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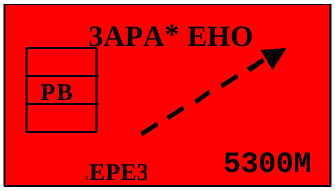
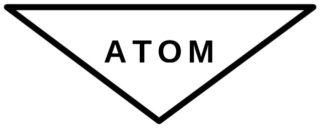
U. S. Army Center for Health Promotion and Preventive Medicine

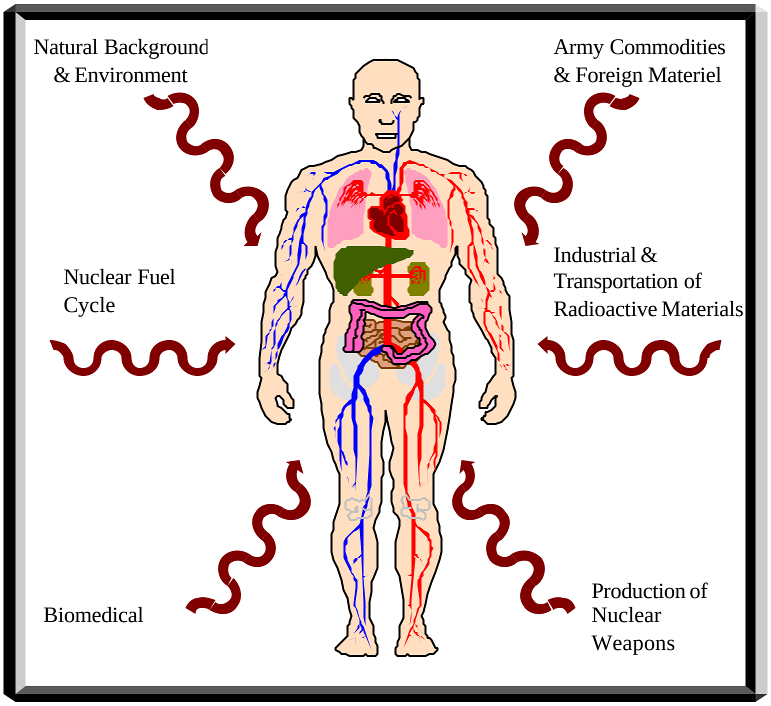
Radiological Sources of Potential Exposure and/or Contamination

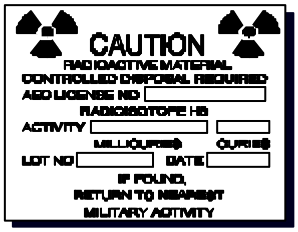
TG-238

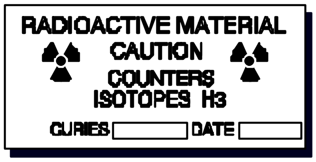
June-1999

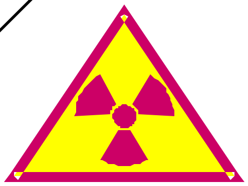


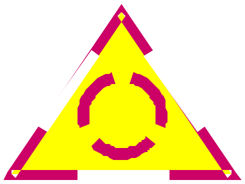


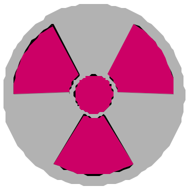


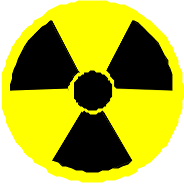


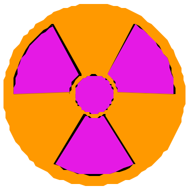












U.S. Army Center for Health Promotion and Preventive Medicine

10 December, 1999

ACKNOWLEDGEMENT

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This Technical Guide was funded by The Office of The Surgeon General.
This research was supported in part by an appointment to the Research Participation Program at the USACHPPM, administered by the Oak Ridge Institute for Science and Education (through an interagency agreement between the U.S. Department of Energy and USACHPPM), and by the Henry M. Jackson Foundation for the Advancement of Military Medicine.

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I. Executive Summary

Technical Guide 238 summarizes sources of potential radiological exposures or contamination to military personnel from both civilian and military origin. Although, there is emphasis on sources that deployed soldiers may encounter, this guide is general enough to be used in non-deployment situations. Scenarios describing exposures to radiation or radioactive materials are presented. Some of these scenarios are illustrative and can aid in identifying and evaluating potential exposures.

Chapter one is a brief overview of the technical guide. Chapters Two through Seven summarize sources of radiation exposures and contamination found in nature, the nuclear fuel cycle, the medical field, in army commodities and foreign materials, the industry, the transportation of radioactive materials, and the production of nuclear weapons.

The appendices contain precautions for reducing or avoiding radiation exposure and contamination and supplemental material that describes nuclear power reactors around the world, radioactive waste, accelerators and generators. A brief description of accidental radiation exposures and radiological accidents and their consequences are also part of the appendices.

The purpose of this guide is to familiarize personnel with potential sources of radiological exposures that may be encountered during combat or peacetime operations. It is not the intent of the guide to frighten 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. It cannot be emphasized enough that in order to estimate the hazard presented by radiological exposure or contamination, one must be aware of the surroundings.

This document has identified many sources of potential radiation exposure and contamination that may be linked to a specific mission, task, or project. Table 1 summarizes the most probable radionuclides found in the identified sources and their corresponding recommended precautions. A more detailed list can be found at the beginning of each chapter as a summary of those sources that are included in that particular chapter.

