as depleted uranium because it is “depleted” of this isotope.

Uranium decays by alpha particle emission. The daughter atoms formed during decay emit alpha, beta, and gamma radiation. Therefore, the radiation emitted from DU contains alpha, beta and gamma radiation. Because of the long half-life of ^{238}U (the major element of DU), the specific activity is relatively low. For example, to obtain 1 curie of radioactivity from DU, it would require a single piece weighing 6,615 pounds.

DU properties that make it of interest to the military are its high density and strength, relative low cost of machining, and availability. Because of its high density and structural properties, DU is useful for nonnuclear applications. It can be applied defensively to protect against penetration by projectiles made of less dense metals, such as tungsten carbide subprojectiles, or offensively to defeat armored targets. U.S. current weapons systems that can fire DU munitions are Abrams tanks, Bradley Fighting Vehicles, Air/Force A-10 aircraft, Marine Corps Harrier aircraft, and the Navy’s ship mounted close in weapon system (Phalanx). DU ammunition is not used for training.

The M1A1 and M1A2 Abrams Tanks produced for the U.S. Army since 1988 use DU armor. Specifically, the turrets of these vehicles contain armor “packages” which use the DU material. Due to the location of the material within the structure, the front slope of the turret has the highest radioactive signature, which is less than 5 microSieverts/hour (0.5 mrem/hr). The “U” at the end of the turret serial number can identify vehicles, which contain DU armor, in the field.

DU is also used in authorized ammunitions such as armor piercing projectiles. The combination of high hardness, strength, and density makes DU alloys well suited for this type of projectile. The design and material composition of these munitions represent a departure from previous generations of armor-piercing ammunitions. These rounds employ kinetic energy subprojectiles composed of DU cores. For general military applications, DU ammunition may only be fired during war. The NRC and/or have Host Nation Agreement prohibit all peacetime firings except on ranges, which are approved and licensed. The following tables include a list of DU ammunitions and their typical characteristics.

Table 4.3. List of DU Ammunitions

TANK AMMUNITION		**BRADLEY**	**A-10**	**HARRIER**	**PHALANX**
105mm	120mm	25mm	30mm	25mm	20mm
M774	M827	M919	PGU-14/B	PGU-20	MK-149
M833	M829		PGU-14A/B		
M900	M829A1		PGU-14B/B		
	M829A2		PGU-14A/A		

Table 4.4. Typical Characteristics for DU Tank Ammunitions

Color	**Black w/white markings**
Muzzle Velocity	4925 + ft/sec
Round Weight	37.8 - 40.8 lb.
Length	35.75 - 39.5 in
Tracer	M13

Instead of placing radioactive markings and labels on packages of DU ammunition, the Army has obtained a Department of Transportation (DOT) exemption for shipment. This DOT exemption covers all models of currently fielded DU munitions.

4.1.8. Americium-241 (^{241}Am)

Americium-241 does not occur in nature. It is a daughter product of the decay process of ^{241}Pu and has a half-life of 432.2 years. Americium-241 is primarily an alpha and gamma emitter (the gamma radiation energy for this isotope is very low). External exposure is not a concern unless large amounts of ^{241}Am are stored in one area and a Solider is in close contact with the material for long periods of time.

The high energy alpha emission can present an internal radiation hazard if it is ingested. Americium-241 is chemically analogous to calcium and can replace calcium in the body, especially in bone material. For this reason, it is often referred to as a “bone seeker.” Once incorporated in the bone, the bone and surrounding tissue are constantly irradiated, which may potentially result in leukemia and malignancies.

Since ^{241}Am primarily emits alpha radiation, alpha detection equipment must be used to accurately assess contamination levels. Personal gamma dosimetry is not usually required unless a person is in close contact with the material throughout most of the day.

Americium-241 is used as a sealed source in the M43A1 Chemical Agent Detector that is a component of the M8A1 alarm. A cell module in the M43A1 contains a radioactive source of 250 µCi of ^{241}Am.

The density and moisture tester (Figure 4.29) MC-1 contains a 50 mCi ^{241}Am and beryllium (Be) source, located within the base of the tester. Neutron emission occurs when an alpha particle emitter from ^{241}Am is mixed with the Be in the tightly compressed pellet. The alpha particles strike the Be atoms to produce “fast” neutrons with an average energy of 5 MeV.

Source: https://www.flickr.com/photos/nrcgov/7845749948/

Figure 4.29. Moisture Density Gauge

4.2. Radiation Safety Information Pertaining to Commodities

Table 4.5 lists the isotopes with information as to their maximum activity in **any** commodity (actual activity in any specific item is typically somewhat less), physical form of the commodity, exposure hazard information, and methods of detection that may be used to detect the presence of the specific isotope externally.

Self-luminous dials and devices, such as weapons sights, are often radioactive sources. These sources typically contain ^{3}H, ^{147}Pm, or ^{226}Ra in varying amounts. An ampoule of tritium gas, the inner surface coated with a zinc sulfide scintillator, is used to backlight the instrument. Promethium-147 and ^{226}Ra are used in luminous paints and applied directly to the surfaces of the dials, switches, and indicators. A damaged gauge creates the primary hazard from these isotopes, such that the ampoule is broken and the radioactive gas escapes, or the solid material flakes off. Radium-226 can also be a source of external exposure and ^{222}Rn gas can escape from the instrument. These problems can cause area or personnel contamination as well as personnel inhalation or ingestion exposures.

The low energy beta radiation from the tritium is an internal hazard only, meaning the isotope must get inside your body to cause damage. Tritium is best detected using surface swipes and liquid scintillation detection for contamination. Another method for detecting tritium contamination is to take a void urine bioassay sample from suspected personnel at least 4 hours post-exposure. Promethium-147 and ^{226}Ra are bound in a solid matrix and painted on the dial or gauge. There is little hazard from ^{147}Pm in this form, unless the paint flakes off and is subsequently ingested. Radium-226 is a hazard through its progeny. It decays into ^{222}Rn, a noble gas, which can leak or be released in much the same way as tritium. The short-lived progeny further down the decay chain can be deposited in the lung and cause substantial internal exposure through alpha decay. The external hazard from this isotope is minimal. Ingestion of the paint flakes directly will cause bone damage over time.

Some commodities found in the military can be found as calibration or check sources: ^{14}C, ^{131}I, ^{133}Ba, ^{210}Bi, ^{234}Pa, ^{238}U, ^{239}Pu, and the Am/Be (Americium/Beryllium) source. As such, they are normally found as sealed sources associated with radiation detection instrumentation or in a calibration lab, and would take some serious effort to release to the environment. Sealed sources represent an external exposure hazard only (unless the source integrity is compromised). This is not to say they are not dangerous, because they can be. None of the sealed sources will present a health hazard as an alpha source (remember, a sheet of paper or the dead layer of the skin will block alphas). Some of the nuclides mentioned above are beta emitters (^{14}C, ^{210}Bi, ^{234}Pa), and while sealed beta sources will not present a serious health hazard, they should be considered (skin is the target organ). One other item that should be considered with respect to sealed source beta emitters is that they are often associated with lower energy gammas due to bremstrahlung, or “braking” radiation, given off because of the beta particles passing through the cladding material. The other sources are gamma emitters, with the exception of the Am/Be source which produces neutrons. The gamma emitters may expose the whole body externally, as will the neutron source. The sealed sources will be detected (dose-rate) in most cases using the AN/PDR-77 with the beta/gamma probe, which is functionally equivalent to the VDR-2. The neutron source is unique, in that it requires special instrumentation (for example, REM Ball) to measure dose rate.

Other isotopes that will be found in calibration sources, as well as in other commodities, are ^{60}Co, ^{85}K, ^{90}Sr, ^{137}Cs, ^{210}Pb, ^{226}Ra, and ^{232}Th. The same considerations discussed above will hold true with these sources as well, depending on the form of the radiation (alpha, beta, or gamma).

Table 4.5. Radiation Safety Information Pertaining to Commodities (DA 1998) (AEPI 1995) (Johnson 2012) (NCRP, Management of Persons Accidentally Contaminated with Radionuclides 1979)

Isotope	Max. Activity -Bq (Ci)[1]	Exposure Hazard (critical organ)[2]	Methods of Detection (external)[3]
^{3}H (T)	1.5E13 (400)	external (skin), internal (whole body)	S (LS), BG (SP)
^{14}C	3.7E4 (50.3E-6)	external (skin)	S (LS), BG (SP)
^{60}Co	4.0E13 (1081)	external, internal (whole body)	BG, S
^{63}Ni	7.4E8 (20E-3)	internal (bone)	BG (SP)
^{85}Kr	1.85E8 (5E-3)	external (whole body) internal (lung)	BG
^{90}Sr	6.66E9 (0.18)	external (skin), internal (bone)	BG, S
^{90}Y	9.25E5 (25E-6)	external (skin), internal (bone)	BG, S
^{131}I	3.7E4 (1.0E-6)	external (skin, whole body)	BG, S
^{137}Cs	4.81E12 (130)	external, internal (whole body)	BG, S
^{133}Ba	3.7E4 (1.0E-6)	external (whole body)	BG, S
^{147}Pm	1.79E8 (4.8E-3)	internal (bone)	BG, S
^{204}Tl	5.92E7 (0.16)	internal	BG
^{210}Pb	2.22E4 (0.6E-6)	internal (kidney)	BG, S

Isotope	**Max. Activity -Bq (Ci)[1]**	**Exposure Hazard (critical organ)[2]**	**Methods of Detection (external)[3]**
^{210}Bi	3.7E4 (1.0E-6)	external (skin)	BG
^{226}Ra	5.55E9 (0.15)	internal (bone)	A, BG, S
^{232}Th	4.3E6 (0.11E-3)	internal (bone)	A, BG, S
^{234}Pa	3.7E4 (1.0E-6)	external (skin)	BG
^{235}U (4)	as comp of DU	int. (kidney)	A, BG
^{238}U (4)	8.4E5 (22.7E-6)	internal (kidney)	A, BG
DU (5)	6.66E11 (18)	internal (kidney)	A, BG
^{239}Pu	1.9E6 (50.3E-6)	internal (bone)	A, BG (SP)
^{241}Am	1.85E9 (0.05)	external (w. body), internal (bone)	A, BG (SP), S
Am/Be	1.5E11 (4.0)	external (whole body)	REM Ball[6]

Notes:

[1] Max Activity is the largest activity of the given isotope found in any military commodity in the references given.

[2] Exposure hazard is given for internal and external exposure, alphas are not dangerous if exposed externally, internal target organs are listed for the various isotopes.

[3] Methods of Detection are given for the listed isotopes for external contamination (A- Alpha counting techniques, BG- Beta/gamma detection, S- Smears, BG (SP)- Beta/gamma, special instrumentation required due to the low energies of the radiations, S (LS)- Liquid scintillation counting techniques)

[4] Primarily found as component of DU.

[5] Depleted uranium (DU) is the material remaining after the uranium enrichment process is used to produce nuclear fuel and weapons grade material. DU is defined as uranium metal containing less than 0.3% ^{235}U, and trace amounts of ^{234}U and ^{236}U, the remainder being ^{238}U. Typical DU used by the DOD is 99.8% ^{238}U by weight.

[6] The REM Ball is not the only method of detecting neutrons, but is one of the most common.

4.3. Radioactive Sources in Foreign Materiel

Radioactive sources in foreign materiel are identified in NGIC 1162-325-98, Identification Guide for Radioactive Sources in Foreign Materiel (For Official Use Only – contact APHC for access). Although these sources do not present a hazard to personnel working close to them, it is important to be aware of their presence, as they could be hazardous if damaged or tampered with.

Finding and identifying a foreign source that is unaccounted for can also be useful for forensic purposes. Follow chain of custody procedures (see APHC Technical Guide 236 for more information) and contact military police, Intelligence staff, and/or the Army's Criminal Investigation Division in accordance with your chain of command and local procedures.

Various instruments and detectors, such as chemical detectors, icing monitors, and smoke detectors use alpha sources. The most common of these sources are ^{241}Am, ^{226}Ra, and ^{239}Pu. These sources' primary hazard is the potential for internal radiation exposure due to contamination from their rupture, as they can be ingested or inhaled.

Gauges, nuclear batteries, static eliminators, luminous dials, and other devices use beta sources. The most common beta sources used are ^{3}H, ^{90}Sr, and ^{147}Pm. The primary hazards associated with these sources are skin contamination and internal exposure if ingested or inhaled.

Some foreign radiological test and measurement equipment use gamma sources. The most common gamma sources used in foreign materiel are ^{60}Co, ^{137}Cs, and ^{226}Ra. The amount of shielding required from these types of sources depends on their strength and the energy of the gamma rays produced during radioactive decay. These sources represent an external and internal radiation hazard.

CHAPTER 5. INDUSTRIAL SOURCES AND THE TRANSPORTATION OF RADIOACTIVE MATERIAL

Industrial processes and transportation of radioactive materials pose a potential exposure risk for Soldiers. This hazard can be found in agricultural, scientific research, manufacturing, and educational facilities. Accidents comprise the most likely exposure scenarios for these sources.