Table 1. Most important identified radioactive sources in TG-238

Radionuclide[1]	Radiation[2]	Half-life[3]	Precaution level[4] (see Table 2)	Reference Chapter
DU(Depleted Uranium)	α; γ	6.5E15 y	I-U	Ch. 5
^{3}H	β^{-}	12.3 y	E-T	Ch. 2, 3, 5, 6, 7
^{14}C	β^{-}	5730y	E-I	Ch. 2, 5, 6
^{32}P	β^{-}	14.3 d	E-I	Ch. 2, 4,
^{60}Co	β^{-}; γ	5.258y	X-E-I	Ch. 3, 4, 5, 6
^{63}Ni	β^{-}	92 y	E-I	Ch. 5
^{90}Sr	β^{-} , γ (^{90}Y radiation)	28 y	X-E-I	Ch. 3, 4, 5
^{99m}Tc	γ	6.0 hr	X	Ch. 4
^{131}I	β^{-}; γ	8.065d	X-E-I	Ch. 3, 4, 5
^{137}Cs	β^{-}, γ	30 y	X-E-I	Ch. 3, 4, 5, 6, 7
^{147}Pm	β^{-} (^{147}Sm radiation)	2.62y	E-I	Ch. 5, 6
^{204}Tl	β^{-}; γ (^{204}Pb radiation)	3.81y	X-E-I	Ch. 5
^{226}Ra	α; γ	1602 y	X-I	Ch. 2, 3, 4, 5,
^{232}Th	α; (Ra L x-rays)	1.4E10 y	X-I	Ch. 2, 5, 7
^{235}U	α; γ	7.1E8	X-I-U	Ch. 2, 3, 5, 6, 7
^{238}U	α; (Th L x-rays)	4.5E9 y	X-I-U	Ch. 2, 3, 5, 6, 7
^{239}Pu	α; β^{-}; γ	2.4E4 y	X-E-I	Ch. 3, 5, 6, 7
^{241}Am	α; γ	458 y	X-E-I	Ch. 5, 6, 7

1. Radionuclide refers to radioactive isotopes (radioisotopes). These are unstable isotopes that undergo spontaneous transformation, emitting radiation (approximately 2500 natural and artificial radionuclides have been identified). The number in front is the mass number that identifies the specific isotope and it is followed by the symbol of the element (list found in Appendix J).
2. This refers to emitting ionizing radiation, such as alpha particles ("), beta particles ($), gamma rays ((), x-rays, neutrons, high-speed electrons, high-speed protons, and other particles capable of producing ions.
3. The half-life is the time in which half the atoms of a particular radioactive substance disintegrate to another particular form.
4. Precaution levels designed to follow general radiation protection guidelines and protect against exposure or contamination. These levels are X, E, I, T, and U and correspond to precautions with external exposures, external contaminants, internal contaminants, tritium and uranium contamination, respectively.

Precaution levels are defined in Appendix A to facilitate immediate and appropriate responses to identified radiological sources. The defined levels encompass radiological protection principles applicable to specific types of radiation sources. The precautions were developed by evaluating the different types of radionuclides and grouping them by their potential to act as external radiation sources or possible sources of external and/or internal contamination. Specific attention was given to tritium (^3H) and depleted uranium (DU) because of their important role in Army commodities and as sources found in the given scenarios. Table 2 shows the precaution levels addressed in this technical guide. Precautions E and I listed in sections A.2 and A.3 may be common to identified sources that are both an external and internal contamination threats.

Table 2. Guidance for recommended precaution levels

Precaution level	Definition (Appendix A)
X	Potential external exposure. Apply precautions in section A.1.
E	Potential external contamination. Apply precautions in section A.2.
I	Potential internal contamination. Apply precautions delineated in section A.3.
T	Potential tritium exposure. Apply precautions in section A.4.
U	Potential DU exposure. Apply precautions in section A.5.

The following sections are the summaries of the technical chapters and are included to provide the user with a quick reference on the identified potential sources of exposure and/or contamination. Tables from these sections are duplicated at the end of each chapter.

I.1. Summary of Natural Radiation Sources Identified in Chapter 2

The following table includes the most important radionuclides that are found in natural sources of radiation. Since they form part of our natural environment, they may be unavoidable and precautions may not apply. Therefore, only principles of radiation protections included in Appendix A would apply in the event that large concentrations are naturally found in the environment[1].

Table 3. Summary of natural radiation sources

Nuclide	Radiation	Longest Half-life	Precaution Level
^{3}H	$	12.3 y	n/a
^{7}Be	γ	55 d	n/a
^{14}C	$	5730 y	n/a
^{40}K	$, γ	1E9 y	n/a
^{87}Rb	$	1E10 y	n/a
^{232}Th and its daughters (^{228}Ra, ^{228}Ac, ^{228}Th, ^{224}Ra, ^{220}Rn and its daughters)	", $, γ	1E10 y	n/a
^{220}Rn and its daughters (^{216}Po, ^{212}Pb, ^{212}Bi, ^{212}Po, ^{208}Tl)	", $, γ	10.6 hr	n/a
^{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)	", $, γ	1E8 y	n/a
^{238}U and its daughters (^{234}Th, ^{234}Pa, ^{234}U, ^{230}Th, ^{226}Ra, ^{222}Rn and its daughters)	", $, γ	1E9 y	n/a
^{222}Rn and its daughters (^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po, ^{210}Pb, ^{210}Bi, ^{210}Po)	", $, γ	21 y	n/a
^{241}Pu and its daughters (^{241}Am, ^{237}Np, ^{233}Pa, ^{233}U, ^{229}Th, ^{225}Ra, ^{225}Ac, ^{221}Fr, ^{217}At, ^{213}Bi, ^{213}Po, ^{209}Tl, ^{209}Pb)	", $, γ	1E6 y	n/a
Other primordial radionuclides (^{40}K, ^{50}V, ^{87}Rb, ^{113}Cd, ^{115}In, ^{123}Te, ^{138}La, ^{142}Ce, ^{144}Nd, ^{147}Sm, ^{152}Gd, ^{174}Hf, ^{176}Lu, ^{187}Re, ^{190}Pt, ^{192}Pt, and ^{209}Bi)	", $, γ	1E18 y	n/a
Other nuclides found in the Earth's crust (^{115}In, ^{138}La, ^{142}Ce, ^{144}Nd, ^{147}Sm, ^{148}Sm, ^{149}Sm, ^{152}Gd, ^{174}Hf, ^{176}Lu, ^{204}Pb)	", $, γ	1E17 y	n/a
Other cosmogenic radionuclides (^{10}Be, ^{18}F, ^{22}Na, ^{24}Na, ^{26}Al, ^{31}Si, ^{32}Si, ^{32}P, ^{33}P, ^{37}Ar, ^{39}Ar, ^{34m}Cl, ^{36}Cl, ^{38}Cl, ^{39}Cl, ^{35}S, ^{38}S, ^{80}Kr)	", $, γ	1E6 y	n/a

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[1] Some of these radionuclides may have been concentrated or used by man and appropriate precautions would then apply. Other chapters cover these radionuclides.