5.1. The Use of Radioisotopes in Industry

Selected radioactive sources are used in industrial radiography, gauging applications, and mineral analysis. Short-lived radionuclides are used in flow tracing and mixing measurements. Gamma sterilization is used for medical supplies, some bulk commodities, and food preservation and sterilization. Table 5.1 encompasses the most common radioisotopes used in industry, the corresponding half-lives, type of radiation, and usage.

Table 5.1. Most Commonly Used Radioisotopes in Industry

Radionuclide	Half-life	Radiation	Usage
Naturally occurring radioisotopes			
^{3}H	12.33 years	β^{-}	Measurement of "young" groundwater (up to 30 years) Tritiated water is used as a tracer to study sewage and liquid wastes.
^{14}C	5730 years	β^{-}	Measurement of the age of water (up to 50,000 years).
^{36}Cl	3.1E5 years	β^{-}, γ	Measurement of sources of chloride and the age of water (up to 2 million years).
^{210}Pb	22.3 years	$\alpha, \beta^{-}, \gamma$	Dating layers of sand and soil up to 80 years.
Artificially produced radioisotopes			
^{46}Sc	83.8 days	β^{-}, γ	Together with ^{60}Co, ^{110m}Ag, ^{140}La, and ^{198}Au, is used in blast furnaces to determine resident time and to quantify yields to measure the furnace performance.
^{51}Cr	27.7 days	γ	Together with ^{198}Au and ^{192}Ir is used to label sand to study coastal erosion.
^{54}Mn	312.7 days	γ	Together with ^{65}Zn is used to predict the behavior of heavy metal components in effluents for mining waste water.
^{57}Co	270.9 days	γ	Together with ^{57}Fe (stable isotope) is used in Mossbauer analysis.
^{60}Co	5.3 years	β^{-}, γ	Gamma sterilization, industrial radiography and food irradiators. Also used for blast furnaces to determine resident time and to quantify yields to measure the furnace performance.
^{65}Zn	244.4 days	β^{+}, γ	Together with ^{54}Mn is used to predict the behavior of heavy metal components in effluents for mining wastewater.
^{82}Br	36 hours	β^{-}, γ	Hydrological tracing.
^{85}Kr	10.7 years	β^{-}, γ	Reservoir engineering.
^{90}Sr	28.74 years	β^{-}, γ	Radiation gauges, automatic weighing equipment.
^{99m}Tc	6.0 hours	γ	Together with ^{198}Au is used to sewage and liquid waste movements.

Radionuclide	Half-life	Radiation	Usage
^{110m}Ag	249.9 days	β^-, γ	Together with ^{46}Sc, ^{60}Co, ^{140}La, and ^{198}Au is used in blast furnaces to determine resident time and to quantify yields to measure the furnace performance.
^{137}Cs	30.17 years	β^-, γ	Industrial radiography, radiation gauges, automatic weighing equipment, food irradiators and for radiotracing techniques in identifying sources of soil erosion and deposition.
^{140}La	1.68 days	β^-, γ	Together with ^{60}Co and ^{198}Au in blast furnaces to determine resident time and to quantify yields to measure the furnace performance.
^{144}Ce	284.3 days	β^-, γ	Radiation gauges, automatic weighing equipment.
^{147}Pm	2.6 years	β^-, γ	Radiation gauges, automatic weighing equipment.
^{169}Yb	32 days	γ	Industrial radiography.
^{170}Tm	128.6 days	β^-, γ	Industrial radiography.
^{192}Ir	74 days	β^-, γ	Industrial radiography and together with ^{51}Cr and ^{198}Au to label sand to study coastal erosion.
^{198}Au	2.7 days	β^-, γ	Tracing of factory waste causing ocean pollution, and to trace sand movement in riverbeds and ocean floors. Also used blast furnaces to determine resident time and to quantify yields to measure the furnace performance and together with ^{51}Cr and ^{192}Ir to label sand to study coastal erosion.
^{239}Pu	2.4.1E4 years	$\alpha, \beta, \gamma, \nu$	Borehole logging. ^{241}Am is also used in smoke detectors.
^{241}Am	432.2 years	$\alpha, \beta, \gamma, \nu$	
^{252}Cf	2.6 years	α, γ, ν	

5.1.1. Gamma Radiography

Gamma radiography uses a small pellet of radioactive material in a sealed titanium capsule to produce effective gamma rays (IAEA 1999). The capsule is placed on one side of the object being screened and some photographic film is placed on the other side. The gamma rays pass through the object and create an image on the film. The gamma rays show flaws in metal castings or welded joints, which allows critical components to be inspected for internal defects without damage. Table 5.2 includes examples of the types of sources used.

Table 5.2. Examples of Radionuclides used in Industrial Radiography

Radionuclide	Gamma energies (MeV)	Optimum steel thickness (mm)
^{60}Co	High (1.17 and 1.33)	50-150
^{137}Cs	High (0.662)	50-100
^{192}Ir	Med (0.2-1.4)	10-70
^{169}Yb	Low (0.008-0.31)	2.5-15
^{170}Tm	Low (0.08)	2.5-12.5

5.1.1.1. Radiography Equipment

Radiographic sealed sources are special form stainless steel capsules with high activity. Their gamma emissions are continuous and during transportation, the sources need to be housed in special portable containers. These containers (also called cameras) completely surround the source with shielding such as lead or DU.

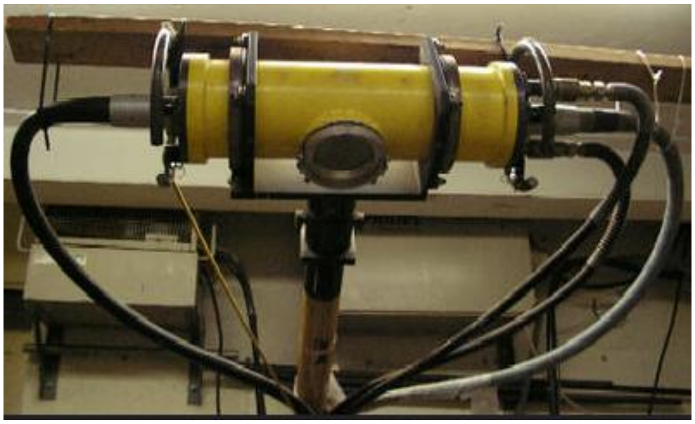
Many types of containers are manufactured but not all are internationally available or used. All generally operate by exposing the useful radiation in one of three ways:

1) Part of the shielding is taken away.
2) The source is moved to a deliberately thin part of the shielding but remains inside the container.
3) The source is fully removed from the container.

The most widely used radiography equipment is the projection container or crank-out camera. This design ensures that the radiographer can nearly always be protected by exposing the source from a distance.

Source: https://www.flickr.com/photos/usgao/14265287289/

Figure 5.1. Industrial Radiography Camera



Source: https://www.flickr.com/photos/154222089@N08/44195108171/

Figure 5.2. Industrial Radiography X-Ray

5.1.1.2. Storage of Equipment

Exposure containers only have sufficient shielding to be carried for short time periods for transportation purposes, meaning contact with them should be limited. Additionally, when a source gets used regularly on a site, special storage is arranged to hold the exposure container during nonuse hours. Coordination with the site operator ensures that the source can be isolated and in particular positioned well away from other hazardous materials such as explosives and corrosive substances.

The storage area should display clear warning notices and be dry inside. The dose rates accessible outside the store should be as low as reasonably practicable, preferably less than 2.5 µSv/hr (IAEA 1999). A lock should be kept on the door to prevent unauthorized access or tampering with the container. A record showing where each source has been at all times may be available.

When a radiographic source is exposed, it will produce dose rates greater than 7.5 µSv/hr over a very large area. The maximum size of the area can be calculated if the radionuclide and its activity are known. In general, such areas should be designated Controlled Areas and access to them should be prohibited to everyone except the radiographer and authorized helpers.

Beam radiography produces the smallest Controlled Areas, especially if the beam is directed into the ground. Another way of reducing the size of the Controlled Area is by setting up local shielding around the radiographed objects to attenuate the beam further when it has passed through the photographic film. Such beam stops can be made from lead or any such heavy metal.

5.1.2. Gauging

The chemical and food industry uses gauges to measure concentrations in various products. Density gauges can be used in monitoring chemical conversions, which result in density changes, such as sludge content in pipelines, bauxite content for aluminum production, coal sludge in coal washing, and sewage sludge in sewage plants. Military commodities identified in Chapter 4 also use gauges.

Radiation is attenuated as it passes through matter and detectors can be used to measure this attenuation or reduction in intensity. This principle can be used to gauge the presence or absence or to measure the quantity of material between a source and a detector. This requires no physical contact with the material being gauged.

A different principle relies on backscatter radiation. As matter attenuates radiation, some scatters back towards the source. Measuring the backscattered radiation provides information that can be used to determine material characteristics. One common use is measuring different coating thicknesses.

Figure 5.3 is an example of a density gauge. Gauging most often uses a ^{137}Cs source. The actual radioactive substance is double encapsulated in welded stainless steel. Each individual layer is checked for leaks after welding. The shielding container consists of cast iron housing filled with lead. For very corrosive environmental conditions, a housing made of stainless steel can be used.

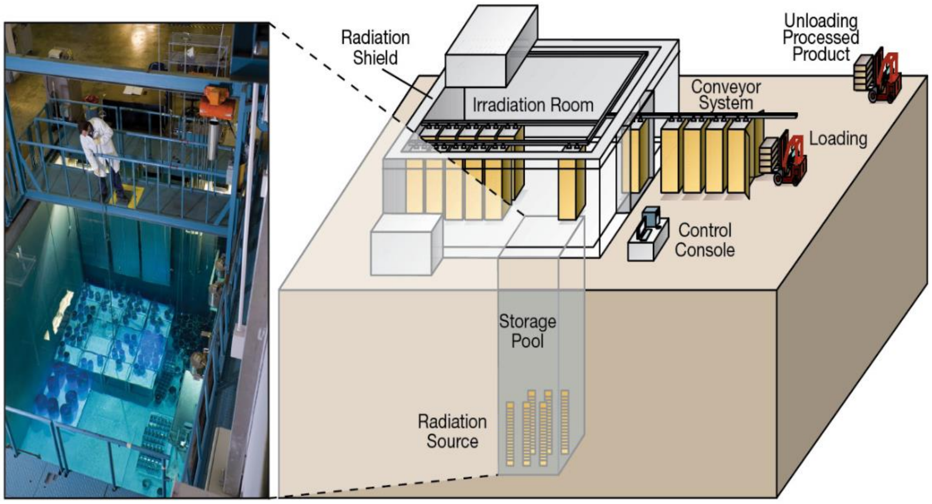
Source: http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/byproduct-materials.html

Figure 5.3. Density Gauge

5.1.3. Gamma Sterilization

Industries use gamma irradiation to sterilize medical, food, and various other products. The main isotope used in gamma sterilization is ^{60}Co because it is an energetic gamma emitter. ^{60}Co is produced in nuclear reactors and sometimes obtained as a byproduct of power generation. Large-scale gamma sterilization is used for disposable medical supplies such as syringes, gloves, clothing, and instruments that would be damaged by heat sterilization. These facilities also process bulk products such as raw wool for export, archival documents, and wood to kill parasites. Smaller gamma irradiators treat blood for transfusions and can be used for other medical applications.

Food irradiators can also be made with electron beams instead of radioactive material (Figure 5.4). However, the most common irradiators use ^{60}Co or ^{137}Cs. A food irradiation facility resembles any other warehouse. Workers typically load untreated food into containers attached to a conveyor system, which then move into the irradiation chamber enclosed by thick concrete walls. Inside the irradiator, one can find racks of pencil-shaped rods that contain radioactive material (^{60}Co or ^{137}Cs). When the containers of food are in place, the source rises from a pool of protective water and emits rays of gamma radiation. Depending on the dose, these rays can retard spoilage, kill insects, or destroy bacteria.



Source: https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/commercial-irradiator-large.jpg

Figure 5.4. Food Irradiator

Radiation sources found at food irradiators are of most concern if exposed or dispersed. Extreme caution must take place and appropriate monitoring equipment should be required when entering this type of facility.

5.2. Transportation of Radioactive Materials

About 100 million packages of hazardous materials are shipped every year in the U.S.; of these, about 3% (3 million) contain materials classified as radioactive. Some of the radioactive materials are low-level waste, the majority of which comes from medical, research, and industrial facilities and a very small amount are from nuclear power plants. Out of the 3 million shipments that are classified as containing radioactive material, 100 are linked to the transportation of spent fuel from nuclear power plants in the U.S. (UNSCEAR 1988). The same situation is common in the rest of the world.