I.2. Summary of Radiation Sources Identified in Chapter 3

The following table summarizes the sources addressed in Chapter 3 throughout the entire fuel cycle. The values for maximum half–life and radioactivity levels are approximated to the nearest power of ten. The precaution column should be used with discretion, as the precautions will depend on the present activity of the radionuclide. In the mining and milling process, precautions are necessary to prevent tailing from contaminating ground water or getting into the air as dust. The radioactivity from the tailings does not pose any more hazard than that of the ore which was removed from the Earth. However, the concentration of the material (radionuclides) and conversion into a new form can pose a hazard, unless layers of dirt or other material are applied to prevent erosion and dispersal.

Table 4. 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]	Precaution Level (Appendix A)
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)	", $, γ	~1 E8 y	Gases ~1E7 [1E-3]	E-I
	^{238}U and its daughters (^{234}Th, ^{234}Pa, ^{234}U, ^{230}Th, ^{226}Ra, ^{222}Rn and its daughters)	", $, γ	~1E9 y	Liquids/solids ~1E10 [1]	E-I
	^{222}Rn and its daughters (^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po, ^{210}Pb, ^{210}Bi, ^{210}Po)	", $, γ	21 y		E-I
Conversion	Same radionuclides as above. Radioisotopes are found in the conversion process and in the low-level waste.	", $, γ	1E9 y	Gases ~1E7 [1E-3] Liquids/solids ~1E7 [1E-3]	E-I-U
Enrichment	Same radionuclides as above. Two main concerns are the enriched product containing ^{235}U and the depleted uranium (mostly ^{238}U) waste.	", $, γ	1E9 y	Gases ~1E7 [1E-3] Liquids/solids ~1E7 [1E-3]	E-I-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]	E-I
	Pu isotopes from the MOX fuel fabrication process, liquid waste and gases.	α, β, γ, n	1E9 y	Liquids/solids ~1E7 [1E-3]	E-I-U

Process	Radionuclides	Radiation	Longest half-life	Approximate radioactivity level in Bq/ton U [Ci/ton U]	Precaution Level (Appendix A)
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, n	1E9 y	Gases ~1E12 [100] Liquids/solids ~1E12 [100]	X-E-I-U
	Fuel (core and spent fuel pool)				
	Same as above and mainly U and Pu isotopes, plus fission products and activation products	α, β, γ, n	1E9 y		X-E-I-U
	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		X-E-I-T
	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		X-E-I-T
	Neutron activation products (in systems, core components, reactor coolant system)				X-E-I
	Gases: ^{13}N, ^{16}N, ^{41}Ar	β, γ	2 hr		X-E-I
	Solids: ^{51}Cr, ^{54}Mg, ^{56}Mg, ^{58}Co, ^{60}Co, ^{59}Fe	β, γ	5.3 y		X-E-I
Waste / Reprocessing	Most of radionuclides with longer half-lives	α, β, γ, n	1E9 y	Gases ~1E14 [1E3] Liquids/solids ~1E17 [1E6]	X-E-I-T

I.3. Summary of Radiation Sources Identified in Chapter 4

Radiation sources used in the medical profession and that may be encountered by deployed soldiers are identified in this chapter. Radiation producing equipment (x-ray, computed tomography (CT), fluoroscopy machines, and linear accelerators) is identified as a potential source if it is in the operation mode (switch is on). Therefore, this type of equipment is included in this section. Nuclear medicine imaging apparatus is not a source of radiation itself, unless it is contaminated with a radioisotope or radiopharmaceutical. Since this is a possible source of contamination and because the presence of this type of equipment is indicative of the proximity to radiopharmaceuticals, it has also been included in this section. Some radiation sources of most importance that are used in nuclear medicine, radiation therapy, and biomedical research are also illustrated in Table 5. A more extensive table, which includes most radionuclides used in the biomedical arena, is Table 4.2.

Table 5. Summary of biomedical radiation sources and most commonly used radionuclides in nuclear medicine, radiation therapy and biomedical research

Source	Radiations	Half-life	Application	Precaution level
X-rays	(	n/a	X-ray equipment, CT, fluoroscopy, linear accelerator (Not a hazard, unless functional)	X
Nuclear Medicine equipment	All	n/a	Nuclear medicine diagnostic equipment, such as Gamma Cameras	X-E-I
Isotopic generators	All	n/a	Generators of radioisotopes to be used in nuclear medicine as radiopharmaceuticals; for example, the ^{99}Mo-^{99m}Tc generator	X-E-I
Therapy Units	(	n/a	Radiation therapy units, such as ^{60}Co or ^{137}Cs therapy units.	X
Equipment used in brachytherapy	All	n/a	Equipment used in the application of brachytherapy	X-E-I
^{198}Au	$-, (	2.7 d	Brachytherapy	X-E-I
^{18}F	$+, (	1.83 hr	PET studies for brain physiology and pathology, for localizing epileptic focus, psychiatry and neuropharmacology studies	X-I
^{67}Ga	(	79.2 h	Tumor imaging and localization of inflammatory lesions (infections)	X-I
^{123}I	$+, (	13.3 h	Diagnosis of thyroid function, brain, kidney and myocardial imaging	X-I
^{125}I	(	60 d	Glomerular filtration rate of kidneys, deep vain thrombosis in the leg, radioimmunoassays, as an x-ray source for bone density measurements, brachytherapy and biomedical research	X-I

Source	Radiations	Half-life	Application	Precaution level
^{131}I	$-, (	8.05 d	Thyroid functional imaging, thyroid therapy, liver function, renal (kidney) blood flow and urinary tract obstruction studies, biomedical research	X-E-I
^{111}In	(	2.83 d	Brain studies, infection and colon transit studies	X-I
^{99}Mo	$-, (	67 hr	Generation of technetium 99m	X-E-I
^{32}P	$-	14.3 d	Treatment of polycythemia rubra vera (excess red blood cells)	E-I
^{226}Ra	", (Rn x-rays)	1602 E	Brachytherapy, target isotope to make ^{227}Ac, ^{228}Th, ^{229}Th	X-I
^{99m}Tc	(	6.02 h	Most commonly used radionuclide in nuclear medicine, use 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.	X
^{201}Tl	(	74 h	Myocardial perfusion imaging, for diagnosis and location of myocardial infarction (heart muscle death)	X-I
^{192}Ir	$-, (	74.2 d	PET studies	X-I
^{127}Xe	(	36.4 d	Pulmonary ventilation studies	X-I
^{133}Xe	$-, (	5.3 d	Pulmonary ventilation studies, SPECT imaging of brain	X-E-I

I.4. Summary of Sources Identified in Chapter 5

The following table summarizes the radiation sources from Army commodities and from foreign materiel that are identified in Chapter 5. Identified nuclides may be common to both Army commodities and foreign materiel but may differ in activity and/or form.