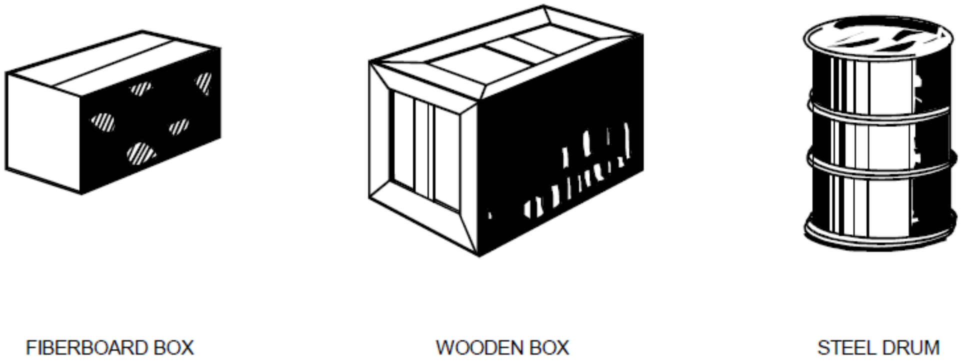
Radioactive sources can be identified in the military and civilian arena as they go through the process of packaging and storage. Basic concepts are further defined in Table 5.3 in order to ease the identification of these sources.

Table 5.3. Basic Concepts for the Storage and Transportation of Radioactive Materials (DOT 1988) (DA 2013) (NRC 1991a)

Concept	Definition
Contamination Wipe Survey	A survey for nonfixed (removable) radioactive contamination on surfaces. This is accomplished by wiping a portion of all surfaces of the package with absorbent material to determine the presence of radiological contamination. *NOTE: Results of the package wipe test must be obtained prior to shipment.
Limited Quantity of Class 7 (Radioactive) Material	A quantity of radioactive material not exceeding the package limits specified in 49 Code of Federal Regulations (CFR) Part 173.425 and conforming with requirements specified in 49 CFR Part 173.421.
Material Movement and Supply Documentation	Forms required for all shipments IAW applicable Army and DOD regulations. All shipments of instruments or calibrators must include documentation describing the purpose of the shipment.
NonFixed Radioactive Contamination	Radioactive contamination that can be readily removed from a surface by wiping with an absorbent material.
Normal Form Radioactive Material	Radioactive material that has not been demonstrated to qualify as “Special Form Radioactive Material.”
Package	For radioactive materials, the packaging together with its radioactive contents as presented for transport.
Packaging	For radioactive materials, the assembly of components necessary to ensure compliance with the packaging requirements of 49 CFR 173.24 and 173.410 through 173.419. It may consist of one or more receptacles, absorbent materials, spacing structures, thermal insulation, radiation shielding, and devices for cooling or absorbing mechanical shocks. The conveyance, tie-down system, and auxiliary equipment may sometimes be designated as part of the packaging.
Radiation Level	The radiation dose equivalent rate expressed in millirem per hour (mrem/hr).
Radiation Survey	This consists of measurements taken with an appropriate RADIAC instrument to ensure that the radiation level at the surface of a package meets the requirements of 49 CFR 173.441. A radiation survey is performed on certain incoming and all outgoing shipments of items containing radioactive materials.
Radioactive Instrument and Article	Any manufactured instrument and article such as an instrument, clock, electronic tube or apparatus, or similar instrument and article having Class 7 (radioactive) material in gaseous or nondispersible solid form as a component part.
Radioactive Contents	The radioactive material, together with any contaminated liquids or gases, within the package.
Radioactive Material	Any material having a specific activity greater than 0.002 microcuries per gram (µCi/g) or 74 Becquerels per gram (Bq/g) (See definition of “Specific activity”).
Special Form Radioactive Material	Radioactive material which satisfies the following conditions: a. It is either a single solid piece or is contained in a sealed capsule that can be opened only by destroying the capsule; b. The piece or capsule has at least one dimension not less than 5 millimeters (mm) (0.197 inch); and c. It satisfies the test requirements of 49 CFR 173.469.
Specific Activity	Specific Activity of a radionuclide is the activity of the radionuclide per unit mass of that nuclide. The specific activity of a material in which the radionuclide is essentially uniformly distributed is the activity per unit mass of the material.
Transport Index (T.I.)	A dimensionless number representing the maximum radiation level in mrem/hr at 1 m , as measured from the surfaces of the shipping container

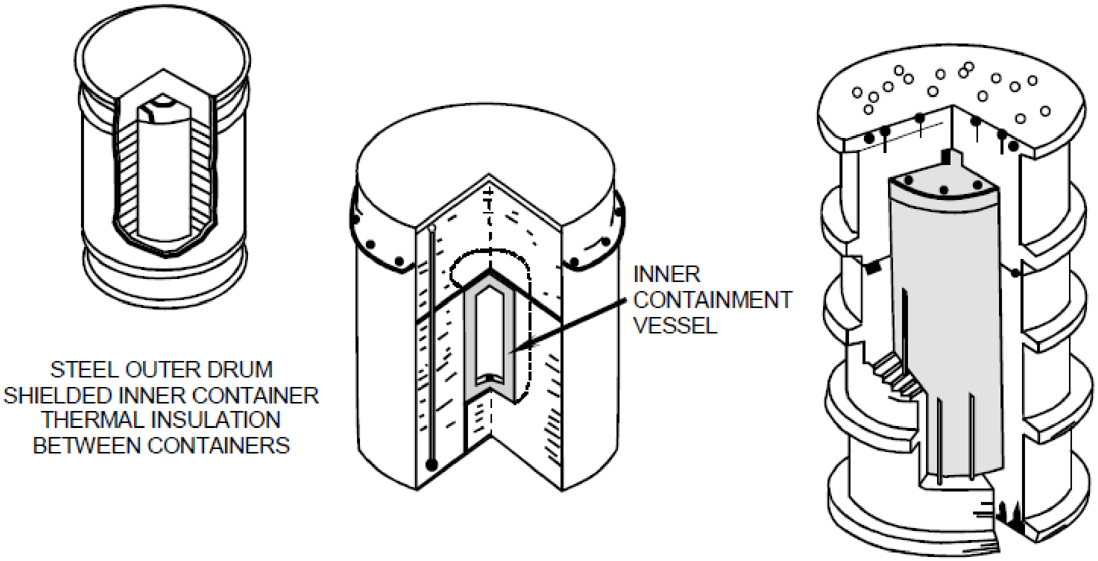
Concept	Definition
	rounded up to the nearest tenth (i.e., 0.13 mrem/hr at 1m equals a T.I. of 0.2). If the radiation reading is in millisieverts per hour (mSv/hr), the T.I. is the reading in mSv/hr multiplied by 100 and raised to the nearest tenth.
Type A Package	Type A packaging together with its limited radioactive contents. A Type A package does not require NRC Competent Authority Certificate of Approval since its contents are limited to A1 or A2 values. Packaging that is designed IAW with the general packaging requirements of 49 CFR Parts 173.24 and 173.412 (DOT 1988). Packaging must be adequate to prevent the loss or dispersal of the radioactive contents and retain the efficiency of its radiation shielding properties if the package is subject to the tests prescribed in 49 CFR 173.465.
Type B Package	Type B packaging together with its radioactive contents. Packaging which meets the standard for Type A packaging and, in addition, meets the standards for the hypothetical accident conditions of transport as prescribed in 10 CFR Part 71 (NRC 1995).

The following figures include examples of the packaging and transportation of radioactive materials. Figures 5.5 and 5.6 include typical type A and type B packages used for the transportation of radioactive materials.



Source: “Reactor Concepts Manual: Transportation of Radioactive Materials (Rev 0703),” Nuclear Regulatory Commission Technical Training Center.

Figure 5.5. Typical Type A Packaging of Radioactive Materials (DOT specification 7A)



Source: "Reactor Concepts Manual: Transportation of Radioactive Materials (Rev 0703)," Nuclear Regulatory Commission Technical Training Center.

Figure 5.6. Typical Type B Packaging Schemes

Table 5.5 summarizes radiation sources found in industrial practices and the transportation of radioactive material. These include radiation-generating machines that produce x-rays, radioisotopes used in the industry, radionuclides found in industrial equipment and sources from the transportation of radioactive material.

Table 5.5. Summary of Radiation Sources from Industry and Transportation of Radioactive Materials

Identified source	Radiations	Longest Half-life	Examples
X-ray machines	γ and x-rays	n/a	Electron microscopes Spectroscopy equipment Diffractometer equipment
Industrial accelerators	γ, x-rays, and neutrons (n)	n/a	See Appendix B for examples
Radioactive waste	α, β, γ, and n	n/a	See waste from industrial and biomedical practices
Transportation of radioactive materials to include spent fuel, ^{235}U, ^{238}U, ^{239}Pu, etc.	α, β, γ, and n	n/a	Packages containing radioactive materials, transportation of nuclear fuel and contaminated equipment or parts of power plants
^{3}H	β^-	12.33 y	Age water measurements
^{14}C	β^-	5730 y	Carbon dating
^{36}Cl	β^-, γ	3.01 E5 y	Age water measurements
^{210}Pb	α, β^-, γ	22.3 y	Sand and soil dating
^{46}Sc, ^{60}Co, ^{82}Br, ^{85}Kr, ^{90}Sr, ^{110m}Ag, ^{137}Cs, ^{140}La, ^{144}Ce, ^{147}Pm	β^-, γ	30.07 y	Resident time determination, gamma sterilization, industrial radiography, hydrological tracing, gauges, food irradiators.

Identified source	**Radiations**	**Longest Half-life**	**Examples**
^{51}Cr, ^{54}Mn, ^{57}Co, ^{65}Zn, ^{99m}Tc, ^{169}Yb	γ	312.5 d	Labeling, spectrometry, industrial radiography
^{170}Tm, ^{192}Ir, ^{198}Au	β^-, γ	128.6 d	Industrial radiography, labeling
^{239}Pu, ^{241}Am	α, β, γ, n	2.4E4 y	Borehold logging, smoke detectors
^{252}Cf	α, γ, n	2.6 y	Borehold logging

APPENDIX A. REFERENCES

U.S. Army Armaments and Chemical Acquisition and Logistics Activity (ACALA). 1998. “Radioactive Material Handling Safety Course,” Washington, D.C.

U.S. Army Environmental Policy Institute (AEPI). 1995. Technical Report, *Health and Environmental Consequences of Depleted Uranium Use in the U.S. Army*. Arlington, Virginia.

APHC. 2008. Technical Guide 244, *The Medical CBRN Battlebook*. Aberdeen Proving Ground, Maryland.

Bevelacqua, Joseph John ed. 1995. *Contemporary Health Physics: Problems and Solutions*. New York: Wiley-VCH.

Bolz, RE and GL Tuve, eds. 1973 CRC Handbook of Tables for Applied Engineering Science. 2nd Edition, Boca Raton: CRC Press.

Cember, Herman, ed. 3rd Edition. 1996. *Introduction to Health Physics,* New York: McGraw-Hill.

Code of Federal Regulations (CFR). 1995. “Packaging and Transportation of Radioactive Material” Title 10, Part 71.

Code of Federal Regulations. 1991b. “Standards for Protection Against Radiation” Title 10, Part 20 revisions.

Code of Federal Regulations. 1988. “Shippers - General Requirements for Shipments and Packagings” Title 49, Part 173.

Department of the Army (DA). 2019. TB 43-0137, *Transportation Information for U.S. Army Radioactive Commodities*.

DA. 2008. STP 21-24-SMCT, Soldier's Manual of Common Tasks (SMCT) Warrior Leader Skill Level 2, 3, and 4.

DA. 2006. TB 43-0197, Instructions for Safe Handling, Maintenance, Storage and Transportation of Radioactive Items Under License 12-00722-06.

DA. 1998. Technical Bulletin (TB) 43-0116, *Identification of Radioactive Items in the Army*.

DA. 1994. Field Manual 3-7 (inactive), *NBC Field Handbook*.

DA. 1987. Field Manual 21-60 (inactive), *Visual Signals*.

Eisenbud M and T Gesell eds. 1997. *Environmental Radioactivity from Natural, Industrial, and Military Sources, 4th Edition*. New York: Academic Press.

U.S. Environmental Protection Agency (EPA). Office of Radiation and Indoor Air. 2019. EPA 402-R-19-002, *External Exposure to Radionuclides in Air, Water and Soil*.

EPA. Office of Radiation Programs. 1988. EPA-520/1-88-020, Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion.

Galea, R et al. 2013. A comparison of rat SPECT images obtained using (99m)Tc derived from 99Mo produced by an electron accelerator with that from a reactor. Phys Med Biol 58(9):2737-2750.

Glasstone, S and WH Jordan. 1980. *Nuclear Power and its Environmental Effects*. Illinois: American Nuclear Society.

Glasstone, S and A Sesonske. 1981. *Nuclear Reactor Engineering, 3rd Edition*, Nuclear Reactor Engineering, Third Edition. New York: Van Nostrand Reinhold Co.

Hilaris, BS ed. 1975. *Handbook of Interstitial Brachytherapy*. Massachusetts: Publishing Science Group.

International Atomic Energy Agency (IAEA). 2000. "IAEA TECDOC No. 1174, *Methods of exploitation of different types of uranium deposits*, Vienna, Austria.

IAEA. 1999. Safety Reports Series No. 13, *Radiation Protection and Safety in Industrial Radiography*, Vienna, Austria.

Limits for Intakes of Radionuclides by Workers. 1979. International Commission on Radiological Protection (ICRP). Oxford: Pergamon Press.

Japan Atomic Energy Agency. U-235 Neutron-induced Fission Yields. 2013. https://wwwndc.jaea.go.jp/cgi-bin/FPYfig .

Johnson, TE and Birky, BK eds. 2012. *The Health Physics and Radiological Health Handbook, 4th Edition*. Baltimore, Maryland: Williams & Wilkins.

Joint Chiefs of Staff. 2018. Joint Publication 3-11, Operations in Chemical, Biological, Radiological, and Nuclear Environments.

Kathren, RL ed. 1984. Radioactivity in the Environment: Sources, Distribution, and Surveillance. Chur, Switzerland: Harwood Academic Publishers.

Khan, FM ed. 1984. *The Physics of Radiation Therapy*. Baltimore: Williams & Wilkins.

Lamarsh, JR ed. 1983. *Introduction to Nuclear Engineering, 2nd Edition*. Massachusetts: Addison-Wesley Publishing Company.

Leclercq, J ed. 1986. *The Nuclear Age*. Poitiers, France: Hachette.

Meisberger, LL, RJ Keller, and RJ Shalek. 1968. The effective attenuation in the water of gamma rays of gold 198, iridium 192, cesium 137, radium 226, and cobalt 60. *Radiology* 90(5):953-957.

National Council of Radiation Protection and Measurements (NCRP). 1980. Report No. 065, *Management of Persons Accidentally Contaminated with Radionuclides*. Bethesda, Maryland.

NCRP. 1988. Report No. 097, *Measurement of Radon and Radon Daughters in Air*. Bethesda, Maryland.

NCRP. 1977. Report No. 051, *Radiation Protection Design Guidelines for 0.1 - 100 MeV Particle Accelerator Facilities*. Bethesda, Maryland.

National Research Council (NRC). 1990. Biological Effects of Ionizing Radiation: Health Effects of Exposure to Low Levels of Ionizing Radiation. Washington, D.C.: The National Academies Press.

NRC. 2008. Directed Self Study, Uranium Enrichment Processes, *Module 5.0: Electromagnetic Separation (Calutron) and Thermal Diffusion*. http://www.nrc.gov/docs/ML1204/ML12045A056.pdf.

NRC. 1976. NUREG-0002, Vol 1, Final Generic Environmental Statement on the Use of Recycled Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors. Washington, D.C.
https://www.nrc.gov/docs/ML0710/ML071000110.pdf

NRC. 2019. NUREG-1350, Volume 31, *Information Digest 2019-2020*.
https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1350/.

ORNL. "Correlation of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle - Nuclear Fuel Reprocessing." 1975.

Patterson, HW and RH Thomas eds. 1973. *Accelerator Health Physics*. New York: Academic Press.

Quimby, EH, S Feitelberg, and W Gross eds. 1970. *Radioactive Nuclides in Medicine and Biology, 3rd Edition.* Philadelphia: Lea & Febiger.

Sorenson, JA and ME Phelps eds. 1987. *Physics in Nuclear Medicine, 2nd Edition*. Philadelphia: W.B. Sounders Company.

Wald, N ed. 1991. Acute Radiation Injuries and their Medical Management: The Biological Basis for Radiation Protection Practice (Proceedings of the 1991 Health Physics Society Summer School). Baltimore, Maryland: Williams and Wilkins.

“What is a gamma knife®?,” Elekta, last modified 2019.
http://gammaknife.com/what-is-gamma-knife/.

UNSCEAR. 1988. 1988 Report to the General Assembly, with annexes, *Sources, Effects, and Risks of Ionizing Radiation*.

"Uranium Production Figures, 2009-2018." WNA. last modified August 2019.
http://www.world-nuclear.org/information-library/facts-and-figures/uranium-production-figures.aspx.

U.S. Army Intelligence and Security Command. 1998. National Ground Intelligence Center (NGIC) 1162-325-98: *Identification Guide for Radioactive Sources in Foreign Material*. Washington, D.C.

APPENDIX B. RADIATION PROTECTION AND PRECAUTIONS

Possible radioactive sources of exposure or contamination, of both Civilian and military origin have been identified to highlight probable scenarios that can be encountered by Soldiers during peacetime operations and war missions. Several documents deal with the handling of these identified sources, preventive measures, decontamination procedures, and risk assessment (APHC 2008). Take several precautions to avoid or minimize the exposure of Soldiers to radiological sources.

B-1. General Precautions when Dealing with Identified Sources of External Exposure

Basic precautions to minimize or avoid external exposure can be defined in terms of time, distance, and shielding. The total radiation dose received depends on the duration of the exposure; therefore, minimizing the time spent around radioactive material minimizes the potential dose. By increasing the distance from a source, one can rapidly decrease the radiation intensity that reaches a Soldier. Doubling the distance decreases the amount of radiation by a factor of four. Appropriately shielding the identified external radiation source will minimize or prevent exposure. Whereas it is probably sufficient to shield a beta source with a thin layer of a material such as aluminum, a gamma source might require thick layers of lead or steel. A Soldier in the field would probably only have access to other types of shielding, such as dirt, sand, water, and so forth, and would need to improvise in order to acquire the necessary shielding.

Because of their different ranges in air and material/tissue, one would use a different type of shield when encountering an alpha, beta, gamma, or neutron source. Figure B-1 is an illustration of the shielding of alpha, beta, and gamma sources. Alpha particles are heavy charged particles with a very short range in air. They can be stopped with a sheet of paper or by the outer dead layer of the skin. A problem arises when an exposure to external contamination with an alpha emitter or to airborne contamination leads to internal contamination. Although beta particles can travel significant distances in air, solid materials easily stop them. Beta emitting sources should be shielded with low-density materials (for example plastics) to reduce *bremsstrahlung* production. One common shielding material for beta sources is aluminum. Leather gloves can greatly reduce the beta radiation dose. Gamma and x-rays require denser materials, such as lead or steel.

X-rays are produced whenever electrons of high energy strike a heavy metal target like tungsten. When electrons hit this material, some of the electrons will approach the nuclei of the metal atoms and are deflected. This deflection causes the energy of the electron to decrease. The decrease in energy appears as photons or electromagnetic radiation called *bremsstrahlung,* a German word for “braking radiation.” Bremsstrahlung x-rays are produced by the rapid slowing of energetic electrons in high Z materials either from radioactive material, in an x-ray machine, or in an accelerator.

Neutron shielding is very complicated because of the range of neutron energies commonly encountered and the dependence of neutron interactions on these energies and the shielding materials. As a general principle, neutrons are slowed and then absorbed. Because elastic scattering with a proton is the most efficient method to slow/moderate a neutron, hydrogen rich materials such as water, paraffin wax, and polyethylene are used. Both ^{10}B and ^{113}Cd are common absorbers of thermal neutrons. Cadmium emits a high-energy gamma ray upon capturing a neutron, and boron emits an alpha particle. Therefore, absorbers using cadmium will need additional shielding for the gamma rays produced.

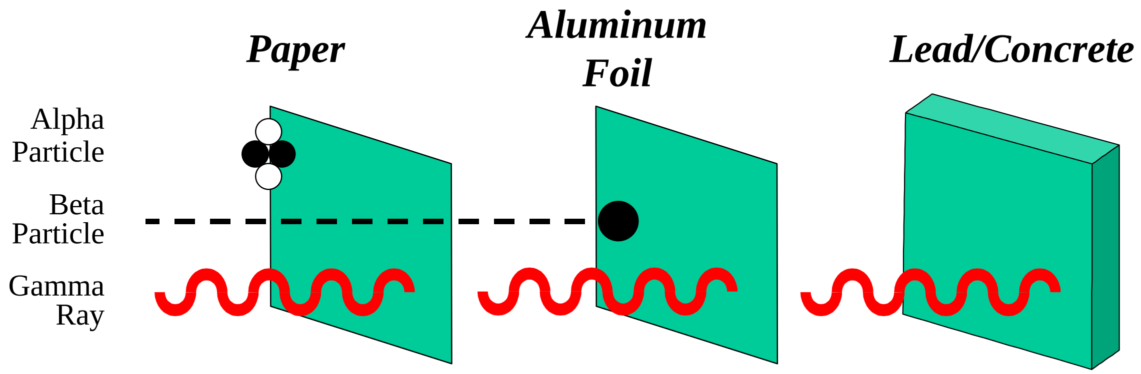


Figure B-1. Shielding of Alpha, Beta, and Gamma Radiation Sources

Table B-1 includes examples of shielding materials, the type of radiation for which they are used and the advantages and disadvantages of using them.

Table B-1. Example of Shielding Materials (Johnson 2012)

Shielding material	Radiation	Advantages	Disadvantages
Iron	Gamma	It is cheap and available in many forms and thickness. It has reasonable density and good structural characteristics.	It activates in neutron fields and leaks intermediate-energy neutrons.
Lead	Gamma	It is cheap and easy to form with moderately high density.	It is a toxic metal with severe restrictions on disposal as a radioactive waste. Impurities may be activated by neutrons.
Tungsten	Gamma	It has the highest available density in a commonly available metal. It has good activation characteristics.	It is very expensive and difficult to form.
Water	Neutrons, gamma	It is cheap, transparent, with good H density.	It can flow and leak out of container and evaporate. It would need 12 times the thickness of Pb to have the same attenuation to gammas.
Paraffin	Neutrons, gamma	It is cheap and easily formed with good H density. It can have various additives. There is no neutron activation.	It is combustible and its final form is not rigid. The neutron capture by H produces a hard-to-shield gamma. Lots of thickness would be needed for gammas.
Polyethylene	Neutron, gamma	It is easily shaped/machined. It has good hydrogen density. It does not activate and can be manufactured with selected additives.	It is semi-rigid and needs support for large sections. Lots of thickness would be needed for gammas.
Concrete	Gamma and neutron	It is cheap, with good structural characteristics. It is of best choice when space is not a concern, has an acceptable hydrogen density	It activates and large shields must be reinforced to avoid cracks. Shields can have voids.

Shielding material	Radiation	Advantages	Disadvantages
		for neutron shielding and it is stable at elevated temperatures.	
Hydrogen	Neutron	It is available in many materials and it is good for reducing energy of neutrons.	It produces high-energy gamma when capturing thermal neutrons.
Boron	Thermal neutron	It is easily added to many materials. It does not result in a radioactive product.	It is difficult to attain high concentrations when added to materials and it is expensive.
Lithium (nat.Li, and ^{6}Li)	Thermal neutron	The neutron absorbing process does not produce any gammas and lithium can be mixed with other materials.	Each absorbed neutron produces a lithium atom and it is expensive.
Cadmium	Thermal neutrons	It is a metal that is easily formed with sharp edges for beam definition. A thin piece can stop all thermal neutrons.	It is a toxic metal that produces a long-lived radioactive nuclide. Neutron capture produces high-energy gammas that are difficult to shield.

B-2. General Precautions when Dealing with Identified Sources of External Contamination

External contamination can occur when the radioactive material is airborne, and when it is in contact with clothing or skin. One can dispose of clothing, clean surfaces, and isolate oneself from airborne radioactivity to eliminate these types of external contamination; however, the skin has to be treated and protected from further contamination.

The U.S. Army has documents that address many different ways to protect exposed and/or contaminated individuals, equipment, and structures (DA 2008). Protocols detailed in these documents may be used after identifying a radiation source or as preventive measures if contamination is suspected. If there is external contamination, decontamination protocols must be followed. Table B-2 outlines some general rules as precautions to avoid further external contamination.

Table B-2. General Precautions for Minimizing or Avoiding External Contamination

If contamination is expected, conduct a radiation survey.
If contamination is confirmed, it is recommended that contaminated clothing be collected and secured, rather than trying to clean it with soap and/or chemical agents (detergents with certain additives, such as citrus acid) to attempt decontamination. Contaminated items should be turned into a Radiation Safety Officer for proper disposition.
Contaminated hands should be washed thoroughly for 2 to 3 minutes by using warm water and a mild soap or detergent. The entire hand surface should be covered with a good lather and rinsed off completely with water. The process should be repeated at least three times.
If precautions in number three does not remove all dirt and contamination, it is recommended to scrub the hands for a period of at least 8 minutes with a liquid or cake soap, hand brush, and warm water. During these 8 minutes there is sufficient time to complete at least three complete changes of water and soap. The entire surface of the hands should be brushed with light pressure, especially around the nails and between the fingers.
If there is contamination of the skin and a few decontamination efforts do not work and the skin starts to become thin, decontamination should be discontinued.
If the integrity of the skin is damaged and contamination is suspected, there is a potential for internal contamination and precautions should be taken (see paragraph B-3).

An example of external contamination is the contamination of the hands with fission products. In this case, it is recommended to use titanium oxide (TiO_2) as outlined in Table B-3.

Table B-3. Precautions for Minimizing Contamination of the Hands with Fission Products

The TiO_2 should be used as a paste or slurry made by shaking the powder compound into the wet palm of the hand until a good paste is formed.
Tap water should be run over the hands continually so that the paste is kept wet, and this paste should be applied thoroughly to all hand surfaces, especially around the finger nails.
The rinse should be done with lukewarm water and followed by a thorough washing with soap and water and a hand brush.
Caution should be made to remove all paste. If any is left under nails after washing, it will form a rather hard cake which is difficult to remove. Cutting fingernails can help to remove this contamination.