Table 6. Summary of radiation sources in Army commodities and foreign materiel

Isotope	Radiations	Half-life	Precaution level(s)
^{3}H	β^-	12.33 y	E-T
^{14}C	β^-	5730 y	E-I
^{60}Co	β^-; γ	5.258 y	X
^{63}Ni	β^-	92 y	E-I
^{85}Kr	β^-; γ	10.76 y	X-E-I
^{90}Sr	β^- (^{90}Y radiation)	28 y	X-E-I
^{90}Y	β^-; γ	64.0 h	X-E-I
^{131}I	β^-; γ	8.065 d	X-E-I
^{137}Cs	β^-; γ	30.2 y	X
^{133}Ba	γ	10.7 y	X
^{147}Pm	β^- (^{147}Sm radiation)	2.62 y	E-I
^{204}Tl	β^-; γ (^{204}Pb radiation)	3.81 y	X-E-I
^{210}Pb	α; β^-; γ	22 y	X-E-I
^{210}Bi	α; β^-; γ	5.01 d	X-E-I
^{226}Ra	α; γ	1602 y	X-I
^{232}Th	α; (Ra L x-rays)	1.4E10 y	X-I
^{234}Pa	β^-; γ (^{234}U radiation)	6.75 h	X-E
^{235}U	α; γ	7.1E8 y	X-I-U
^{238}U	α; (Th L x-rays)	4.5E9 y	X-I-U
DU	α; γ	6.5E15 y	I-U
^{239}Pu	α; β; γ	2.4E4 y	X-E-I
^{241}Am	α; γ	458 y	X-E-I

I.5. Summary of Radiation Sources Identified in Chapter 6

Chapter 6 identifies radiation sources of possible exposure and/or contamination that can be found in industrial practices and the transportation of radioactive materials. 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 nuclear fuel and other radioactive material. The following table summarizes these sources.

Table 7. Summary of radiation sources from industry and transportation of radioactive materials

Identified source	Radiations	Longest Half-life	Examples	Precaution level(s)
X-ray machines	γ and X-rays	n/a	Electron microscopes Spectroscopy equipment Diffractometer equipment	X
Industrial accelerators	γ, x-rays, and neutrons (n)	n/a	See Appendix E for examples	X
Radioactive waste	α, β, γ, and n	n/a	See Appendix C and waste from industrial and biomedical practices	X-E-I
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 as those identified in Appendix B	X-E-I-U
Naturally occurring radioisotopes				
^{3}H	$\$^-$	12.3 y	Age water measurements	E-T
^{14}C	$\$^-$	5730 y	Carbon dating	E-I
^{36}Cl	$\$^-$, (	3.1 E5 y	Age water measurements	X-E-I
^{210}Pb	", $\$^-$, (	22.3 y	Sand and soil dating	X-E-I
Artificially produced radioisotopes				
^{46}Sc, ^{60}Co, ^{82}Br, ^{85}Kr, ^{90}Sr, ^{110m}Ag, ^{137}Cs, ^{140}La, ^{144}Ce, ^{147}Pm	$\$^-$, (	30 y	Resident time determination, gamma sterilization, industrial radiography, hydrological tracing, gauges, food irradiators.	X-E-I
^{51}Cr, ^{54}Mn, ^{57}Co, ^{65}Zn, ^{99m}Tc, ^{169}Yb	(	312.5 d	Labeling, spectrometry, industrial radiography	X
^{170}Tm, ^{192}Ir, ^{198}Au	$\$^-$, (	5.3 y	Industrial radiography, labeling.	X-I
^{239}Pu, ^{241}Am	α, \$, (, n	2.4E4 y	Borehold logging, smoke detectors	X-E-I
^{252}Cf	α, (, n	2.65 y	Borehold logging	X-E-I

I.6. Summary of Sources Identified in Chapter 7

Chapter 7 identifies possible sources of radiation exposure and contamination in the production and use of nuclear weapons. The following is a list of the countries that have nuclear weapons or the technical ability to produce them.

1. Argentina
2. Australia
3. Belarus
4. Brazil
5. Britain
6. Canada
7. China
8. France
9. Germany
10. India
11. Iran
12. Iraq
13. Israel
14. Japan
15. Kazakhstan
16. Libya
17. North Korea
18. Pakistan
19. Russia
20. South Africa
21. Sweden
22. Switzerland
23. Taiwan
24. Ukraine
25. United States

Table 8 includes the identified types of nuclear weapons, namely fission-only and fission-fusion weapons. The simplest nuclear weapon design is a fission-only weapon. To achieve higher yields, combined fission-fusion weapons can be assembled in stages.

Table 8. Identified types of nuclear weapons

Type of weapon	fission only weapons	fission-fusion weapons
Description	These weapons use only the energy released by fissionable elements. The main radionuclides used are highly enriched uranium (HEU) and ^{239}Pu. Enriched uranium is uranium whose ^{235}U content is greatly increased over natural uranium. The largest yield fission weapon tested may have been 500 kt	Any of the weapon types can be salted with elements to enhance residual radiation through contamination. Fusion weapons can be made in stages to achieve very high yields (tens of megatons), designed to enhance neutron output to make neutron bombs
Example	Fissile HEU can be up to 93.5% ^{235}U or plutonium mix, wrapped by a layer of ^{238}U. The weapon can take advantage of the high-energy neutrons produced by the fission reactions in the fissile center. In effect, neutrons escaping from the first fission explosion induce additional fissions in the outer shell causing a second explosion.	Combined fission-fusion weapon with an outer jacket of ^{59}Co to enhance the production of radioactive ^{60}Co.