Table B-4 includes precautions for minimizing external contamination with plutonium by removing it with potassium permanganate ($KMnO_4$).

Table B-4. Precautions for Minimizing External Contamination with Plutonium

An equal volume of a saturated solution of $KMnO_4$ must be mixed with 1% sulfuric acid solution and poured over wet hands, covering the nails and cuticles thoroughly.
The entire surface must be rubbed lightly with a brush without bending the bristles out of shape.
Warm running water should be used to rinse off after the application has thoroughly covered hands. (This procedure should not be extended for more than 2 minutes. The process will stain the skin a deep brown.)

Freshly prepared 5% sodium acid sulfite solution should be used in the same manner as above, using the hand brush and warm running water for a 2-minute period. This solution will remove the brown stain of the skin. (Keep labeled packages containing 10 g $NaHSO_3$ on hand and dissolve this amount in 200 milliliters (mL) of water.)
The procedures listed in 1-4 may be repeated several times without appreciable harm to the skin if each washing is limited to about 2 minutes.
To wash other skin surfaces such as neck, face, ears, etc., the solutions may be applied with absorbent cotton. If another person is manipulating the solution, rubber gloves should be worn as protection from both contamination and permanganate staining.

B-3. General Precautions when Dealing with Identified Sources of Internal Contamination

Internal contamination may occur via inhalation, ingestion, injection, or absorption through the skin. Radionuclides deposited in the body (tissue or organ) leave the body via exhalation, feces, urine, or sweat at different rates.

This elimination rate directly affects the specific approach that needs to be taken in order to eliminate or minimize exposure to an internal contaminant. Internal contamination is treated depending on the type of isotope, how it is distributed within the body, its biological half-life ($T_{1/2\ BIO}$, the time that the body would take to eliminate one-half of the radionuclide), and its effective half-life (a combination of the physical and biological half-lives. The inverse of the effective half-life is equal to the addition of the inverse of both the radiological ($T_{1/2\ RAD}$) and biological half-life $1/T_{1/2\ EFF} = 1/T_{1/2\ RAD} + 1/T_{1/2\ BIO}$).

As a precautionary measure to avoid internal contamination, Soldiers must wear protective clothing when performing a task in a contaminated environment. Examples are the use of a mask, hood, helmet, gloves, footwear covers, and protective clothing or Mission Oriented Protective Posture gear upon entering a contaminated area (Army, Marine Corps, Navy, Air Force 2013).

B-3.1. Precautions Recommended for Working in a Contaminated Area

Table B-5 includes some general precautions for Soldiers encountering a contaminated area.

Table B-5. Precautions for Entering a Contaminated Area

Assigned duties in contaminated radiation areas must be completed promptly to minimize exposure.
When working around radioactive materials, one should not improvise. Appropriate procedure must be followed and no maintenance that is beyond one’s level should be performed. Activities are planned and practiced to minimize time if mission allows.
Protective wear is to be used when required.
Radioactive materials should be isolated and shielded to reduce exposures to individuals.
Maintaining maximum distance between a radioactive source and the body can significantly reduce exposure.

Table B-6 includes techniques for reducing internal contamination. All of these techniques require medical supervision for administration.

Table B-6. Techniques for Reducing Internal Contamination (Wald 1991)

Method	Agent	Example radioisotope
Dilution	Water	^{3}H
	Phosphorous (Neutrophos)	^{32}P
Blocking	Ferric Ferrocyanide (Prussian blue)	^{137}Cs
	KI (Lugol's solution)	^{131}I, ^{99m}Tc
	Al-phosphate, Al-hydroxide	^{89}Sr, ^{85}Sr
Mobilization	Chlorthalidone (Hygroton)	^{86}Rb
Chelating	DTPA	^{252}Cf, ^{242}Cm, ^{241}Am, ^{249}Pu, ^{144}Ce, ^{143}Pm, ^{140}La, ^{90}Y, ^{65}Zn, ^{46}Sc, rare earths
	EDTA, penicillamine	^{210}Pb
	Penicillamine	^{203}Hg, ^{60}Co

Eliminate radioactive material from the body to remove its hazard. The biological methods of elimination include renal excretion for most soluble materials, elimination in the feces for materials which are retained in the gut or which can be secreted in the bile, and exhalation for volatile materials and gases. Chelating agents such as calcium or zinc DTPA, if administered soon after exposure, are effective in enhancing the elimination of certain radioisotopes. These materials are not very effective for radioisotopes which have been incorporated and fixed in organs and tissues.

The uptake by the body of radioisotopes can be blocked in some cases. For example, potassium iodide or iodate if given prior to or soon after an intake of radioiodine, will reduce the uptake of radioiodine by the thyroid gland. Similarly, orally administered Prussian Blue will reduce the absorption of cesium from the gut and Alginate will reduce strontium absorption.

B-3.2. Precautions when Dealing with Equipment Containing Radioactive Sources

Common rules that apply to personnel working with equipment containing radioactive material are shown in Table B-7.

Table B-7. Precautions for Handling Equipment Containing Radioactive Sources

No smoking, eating, drinking, gum or tobacco chewing, and applying of cosmetics permitted in the area. This helps reduce the potential for ingestion of radioactive materials.
Always wash hands after handling radioactive materials or sources with nonabrasive soap, even if disposable gloves were used.
Medical injuries take precedence over radiological contamination concerns. In the event of an accident or injury, injured personnel should be removed under the supervision of medical personnel. If injury occurs inside a building or room with possible radioactive contamination, the injured person should be moved to limit exposure.
Chain of command must be informed of radiological handling operations.

B-4. Precautions when Dealing with Tritium Sources

Over 99% of the tritium in light sources is in gaseous form (DA 1997). Tritium oxide, which is readily absorbed by the body, poses no radiation hazard as long as it is contained within the Pyrex tube. If the tube is broken or damaged while it is still contained, for example in a fire control device, the tritium gas is released into the interior of the device. The gas does not dissipate and will combine with oxygen molecules to form significantly more tritium oxide. The tritium will leach into the metal and other materials in the interior of the device creating a contact hazard. No maintenance is to be performed on devices that contain tritium, even if it is suspected that the Pyrex tube containing the tritium gas has been broken or is leaking. Lack of illumination is an indication that the source may be damaged. To test for illumination of the light source, one can follow with the simple steps listed in Table B-8.

Table B-8. Illumination Test for Equipment Containing Tritium Sources

Place the device in a dark place for a long enough time to ensure that the phosphor agent is not being activated by an outside light source. If in doubt, double bag source.
View the device in low light after your eyes have become accustomed to the dark.
If there is no evidence of illumination, consider the light source to be broken.

If a tritium source is broken during handling at site, one must inform all personnel to vacate the area and move upwind from the device. Figure B-2 is a flow diagram of the recommended precautions when dealing with a broken tritium source. When a tritium source breaks or is no longer illuminated, notify local CBRN personnel, and take the following actions under their direction, as listed Table B-9.

Table B-9. Directions and Precautions for Dealing with a Broken Tritium Source

Wash hands with nonabrasive soap and lukewarm water as soon as possible when touching or handling broken Pyrex tubes.
Wear rubber or latex gloves when handling the device.
Ensure the device is immediately double wrap in plastic, sealed, packaged, and shipped to the designated location.
The outside container must be labeled “BROKEN TRITIUM DEVICE - DO NOT OPEN.”
The broken device must be stored outdoors in a secured container. Used gloves should be disposed of as radioactive waste per direction of the local CBRN personnel, and then hands should be washed well.
Personnel who may have handled the broken tritium device should report to the health clinic for a tritium bioassay. The optimum bioassay sample time is approximately 4 hours after the exposure. A minimum of 2 to 4 hours are necessary for tritium to reach equilibrium and only after this minimum time should a urine sample be taken (DA 1998).
Personnel should drink lots of fluid/water to enhance the tritium biological elimination from the body.
The area where the tritium contamination has occurred must be cordoned off and restricted until a wipe test in the area indicates that no contamination remains on the surface. Broken tritium devices indoors may result in tritium contamination of the workbench, table, or the surrounding area.

Notes:
Bioassay refers to the determination of kinds, quantities or concentrations, and, in some cases, the locations, of radioactive material in the human body, whether by direct measurement (in vivo counting) or by analysis and evaluation of materials excreted or removed from the human body. A wipe test or smear test is a method of determining the removable contamination on a surface. The suspected area is wiped with a filter paper and the radioactivity on paper is measured.

If tritiated water is incorporated into the body, the biological half-life is the factor determining the extent of the hazard since the biological half-life is so much shorter than the physical half-life of about 12 years. Reduction of the biological half-life to a minimum by overhydration and the administration of diuretics is the recommended therapy in cases of exposures to tritium.

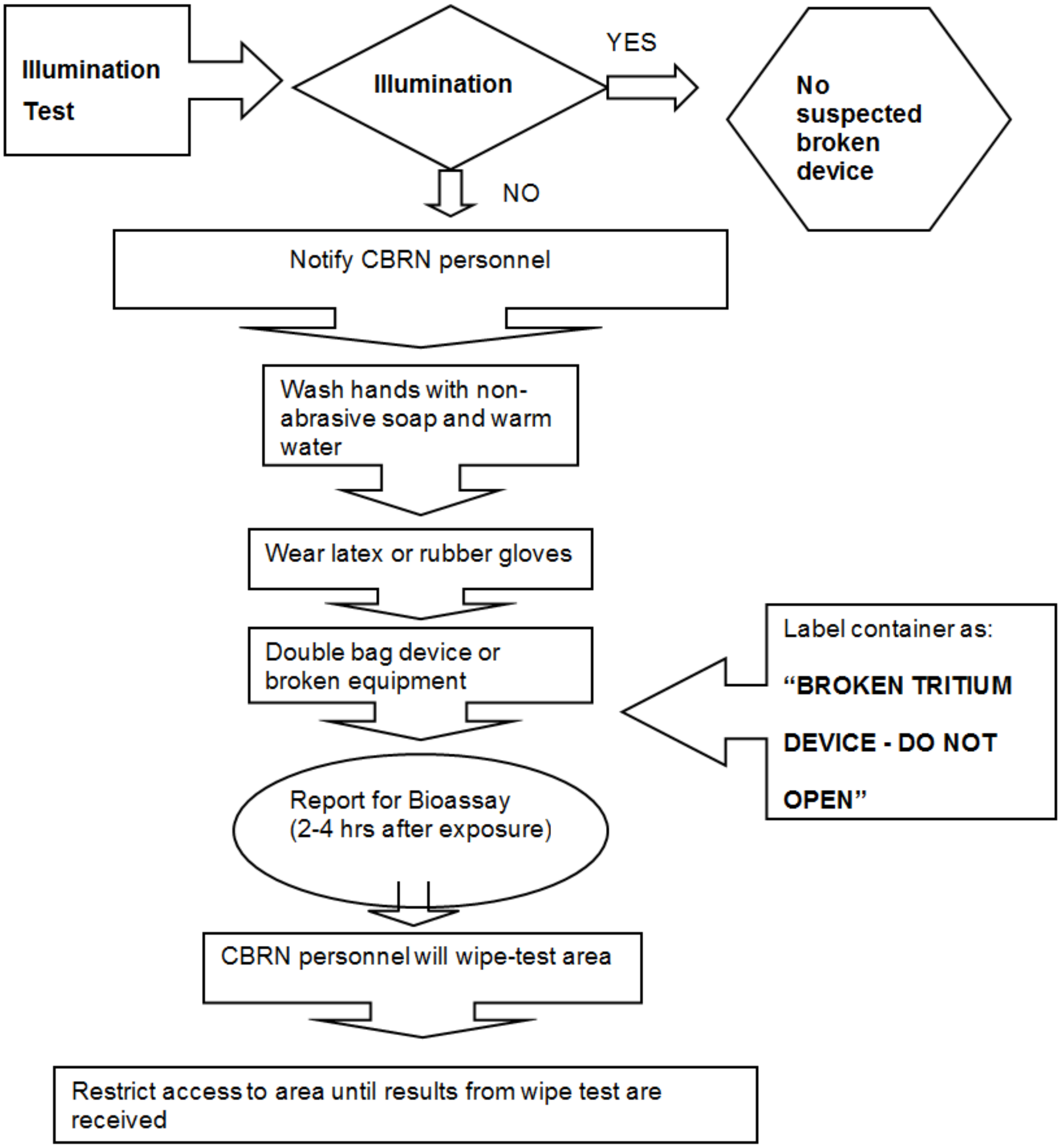


Figure B-2. Flow Chart Indicating Precautions when Dealing with Broken Tritium Source

B-5. Precautions when Dealing with DU

Special precautions may be required for protection from DU exposure in four common situations. The first is being within 50 m of any equipment struck by DU munitions. The second is being required, by the nature of job or mission, to routinely enter damaged vehicles struck by DU or containing damaged DU armor. The third is being within 50 m of any fire involving DU munitions. The fourth is when welding DU armor.

The best protective measure is simply avoiding these situations unless required by the job or mission. One should stay upwind of a visible smoke plume involving DU. In most of the situations where additional protective measures may be warranted, personnel will have special training and equipment. If one encounters any one of these situations, some standard protective measures can be taken (see Table B-10).

Table B-10. Precautions to Minimize or Avoid DU Contamination

Wear respiratory protection
Keep exposed skin covered
Brush off clothing and equipment to remove potential contamination
Wash hands before eating and shower when available

If a DU exposure is suspected (internal intake via ingestion, inhalation, or wound), a bioassay must be recommended. U.S. Army Medical Command (MEDCOM) Policy Memo 14-021 describes when a bioassay is required and the procedures for collecting the sample.

One should remember that brief exposures to DU, even in a situation where protective measures may be necessary, are safe. Mission accomplishment and the saving of life and limb should never be delayed because of potential DU exposure.

B-5.1. The Nature of the Potential DU Hazard

The external radiation effects of DU are minimal. Most of the radiation emitted by DU is weak and cannot penetrate the skin or a layer of clothing; however, what can penetrate is well below the U.S. safety standards. Following standard safety precautions and observing good personal hygiene mitigates health effects. The internal radiation effects are of more importance. Breathing in the DU dust is of most concern. Heavy metal toxicity is of significance when internal exposure has occurred. Like any other heavy metal, such as lead and tungsten, DU can cause chemical effects in the organs and other systems of the body. When considering the chemical toxicity of DU, the kidney is the most likely organ to be affected.

DU can be considered a low-level operational exposure, and Table B-11 below provides guidance on how to deal with these types of exposures.

Table B-11. Modified Table for Guidance Low Level Radiation Operational Exposure (Johnson 2012)

TOTAL CUMULATIVE DOSE (cGy) (See notes 1, 2 &3)	TOTAL DOSE (mSv)	RES Category	STATE (See notes 4 & 5)	ACTIONS
<0.05 cGy	<0.5 mSv	0	NO RISK	- None
0.05 To 0.5 cGy	0.5 To 5 mSv	1A	NORMAL RISK	- Record individual dose readings - Initiate periodic monitoring
0.5 To 5 cGy	5 To 50 mSv	1B	MINIMAL RISK	- Record individual dose readings - Continue monitoring - Initiate rad survey - Establish dose control measures as part of operations - Prioritize tasks
5 To 10 cGy	50 To 100 mSv	1C	LIMITED RISK	- Record individual dose readings - Continue monitoring and update survey - Continue dose control measures - Execute priority tasks only (See note 6 below)
10 To 25 cGy (See note 7)	100 To 250 mSv (See note 7)	1D	INCREASED RISK	- Record individual dose readings - Continue monitoring and update survey - Continue dose control measures - Continue to execute priority tasks only - Execute critical tasks only (See note 6 below)
25 To 70 cGy (See note 8)	250 To 700 mSv (See note 8)	1E	SIGNIFICANT RISK	- Record individual dose readings - Continue monitoring and updating survey - Continue dose control measures - Execute critical tasks only

Notes:

Dose is uniform to the entire body due to whole body radiation and including internal contamination.

All doses should be kept as low as reasonably achievable (ALARA). This will reduce individual Soldier risk as well as retain maximum operational flexibility for future employment of exposed Soldiers.

The use of millisieverts (mSv) is preferred in all cases. However, due to the fact that normally the military has only the capability to measure directly in centigray (cGy), as long as the ability to obtain measurements in mSv is not possible, Joint Forces will use cGy.

1 cGy = 10 mSv for x-ray and gamma doses

Risk is of long-term health consequences, primarily induction of fatal cancer starting two years post exposure. Total lifetime risk is assumed to be 4 to 7% per 100 cGy (= 1000 mSv). This is in addition to the 20 to 25% incidence of fatal cancer among the general population. Additional health risks that may occur are teratogenesis and mutagenesis and their associated psychological and social consequences.

It must be noted that higher radiation dose rates produce proportionally more health risks than the same total dose given over a longer period.

Examples of priority tasks are those missions to avert danger to persons or to prevent damage from spreading.

Examples of critical tasks are those missions to save a human life.

During peacetime, normally this dose will not be exceeded except to save human lives.

RES category 1E covers a wide range of doses and its lower level (25 cGy = 250 mSv) is the peacetime operational dose guide in many North Atlantic Treaty Organization nations. This category is normally only applicable in wartime.

APPENDIX C. ACCELERATORS AND CLINICAL RADIATION GENERATORS

An accelerator takes a charged particle, speeds it up using electromagnetic fields, and collides the particle onto a target. In scientific endeavors there are usually arrays of detectors surrounding the target. In industrial situations, there are fewer and less sophisticated detectors, but there may be conveyors and other means of transport for materials to be processed.

Accelerators may be classified according to geometry or according to the means of particle acceleration. Geometrically, there are linear and cyclic accelerators. In a linear accelerator, the particle beam travels in a straight line. In a cyclic accelerator, the beam travels along a curved path. If the particles are accelerated directly by an electric field, they are called direct accelerators. If radiofrequency fields are used to accelerate and magnetic fields are used to steer the beam, the accelerators are called indirect. The basic types of linear accelerators grouped by means of acceleration are shown in Table C-1 below. Table C-2 shows the applications of these accelerators.

The National Council of Radiation Protection and Measurements (NCRP) has published a comprehensive report on radiation safety at accelerators: *Radiation Protection Design Guidelines for 0.1 - 100 MeV Particle Accelerator Facilities*, NCRP Report Number 51 (NCRP 1977).

Table C-1. Basic accelerator types (NCRP 1977)

General	Type
Direct (Potential Drop)	1. Electrostatic High Voltage Belt-charging (for example, Van de Graaf) Rotating cylinder charging system 2. High Voltage Transformers Transformer rectifier set Voltage multiplying (for example, Cockcroft-Walton generator) Cascaded transformer system
Indirect (Cyclic)	1. Linear Beam Trajectory Ion linear accelerator Electron linear accelerator 2. Circular or Spiral Beam Trajectory Cyclotron (Ions only) Synchrotron (Ions or electrons) Betatron (Electrons only) Microtron (Electrons only)

Notes: For accelerating ions either a single stage or tandem accelerator may be used. Electrons are generally accelerated in a single stage.

Table C-2. Applications of Particle Accelerators (NCRP 1977)

Application	Electron	X-ray	Ion	Neutron
Diagnostic Radiology		✓		
Radiotherapy	✓	✓	✓	✓
Industrial Radiography		✓		✓
Material Analysis				
Activation Analysis			✓	✓
Microscopy	✓		✓	
Fluorescence	✓	✓	✓	
Ion Implantation			✓	
Radionuclide Production			✓	✓
Research and Training	✓	✓	✓	✓

Table C-3 lists possible radiation concerns associated with the use of particle accelerators.

Table C-3. Radiation Concerns in the Vicinity of Particle Accelerators (Johnson 2012)

Accelerator	Particles	Energy (MeV)	Radiological Concerns
Potential Drop	Protons Deuterons (^{2}H) Alpha Particles (^{4}He)	1 - 10 1 - 10 2 - 20	Fast neutrons, thermal neutrons, gamma rays, and activation of surrounding materials
	Electrons	1 – 10	Electrons, x-rays
Linear Electron	Electrons	1 - 10	Electrons
	Electrons	>10	Electrons, x-rays, fast and thermal neutrons, gamma rays, and activation of surrounding materials
Cyclotrons	Protons Deuterons (^{2}H) Alpha Particles (^{4}He)	15 - 20 7.5 - 24 15 – 50	Fast neutrons, thermal neutrons, gamma rays, and activation of surrounding materials
Betatron	Electrons	1 – 50	Electrons, x-rays, and activation of surrounding materials

Table C-4 gives rough guidelines concerning the activation of target materials and materials surrounding the accelerator.

Table C-4. Activation near Particle Accelerators (Johnson 2012)

Particle	Energy	Activation of Target	Activation of Surroundings
Electrons	< 1.67 MeV	None	None
	1.67 - 10 MeV	Limited	Very little
	> 10 MeV	Probable	Suspect
Protons and Alpha Particles	< 1 MeV	Limited	None
	1 - 10 MeV	Limited	Suspect
Deuterons and Tritons (^3H)	Any Energy	Limited	Suspect
Light Ions	> 10 MeV	Probable	Suspect

Table C-5 gives a summary of radionuclides often found near accelerators. Generally, only the external radiation is of concern. The exception is for hydrocarbons, especially lubricants and plastics, which may pose a potential for internal exposures. The production of ozone and other noxious gases is not a radiological hazard but must also be considered.

Table C-5. Activation Products often found near Accelerators (Patterson 1973)

Exposed Material	Radionuclides	Half Life
Hydrocarbons	^{7}Be	days
	^{11}C	20.5minutes
Duralumin (aluminum alloy)	As above, and	
	^{18}F	1.8hours
	^{22}Na	years
	^{24}Na	15hours
Steel	As above, and	
	^{42}K	hours
	^{43}K	hours
	^{44}Sc	hours
	^{44m}Sc	58.6 hours
	^{46}Sc	83.8 days
	^{47}Sc	3.4 days
	^{48}Sc	1.8 days
	^{48}V	16 days
	^{51}Cr	27.7 days
	^{52}Mn	5.6 days
	^{52m}Mn	21.4 minutes
	^{54}Mn	312.7 days
	^{56}Co	78.8 days
	^{57}Co	270.9 days
	^{58}Co	70.8 days
	^{55}Fe	2.74 years
	^{59}Fe	44.6 days
Stainless Steel	As above, and	
	^{60}Co	years
	^{57}Ni	36 hours
	^{60}Cu	23.7 minutes
Copper	As above, and	
	^{65}Ni	hours
	^{61}Cu	hours
	^{62}Cu	9.7 minutes
	^{64}Cu	12.7 hours
	^{63}Zn	38.17 minutes
	^{65}Zn	244.4 days

Radionuclides have been measured in room air surrounding several accelerators. These are mainly the results of neutron interactions in air. Radionuclides found are: ^{7}Be, ^{11}C, ^{13}N, ^{14}O, ^{15}O, ^{16}N, ^{38}Cl, and ^{41}Ar (Patterson 1973). Because these are airborne radionuclides, ventilation rates are very important in controlling the concentrations. The half-lives of all the radionuclides listed are approximately minutes or seconds, except ^{7}Be (53.4 days) and ^{41}Ar (1.8 hours).

APPENDIX D. POSTINGS IN A NUCLEAR/RADIOLOGICAL ENVIRONMENT

Warning sign posting is an important part of radiation safety. Warning signs and other postings are used to inform or warn of possible hazards. These postings can warn Soldiers in the vicinity of a radiation source or an area of possible exposure/contamination. This section includes posting requirements in the U.S. and abroad, as Soldiers may encounter them. The following is a summary of the tables included in this appendix.

Table	Contents
D-1	Posting requirements in the United States, found in 10 CFR 20 (NRC 1991b).
D-2	Definitions of the Annual Limit Intake (ALI) and the Derived Air Concentration (DAC), used in the derivation of internal dose. These values were referred to in Table D-1.
D-3	Postings required for the transportation of radioactive materials in the United States found in Title 49 CFR (DOT 1988). Subpart I, Sections 173.400 -173.478; Radioactive Materials, Parts 174.700, 175.700, 176.700 and 177.700; Sections dealing with carrier requirements for radioactive materials shipments.
D-4	Contamination marking signs used by the Department of the Army (DA 1994).

Table D-1. Posting Requirements (NRC 1991b)

Posting Type	Dose Rate Limits	Sign Text	Sign
"Controlled" or "Restricted" Areas	Occupational dose limits	None, this is a limited access area to protect people against undue risk from exposures to radiation and radioactive materials.	
Radioactive Materials (rooms)	Materials with activities exceeding the limiting standard values.	CAUTION RADIOACTIVE MATERIALS	
Radiation Area (external radiation)	≥ 50 μSv (5 mrem) in any one hour at 30 cm from any radiation source.	CAUTION RADIATION AREA	
High Radiation Area (external)	≥ 1 mSv (100 mrem) in any one hour at 30 cm from any radiation source or surface.	CAUTION HIGH RADIATION AREA	
Very High Radiation Area	≥ 5 Sv (500 rem) (a lethal absorbed dose) in any 1 hour at 1 m from any radiation source. (Note the change in units.)	GRAVE DANGER VERY HIGH RADIATION AREA	
Airborne Radioactivity Area	Airborne concentration in excess of occupational limits: I/week > 0.6 % ALI Cumulative in week >12 DAC-hour	CAUTION AIRBORNE RADIOACTIVITY AREA	

Table D-2. ALI’s and DAC’s (ICRP 1979) (EPA 1988)

Concept	Definition
ALI	An ALI is an Annual Limit on Intake. The ALI is that amount of a radionuclide that when taken in gives a dose commitment of 0.05 Sv (5 rem). In most cases, the ALI is calculated to limit the risk of stochastic effects of an internal exposure to the risk of a uniform whole body exposure of 0.05 Sv (5 rem). Sometimes the ALI’s are based on limiting the risk of nonstochastic effects to a particular organ; for example, ^{131}I for thyroid damage and ^{239}Pu for bone damage.
DAC	The DAC is the Derived Air Concentration. The DAC is the radionuclide concentration in air that would give a “radiation worker” an intake of 1 ALI if the worker was exposed to the contaminated air for 1 working year (8 hours per day, 5 days per week, and 50 weeks per year or 2000 hours).