The enormous destructive power of nuclear weapons and the long-term contamination that follows detonation places them among the most dangerous possible sources of radiation exposure and/or contamination. However, radiation dispersal weapons are also dangerous. These weapons have been identified in this chapter as simply conventional weapons used to disperse radioactive material into the environment. Radiological consequences from the explosion of this type of weapon are similar to those of conventional contamination accidents.

Table 9 includes identified nuclides in the production of nuclear weapons. However, in the event of a nuclear detonation, many other radionuclides will result from activation. This chapter has further identified prompt neutrons, prompt gamma rays, fission fragments, and fission products as radiation sources.

Table 9. Summary of radiation sources from the production of nuclear weapons

Isotope	Radiation	Half life	Precaution level (s)
^{3}H	$	12.33 y	E-T
^{137}Cs	β, γ	30.2 y	X-E-I
^{210}Po	", γ	138.4 d	X-I
^{234m}Pa	β, γ	1.18 m	X-I
^{231}Th	β, γ	25.5 h	X-I
^{232}Th	", γ	1.4E10 y	X-I
^{234}Th	β, γ	24.1 d	X-I
^{234}U	α, γ, n	2.44E5 y	X-I-U
^{235}U	α, β, γ, n	7.04E8 y	X-I-U
^{238}U	α, γ, n	4.5E9 y	X-I-U
^{234m}Pa	β, γ	1.17 m	X-E
^{239}Pu	α, β, γ, n	2.4E4 y	X-E-I
^{240}Pu	α, β, γ, n	6.6E3 y	X-E-I
^{241}Pu	α, β, γ, n	14.4 y	X-E-I
^{241}Am	α, β, γ, n	458 y	X-E-I

Chapter 1. Introduction

Commanders need to be aware of the risks their soldiers may encounter around radioactive sources. This technical guide is intended to familiarize personnel with sources of radiation exposure and/or contamination. Understanding the risks requires knowledge of possible sources of exposure and scenarios in which soldiers might be exposed.

1.1. Purpose

In combat, commanders and troops are concerned with immediate survival, and in preserving their combat power (i.e., not doing anything that will contribute to a performance decrement amongst the soldiers in the command). In the deployment environment where the possibility of actual combat is remote (support and stability operations), commanders and soldiers are more concerned with hazards that may not cause immediate performance decrement, or lead to the loss of life or limb. One of the hazards that exist in modern societies is radiation and radioactive materials. This document does not intend to imply that loss of life and limb cannot occur with exposure to sufficiently high levels of radiation, because it certainly can and soldiers should be aware of this possibility. However, armed with knowledge, soldiers can identify and take measures to prevent or reduce risk from this type of hazard.

This manual has been prepared to foster awareness of radiological hazards and provide you, the soldier, with the knowledge necessary to take the first step in risk reduction: recognition of the hazard. This guide is also intended to give you general initial guidance (precaution levels) of what you can do in order to reduce or eliminate the hazard.

1.2. Background

The nature of recent deployments, and concern for exposure of troops to environmental contamination of a radiological, chemical, or biological nature, has driven research and development in an effort to identify and quantify these hazards in a tactical environment. The traditional perception of a military hazard is that which will cause tactical or operational level performance decrement (reduced capacity to perform a given mission). Environmental radiological problems have not been considered in this light, because at very low levels of radiation, there will not be any immediate outward sign of exposure.

The soldier has been taught to maintain an awareness of his surroundings, and the commanders have been taught risk assessment and management. One would be remiss for not considering the byproducts of a modern industrial society as a risk to be managed with all the others that may be encountered. For example, the liberation of an industrial city, which is serviced by a nearby nuclear power plant and that has hospitals that use radioactive materials, must be planned taking into account potential radiological sources of exposure and/or contamination. The threat of encountering other radiological sources, such as those of industrial origin, or sources that may be used as booby traps to enhance exposure/contamination, or radiological sources that may be dispersed, must also be considered in this example.

Merely recognizing that such hazards exist in an area of operations will allow assessment and planning with the intent of hazard minimization (avoidance, prevention, reduction of effects in the event of exposure, contingency plans for dealing with such hazards). This guide is intended to forewarn soldiers of radiological hazards that may be encountered, and provide them with the knowledge needed to identify such hazards and apply the developed precaution levels.

1.3. Scope

Personnel must be aware of risks that will potentially be faced by the command in the performance of its mission. This is part of the process of risk management as described in FM 100-14, Risk Management, which dictates that the first step in risk management is the identification of the hazard. In order to identify a hazard, one must be aware of its possible existence.

This manual will provide users with an appreciation of the presence of sources of radiation; thereby, increasing awareness of the potential for exposure and/or contamination. This manual will also provide guidance on the explicit identification of many radiological hazards from various diverse sources with the intent of familiarizing users with the potential sources that may be encountered in a deployment situation. Precaution levels are recommended to avoid and/or reduce the external exposure or contamination for all identified sources.

This guide sets the stage for further investigation of identified sources in the form of surveys or sampling of potential radiological sources (see TG 236 Radiological Health Risk Planning and Projection, for information on this subject). Therefore, it can be considered the initial step in the process of risk assessment on any potential radiological source from a specific identified scenario. These scenarios include radiological sources found in nature, sources from the nuclear fuel cycle and the biomedical arena, sources among Army commodities and foreign materiel, sources from industry and the transportation of radioactive material, and sources from the production of nuclear weapons.

Radiation sources can be broadly classified as natural or manmade sources. Natural sources include cosmic radiation and radiation from naturally radioactive elements that are present in the air, ground and water. The nuclear fuel cycle has a subset of radioactive sources; most of them are concentrated natural sources but some manmade sources are also involved in the cycle. Most sources used in medicine are produced in reactors or accelerators, and are therefore considered manmade. These sources are commonly used in diagnostic and therapeutic clinical procedures. Industrial and academic sources can be natural or manmade. Manmade sources, found in the academic arena, are used in course work and research at universities, research institutes, and laboratories. In the industry, sources are used in such areas as radiography, gauging devices, gas chromatography, well logging and smoke detectors. Radiation sources are also found throughout the construction and use of nuclear weapons, the transportation of radioactive material, and in military commodities, such as in the most recent land-mine detectors. Chapters 2 through 7 cover these sources of radiation.