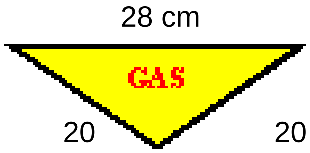
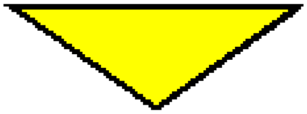
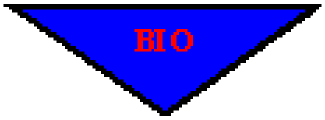
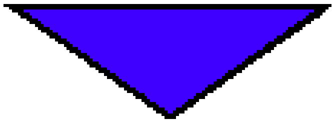
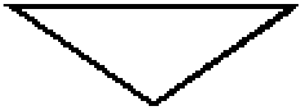
Note: DAC Bq/m^3 = ALI / 2400 Bq/m^3

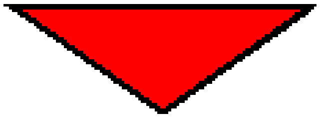
Table D-3. Requirements for the Packing and Transportation of Radioactive Materials (DOT 1988)

Type			Label
Packaging			
Name / Contents	**Radiation Level at Package Surface (RL)**	**Transport Index (TI)**	
White-I Label includes contents and activity	$RL \leq 0.005$ mSv/h ($RL \leq 0.5$ mrem/h)	TI = 0	
Yellow-II Label includes contents, activity, and in boxed TI	0.005 mSv/h $< RL \leq 0.5$ mSv/h (0.5 mrem/h $< RL \leq 50$ mrem/h)	$0 < TI \leq 1.0$	
Yellow-III Label includes contents, activity, and in boxed TI	0.5 mSv/h $< RL \leq 2$ mSv/h (50 mrem/h $< RL \leq 200$ mrem/h)	$1.0 < TI \leq 10$	
Yellow-III	2 mSv/h $< RL \leq 10$ mSv/h (200 mrem/h $< RL \leq 1000$ mrem/h) (the Yellow-III type of package must be shipped under exclusive use provisions, as detailed in 49 CFR, section 173.441(b).)	$TI > 10$	

Type			**Label**
Packaging			
Name / Contents	**Radiation Level at Package Surface (RL)**	**Transport Index (TI)**	
Transportation			
Function			Placard
Transporting vehicle must be placarded on all sides of vehicle or the cargo-carrying body, if any quantities of packages bearing the RADIOACTIVE-YELLOW III labels are present on the vehicle.			
Highway route control quantity shipment. The radioactive placard is placed on a white, 14 inch square, surrounded by a rectangular (1 inch thick) black border.			

Table D-4. CBRN Contamination Marking Signs (DA 1994)

CBRN Sign	**Front**	**Back**
CHEMICAL YELLOW background with RED lettering	 Name of Agent (if known) Date and Time of Detection	
BIOLOGICAL Blue background with RED lettering	 Name of Agent (if known) Date and Time of Detection	
RADIOLOGICAL WHITE background with BLACK lettering	 Dose Rate Date and Time of Reading Date and Time of Burst (if known)	

CBRN Sign	Front	Back
	Surface of Marker FACING AWAY from Contamination	Surface of Marker FACING Contamination
CHEMICAL MINEFIELD (Unexploded Mines) RED background with YELLOW lettering and stripe	 Chemical Agent in Mine Date of Emplacement Surface of Marker FACING AWAY from Minefield	 Surface of Marker FACING Minefield

Figures D-1, D-2, and D-3 are illustrations of the typical universal radiation symbols and a representation of a signal that means that there is a Nuclear, Biological, or Chemical hazard present; this is a signal used for armored and mechanized units and are detailed in Chapter 3 of Field Manual (FM) 21-60 (DA 1987).

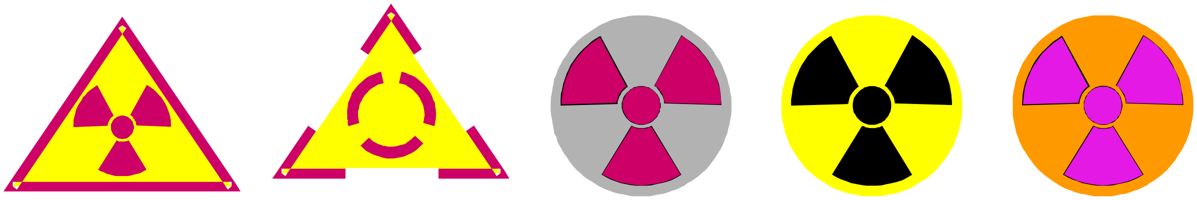


Figure D-1. Typical Radiation Symbols

Figure D-2. International Radiation Symbol

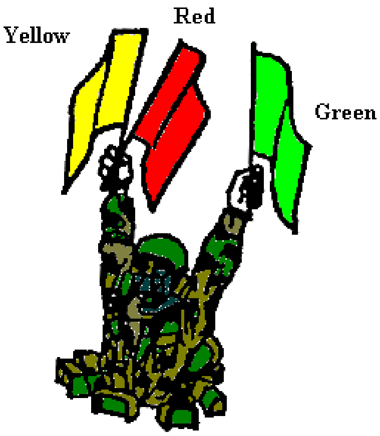


Figure D-3. Signal Flags Representing: NUCLEAR, BIOLOGICAL, CHEMICAL HAZARD PRESENT (DA 1987)

APPENDIX E. NATURAL RADIOACTIVE SOURCES

Natural background radiation comes from the sun, radioactive elements in the earth’s crust, rocks, air, water, and radioactive materials in plants and the human body. Background radiation is unavoidable and the amount varies from one location to another. Table E-1 includes examples of background radiation sources.

Table E-1. Examples of Background Radiation

Source	Examples of radiation type or radionuclide
Cosmic Radiation	Gamma, Electrons, Protons, Neutrons and Cosmic rays
Earth Crust	U, Th, ^{40}K, Natural decay series elements and others
Air	Radon (^{222}Rn), Thoron (^{220}Rn), ^{3}H, ^{14}C, others
Water	U, Th, Ra, ^{40}K others
Plants and Human Body	^{226}Ra, ^{228}Ra, ^{3}H, ^{14}C, ^{40}K, others

Soil contains radioactive materials such as uranium, radium, thorium, ^{40}K, and other elements found in the natural radiation decay series (thorium, neptunium, uranium, and actinium series). Radon and thoron are radioactive gases that become airborne as they leak out from the earth or building materials. Carbon-14 and tritium (^{3}H), as well as other radioactive nuclides that are created by cosmic radiation, are also present in the air. The radioactive materials found in water depend on the source of water. For instance, well water may contain traces of uranium, thorium and radium and it is often high in radon; whereas, seawater may have higher concentrations of ^{40}K. Plants and the human body also have radioactive materials that have been transferred by the food chain.

Ninety percent of the tritium from cosmic rays is found in the ocean and other terrestrial waters. The remaining 10% is found in the stratosphere, where the tritium is produced by the cosmic-ray reactions.

E-1. Ionizing Radiation and Radionuclides

Radiation can mean different things to different people. For this discussion, radiation means energy in the form of waves or particles. The waves are invisible, weightless, and odorless; human senses cannot detect them. The particles cannot be seen, but they do have weight and can have an electric charge. These waves and particles are part of a spectrum of energy. For this discussion, we are also interested in those waves and particles that have enough energy that can change atoms and molecules by a process called ionization. This is ionizing radiation.

You might be familiar with the names of the more commonly known waves and particles: x-rays, gamma rays, alpha particles, and beta particles. X-rays and gamma rays are waves that are usually blocked by different thicknesses of lead or steel. Alpha particles are the heaviest and can be stopped by air, clothing, or the outer layer of our skin. Beta particles are much lighter than alpha particles are can be stopped by tissue or plastic.

A radionuclide is a radioactive form of an element. When working with or near radiation sources, it is prudent (within mission constraints) to minimize the amount of time in the area, maximize your distance from the source, and to use appropriate shielding and personal protective equipment (PPE), if needed. Additional information on radiation, detection, protection, and precautions that can be taken when working with or near radiation sources is in Appendix B.

E-2. Uranium

Uranium is a radioactive metal and like most metals it is usually present in nature as an oxide, not as a pure metal. Pure uranium metal has a silvery luster in its freshly milled and polished state. However, like many metals, uranium oxidizes rapidly and becomes coated with a black layer of oxide from air and moisture contact. Uranium is about 65% denser than lead. Table E-2 includes some of the properties of uranium.

Table E-2. Properties of Uranium (Bolz 1973)

Property or Characteristic	Value/Example
Composition	Natural uranium normally contains by weight approximately 99.2830 % ^{238}U, 0.7110 % ^{235}U and 0.0054 % ^{234}U.
Atomic weight (A)	238.029
Atomic number (Z)	92
Physical Appearance	Uranium is a heavy radioactive silvery-white metal. In the air, the metal becomes coated with an oxide layer.
Physical Properties	It is malleable, ductile, and slightly paramagnetic. Uranium metal can be dissolved in acids but it is unaffected by alkalis. U metal is pyrophoric (i.e. it can ignite when exposed to air). Melting point = 1132.3 ^{o}C Boiling point = 3818 ^{o}C
Isotopes	Uranium has fourteen isotopes, all of which are radioactive.

E-3. Thorium

Thorium is a radioactive metal found in thorite ($ThSiO_4$) and in thorianite ($ThO_2 + UO_2$). It is now thought to be about three times as abundant as uranium. A particular characteristic of its decay scheme is the presence of thoron (^{220}Rn $T_{1/2}$=55.6 sec.), which is an alpha emitter that continues to decay into its progeny, as detailed in Table E-3. Therefore, it is essential to have good ventilation areas where thorium is stored.

Table E-3. Thoron and Progeny (Johnson 2012)

Nuclide	Radiation	Half-life
^{220}Rn	α, γ	55.6 sec
^{216}Po	α, γ	0.1 sec
^{212}Pb	β, γ	10.6 hr
^{212}Bi	β, γ (64 % to ^{212}Po) α, γ (36 % to ^{208}Tl)	1 hr
^{212}Po	A	0.299 μsec
^{208}Tl	β, γ	3.1 min
^{208}Pb	------------Stable------------	

Table E-4. Properties of Thorium (Bolz 1973)

Property or Characteristic	Value/Example
Composition	Natural thorium is assumed to be all ^{232}Th. However, other isotopes do exist because of the natural decay series
Atomic weight (A)	232.0381
Atomic number (Z)	90
Physical Appearance	When pure, thorium is a silvery-white metal, which is air-stable and retains its luster for several months. Thorium slowly tarnishes becoming gray and finally black when it oxidizes in air.
Physical Properties	When pure, it is soft, very ductile, and can be cold-rolled, swaged and drawn. Powdered thorium metal is pyrophoric and should be carefully handled. Thorium turnings ignite when heated in air and burn brilliantly with a white light. Thorium can be slowly attacked by water and dissolve. With the exception of hydrochloric acid, thorium does not dissolve readily in most common acids. Melting point = 1750 °C Boiling point = 4790 °C
Isotopes	^{227}Th (($T_{1/2}$=18.7 d), ^{228}Th ($T_{1/2}$=1.9 y), ^{229}Th ($T_{1/2}$=7340 y), ^{230}Th ($T_{1/2}$=7.7E4 y), ^{231}Th ($T_{1/2}$=1.1 d), ^{232}Th ($T_{1/2}$=1.4E10 y), and ^{234}Th ($T_{1/2}$=24.1 d).

The principal use of thorium has been in the preparation of the Welsbach lantern mantle, which is used for portable gas lights. Thorium is used to coat tungsten wire in electronic equipment because of its high electron emission. Its oxide is also used to control the grain size of tungsten in electric lamps. Another application of thorium is in high-temperature laboratory crucibles. Thorium oxide can also be used as a catalyst in the conversion of ammonia to nitric acid, in petroleum cracking and in producing sulfuric acid (Kathren 1984).

E-4. Radon

We get about three quarters of our radiation dose from radon inhalation (National Research Council 1990). Radon is a colorless, tasteless, and odorless gas. Radon usually moves from the ground up and migrates into homes and other buildings through cracks and other holes in their foundations. Buildings trap radon inside, where it accumulates and may become a health hazard without proper ventilation.

Radon (^{222}Rn, $T_{1/2}$= 3.8 days), is a daughter product of radium (^{226}Ra), which in turn is derived from the longer-lived antecedent ^{238}U. Most of the actual dose would come from the decay products of radon, sometimes called radon daughters or radon progeny. Table E-5 includes a list of the radon progeny, its type of radiation and half-life. These radon progeny are usually attached to particles, not gases, and can be deposited in the lungs. There, they have some chance of decaying before the body can get rid of them, resulting in a radioactive dose.

Table E-5. Radon and its Progeny (Johnson 2012)

Nuclide	Radiation	Half-life
^{222}Rn	α, γ	3.8 d
^{218}Po	α, β, γ	3.1 min
^{214}Pb	β, γ	26.8 min
^{214}Bi	α, β, γ	19.9 min
^{214}Po	α, γ	0.164 milliseconds
^{210}Pb	α, β, γ	22.3 y
^{210}Bi	α, β	5.01 d

Nuclide	Radiation	Half-life
^{210}Po	α, γ	138 d
^{206}Pb	------------Stable------------	

Dose calculations depend on the airborne radiation levels and concentration of radon and its progeny and on the modeling assumptions. Widely varying radon levels exist in different regions and are related to geological circumstances.

Radon measurement techniques can be classified in three categories: grab sampling, continuous active sampling, and integrative sampling. Grab sampling provides instantaneous measures of radon or radon progeny in air and it is commonly used in industrial monitoring. Continuous active sampling involves multiple measurements at closely spaced time intervals over a long period. These are costly and only recommended when other measures indicate a problem and the source of radon entry needs to be pinpointed precisely. Integrative sampling devices are passive, and collect data on radon levels over a fixed period of time (NCRP 1988).

E-5. Radiation from the Ground and Outer Space

We receive about 8% of our exposure to natural radiation from other radioactive elements in the earth's crust, such as thorium and potassium (National Research Council 1990). Radiation levels from these sources vary in different areas of the Earth. Another 8% of our radiation exposure comes from outer space. Our exposure to cosmic radiation depends primarily on the altitude; a thicker atmosphere can filter out more cosmic radiation than a thinner atmosphere (EPA 1993).

E-6. Radionuclides in the Human Body

Humans are made up of chemicals, some of which contain radionuclides ingested daily with food and water. Table E-6 includes some of the ICRP 30 estimates of the concentrations of radionuclides based on a 70 kg reference adult (ICRP 1979).

Table E-6. Natural Radioactivity found in the Human Body (ICRP 1979)

Nuclide	Amount in body	Activity of nuclide	Daily intake of nuclide
Uranium	100 µg	30 pCi (1.1 Bq)	1.9 µg
Thorium	30 µg	3 pCi (0.11 Bq)	3 µg
Potassium-40	17 mg	120 nCi (4.4 kBq)	0.39 mg
Radium	31 pg	30 pCi (1.1 Bq)	2.3 pg
Carbon-14	195 µg	0.9 mCi (33 MBq)	1.8 µg
Tritium	0.06 pg	0.6 nCi (23 Bq)	0.003 pg
Polonium	0.2 pg	1 nCi (37 Bq)	~0.6 µg

E-7. Natural Radioactivity found in Building Materials

Radioactivity is also found in building materials. Depending on the composition, the level of radiation may be higher or lower than the background radiation reading. Granite and concrete have a higher concentration of naturally occurring radioactive material and can cause background readings to be higher than nearby open-air readings.

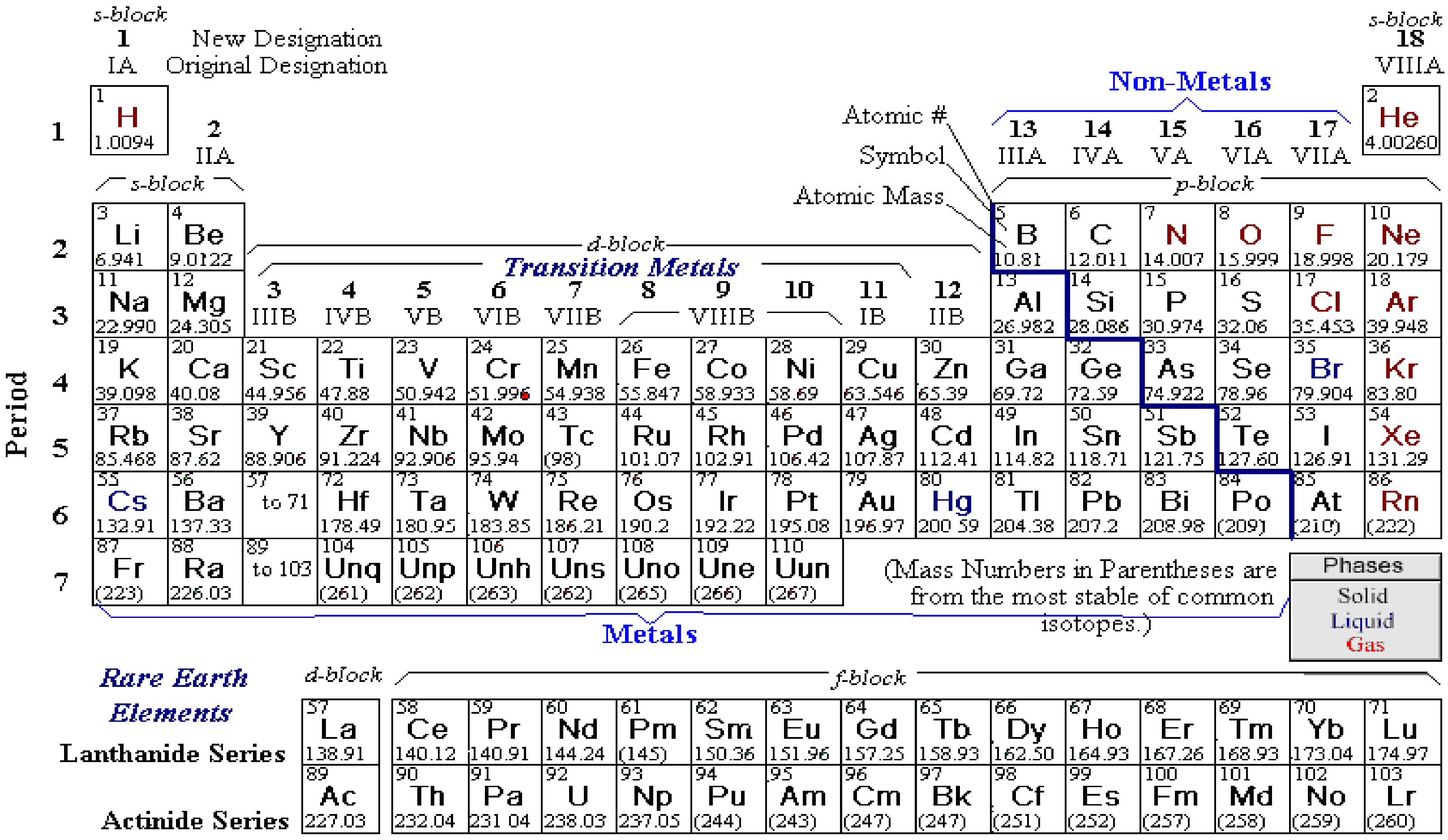
APPENDIX F. IDENTIFICATION OF NUCLIDES AND THEIR SYMBOLS

The following tables identify the elements cited in this TG and their symbols. Table F-1 includes the name of the elements and their corresponding symbols and Figure F-1 is the periodic table of elements.

Table F-1. List of Elements with their Symbol and Atomic Number

Symbol	Element	Atomic Number	Symbol	Element	Atomic Number
Ac	Actinium	89	Md	Mendelevium	101
Al	Aluminum	13	Hg	Mercury	80
Am	Americium	95	Mo	Molybdenum	42
Sb	Antimony	51	Ns	Neilsborium	107
Ar	Argon	18	Nd	Neodymium	60
As	Arsenic	33	Ne	Neon	10
At	Astatine	85	Np	Neptunium	93
Ba	Barium	56	Ni	Nickel	28
Bk	Berkelium	97	Nb	Niobium	41
Be	Beryllium	4	N	Nitrogen	7
Bi	Bismuth	83	No	Nobelium	102
B	Boron	5	Os	Osmian	76
Br	Bromine	35	O	Oxygen	8
Cd	Cadmium	48	Pd	Palladium	46
Ca	Calcium	20	P	Phosphorus	15
Cf	Californium	98	Pt	Platinum	78
C	Carbon	6	Pu	Plutonium	94
Ce	Cerium	58	Po	Polonium	84
Cs	Cesium	55	K	Potassium	19
Cl	Chlorine	24	Pr	Praseodymium	59
Cr	Chromium	17	Pm	Promethium	61
Co	Cobalt	27	Pa	Protactinium	91
Cu	Copper	29	Ra	Radium	88
Cm	Curium	96	Rn	Radon	86
Dy	Dysprosium	66	Re	Rhenium	75
Es	Einsteinium	99	Rh	Rhodium	45
Er	Erbium	68	Rb	Rubidium	37
Eu	Europium	63	Ru	Ruthenium	44
Fm	Fermium	100	Rf	Rutherfordium	104
F	Flourine	9	Sm	Samarium	62
Fr	Francium	87	Sc	Scandium	21
Gd	Gadolinium	64	Sg	Seaborgium	106
Ga	Gallium	31	Se	Selenium	34
Ge	Germanium	32	Si	Silicon	14
Au	Gold	79	Ag	Silver	47
Hf	Hafnium	72	Na	Sodium	11
Ha	Hahnium	105	Sr	Strontium	38
Hs	Hassium	108	S	Sulfur	16
Hi	Helium	2	Ta	Tantalum	73
Ho	Holmium	67	Tc	Technetium	43
H	Hydrogen	1	Te	Tellurium	52
In	Indium	49	Tb	Terbium	65
I	Iodine	53	Tl	Thallium	81
Ir	Iridium	77	Th	Thorium	90

Symbol	Element	Atomic Number	Symbol	Element	Atomic Number
Fe	Iron	26	Tm	Thulium	69
Kr	Krypton	36	Sn	Tin	50
La	Lanthanum	57	Ti	Titanium	22
Lr	Lawrencium	103	W	Tungsten	74
Pb	Lead	82	U	Uranium	92
Li	Lithium	3	V	Vanadium	23
Lu	Lutetium	71	Xi	Xenon	54
Mg	Magnesium	12	Yb	Ytterbium	70
Mn	Manganese	25	Yb	Yttrium	39
Mt	Meitnerium	109	Zn	Zinc	30
			Zr	Zirconium	40



(Mass Numbers in Parentheses are from the most stable of common isotopes.)

Period	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIIIB	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 H 1.0094																	2 He 4.00260
2	3 Li 6.941	4 Be 9.0122											5 B 10.81	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.179
3	11 Na 22.990	12 Mg 24.305											13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.06	17 Cl 35.453	18 Ar 39.948
4	19 K 39.098	20 Ca 40.08	21 Sc 44.956	22 Ti 47.88	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.847	27 Co 58.933	28 Ni 58.69	29 Cu 63.546	30 Zn 65.39	31 Ga 69.72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.80
5	37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.75	52 Te 127.60	53 I 126.91	54 Xe 131.29
6	55 Cs 132.91	56 Ba 137.33	57 to 71	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.21	76 Os 190.2	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200 59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra 226.03	89 to 103	104 Unq (261)	105 Unp (262)	106 Unh (263)	107 Uns (262)	108 Uno (265)	109 Une (266)	110 Uun (267)								

Lanthanide Series	57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
Actinide Series	89 Ac 227.03	90 Th 232.04	91 Pa 231 04	92 U 238.03	93 Np 237.05	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (260)

Figure F-1. The Periodic Table of Elements

GLOSSARY

ALI
Annual Limit on Intake

APHC
U.S. Army Public Health Center

BWR
Boiling Water Reactor

CAM
Chemical Agent Monitor

CBRN
Chemical, Biological, Radiological, and Nuclear

CFR
Code of Federal Regulations

DA
Department of the Army

DARA
Department of the Army Radiation Authorization

DOD
Department of Defense

DOE
Department of Energy

DOT
Department of Transportation

DTPA
Diethylenetriaminopentaacetate

DU
Depleted Uranium

EPA
Environmental Protection Agency

HEPA
High-Efficiency Particulate Air

HLW
High-Level Wastes

IAEA
International Atomic Energy Agency

ICAM
Improved Chemical Agent Monitor

ICRP
International Commission on Radiological Protection

JP
Joint Publication

LAW
Light Anti-tank Weapon

LWR
Light Water Reactor

MEDCOM
U.S. Army Medical Command

MOX
Mixed Oxide

MRS
Muzzle Reference Sensor

mrem/hr
millirem per hour

NCRP
National Council of Radiation Protection and Measurements

NRC
U.S. Nuclear Regulatory Commission

NSN
National Stock Number

ORNL
Oak Ridge National Laboratory

PET
Positron Emission Tomography

PWR
Pressurized Water Reactor

RADIAC
Radioactivity, Detection, Indication and Computation

RCS
Reactor Coolant System

SF
Spontaneous Fission

SPECT
Single Photon Emission Computed Tomography

TACOM
Tank-Automotive and Armaments Command

TB
Technical Bulletin

TG
Technical Guide

TM
Technical Manual

UNSCEAR
United Nations Scientific Committee on the Effects of Atomic Radiation