Appendix A includes recommendations for precaution levels that can be used to prevent or reduce the possibility of radiation exposure or contamination. Appendices B and C support

Chapter 3 in the identification of radioactive sources from the nuclear fuel cycle. Appendix D includes a description of accidents that relate to nuclear power plants. Familiarity with possible and past exposure scenarios is useful in understanding potential exposure from similar situations. Appendices E and F identify sources in accelerators and clinical radiation generators and accidents in this type of facilities.

Postings in the NBC environment and specifically in the nuclear arena are indicative of the proximity to a radiation source, as well as other chemical and biological agents. Appendix G includes the most common posting and signals in a nuclear environment that would help caution soldiers of the possible radiation sources or contamination. Appendix H includes example computations of activity, dose and related parameters using the tables from Chapter 7. Appendix I encompasses a case study that illustrates a potential radiation contamination accident and Appendix J includes a list with the name and symbol of all elements and a periodic table.

Chapter 2. Natural Radioactive Sources

Radiation is a natural part of our environment that has always existed on Earth. Natural background radiation comes from the sun (cosmic radiation), radioactive elements in the earth's crust, rocks, air, water, and radioactive materials in plants and in the human body. Background radiation is unavoidable and the amount varies from one location to another. Examples of natural sources of background radiation are included in Table 2.1.

Table 2.1. Examples of background radiation [1]

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

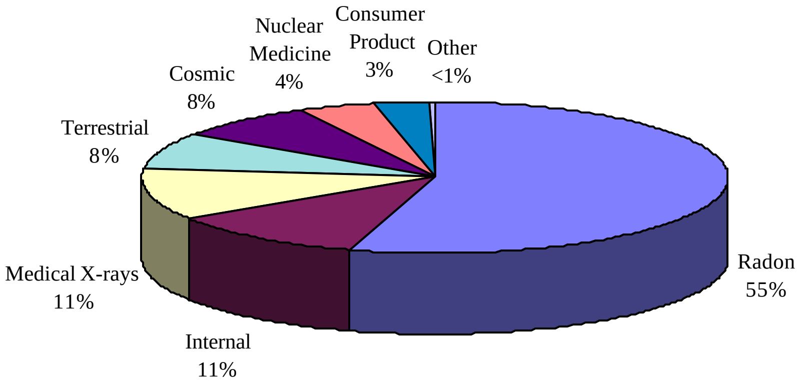
Prior to entering the earth's atmosphere, cosmic rays mainly consist of protons and alpha particles. Upon the interaction of cosmic rays with atoms in the atmosphere, electrons, photons, protons and neutrons are created. Soil contains radioactive materials such as uranium, radium, thorium, potassium 40 and other elements found in the natural radiation decay series (thorium, neptunium, uranium, and actinium series). Some radioactive elements that are found in soil and air decay to become part of these series. For example, radon (^{222}Rn) and thoron (^{220}Rn) are part of the decay process in the uranium and thorium series.

Radon and thoron are radioactive gases that become airborne as they leak out from the earth or building materials. Therefore, the amount of these gases present depends on the amount of radioactive material present in the soil, the porosity of the surface materials, meteorological conditions and ventilation of enclosed areas. 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 would 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. For example, bones contain radioactive radium and can have other bone seeker radioisotopes.

Ninety percent of the tritium from cosmic rays is found in the ocean and other terrestrial waters. The remaining ten percent is found in the stratosphere, where the tritium is actually produced by the cosmic-ray reactions. From the stratosphere, the tritium gradually descends into the lower part of the atmosphere by natural diffusion. It is then brought down as tritiated water by rain or snow to the earth's surface, and accumulates in the hydrosphere (terrestrial waters) [2]. The testing of thermonuclear weapons in the atmosphere brought a considerable increase in the amount of tritium on the earth; however, tritium is fairly uniformly distributed wherever water is present, including plants and animals [3].

The 1990 Biological Effects of Ionizing Radiation Committee (BEIR) report, known as the BEIRV Report: *Health Effects of Exposure to Low Levels of Ionizing Radiation*, includes a visual representation of sources of radiation exposure for an average member of the general public, as shown in Figure 2.1. This figure represents an annual total dose of 360 mrem (3.6 mSv), 82 percent of which is from natural sources and the remaining 18 percent from manmade sources. The 360 mrem total and the component exposure sources are a national average. Even within the continental United States, the total and component proportions vary considerably. For soldiers deployed in an area that is not contaminated, the background exposure levels may be higher or lower. Estimated background radiation levels will vary considerably based on altitude, location, and type of building material [4].

Figure 2.1. Sources of radiation exposure in the US (BEIR V, 1990) [4]



2.1. Primordial Radionuclides

Primordial radionuclides are left over from when the world and the universe were created. They are all long lived, with half-lives often on the order of hundreds of millions of years. The progeny or decay products of the long-lived radionuclides are also present, as their long-lived parents continuously produce them. Among the most commonly known primordial radionuclides are the isotopes of uranium (^{234}U, ^{235}U, and ^{238}U), ^{232}Th, ^{40}K. Some other primordial radionuclides are: ^{50}V, ^{87}Rb, ^{113}Cd, ^{115}In, ^{123}Te, ^{138}La, ^{142}Ce, ^{144}Nd, ^{147}Sm, ^{152}Gd, ^{174}Hf, ^{176}Lu, ^{187}Re, ^{190}Pt, ^{192}Pt, and ^{209}Bi.

The nucleus of unstable atoms is a source of radiation. In order to become more stable, these types of radioactive atoms (also referred to as radionuclides or radioisotopes) eject or emit subatomic particles and may emit high-energy photons (gamma rays) from their nuclei. This process is called radioactive decay. Typically, one unstable nucleus will decay into another unstable nucleus, over and over in a "decay series" until a stable nucleus is reached as the end product. The most important series of natural decay in radiation protection are the thorium, uranium and actinium decay series. Table 2.2 includes the abundance of these series along with some specific decay facts. More detailed information can be found in the literature, such as in the Radiological Health Handbook [5].

Table 2.2. Facts about the natural decay series

Series	Thorium	Neptunium	Uranium	Actinium
Parent isotope	^{232}Th	^{237}Np	^{238}U	^{235}U
Abundance	100%	Series may start from the production of ^{241}Pu (see footnote[2])	99.27%	0.72%
Alphas in series	6	7 – 8	8	7
Betas in series	4	5 – 6	6	4
Stable isotope	^{208}Pb	^{209}Bi	^{206}Pb	^{207}Pb

The following Figures 2.2, 2.3, 2.4 and 2.5 are a representation of the four most common natural decay series. Important members of the thorium series from the standpoint of dose include ^{228}Ra, ^{228}Th, and ^{224}Ra. The neptunium series might have started as an abundant series but the half-lives of its radionuclides are short compared to that of earth. Therefore, in this series ^{241}Pu, which is a manmade radionuclide, is commonly included as an alternate parent nuclide as it is produced in neutron irradiation process of ^{238}U (see Figure 3.23). More information on the neptunium series can be found in International Commission on Radiological Protection, ICRP Report No. 38 [6]. The uranium series includes ^{230}Th, which has a half-life of 80,000 years, and may be the most significant contributor to the lung dose from inhaled uranium-bearing dusts [7]. Radium 226 is another important member of this series as is its daughter ^{222}Rn (radon), which is a radioactive gas that diffuses out of the ground and into the atmosphere. The parent nuclide of the actinium series is ^{235}U. The radionuclides in this series, other than ^{235}U and ^{231}Pa, are relatively short-lived. However, the radioactivity composition is constantly changing, along with the corresponding radiotoxicity of progeny.

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[2] Series might have started out abundantly but half-life is short compared to that of earth. Therefore, current abundance can be linked to the production of ^{241}Pu from the neutron irradiation of ^{238}U (see Figure 3.23).

Figure 2.2. Thorium natural decay series

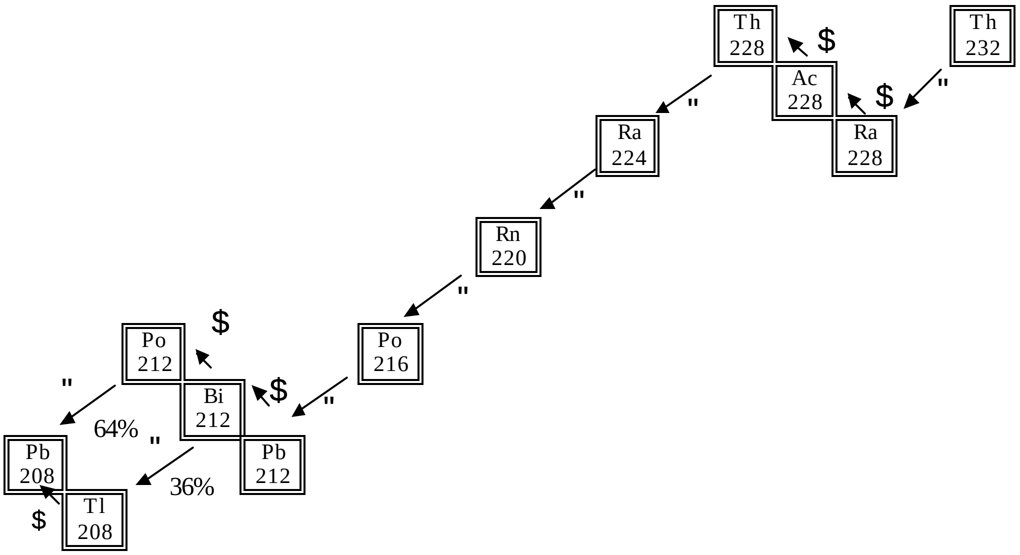


Figure 2.3. Neptunium decay series

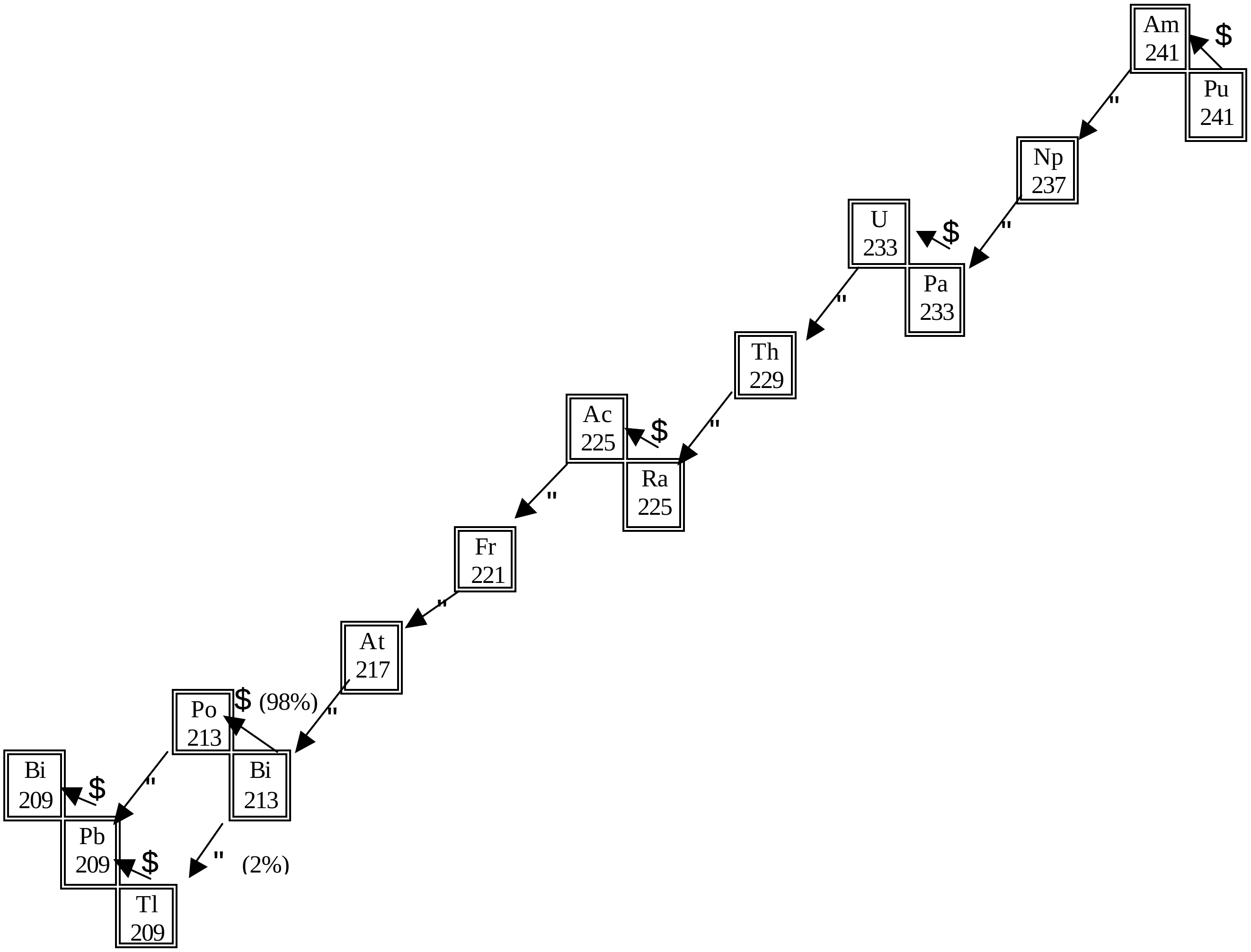


Figure 2.4. Uranium natural decay series

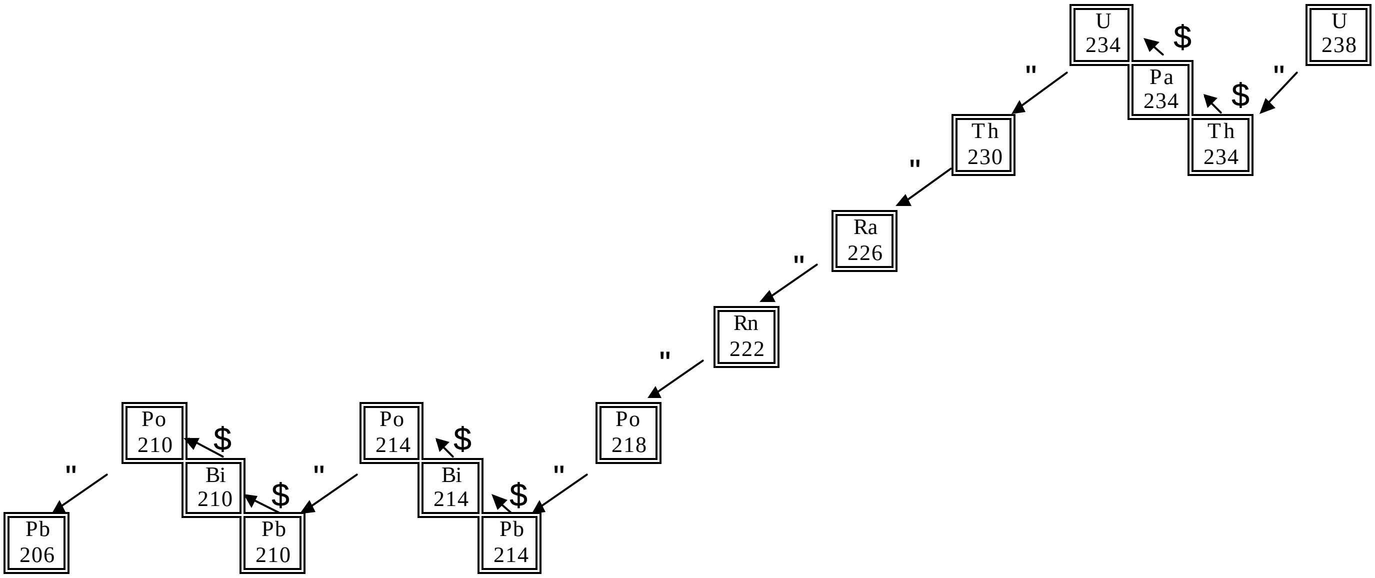
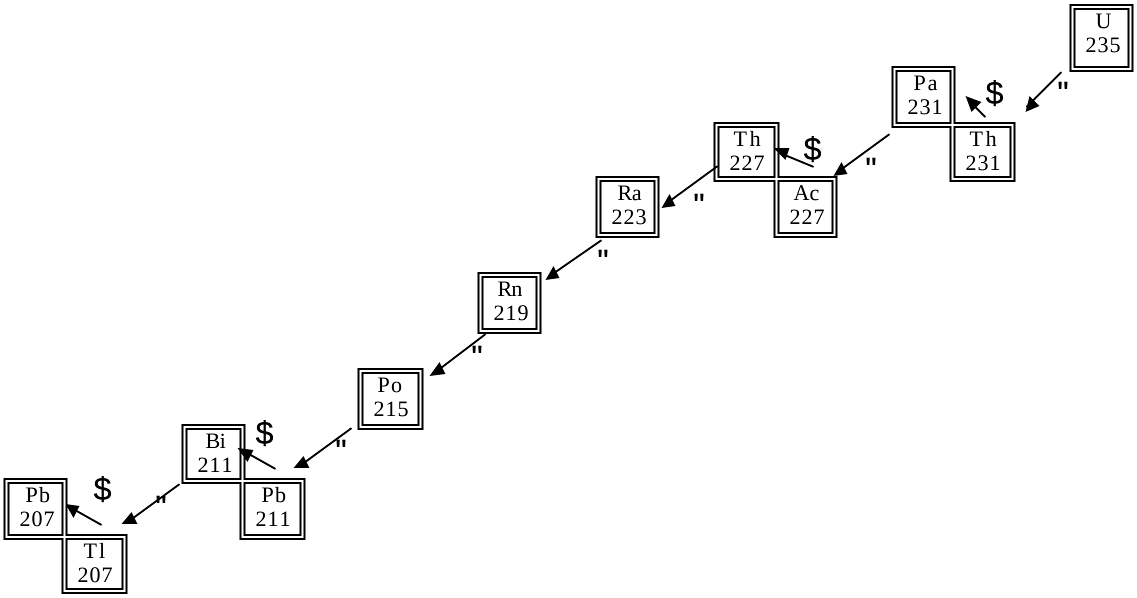


Figure 2.5. Actinium natural decay series



2.2. Uranium

Uranium is associated with three of the four naturally occurring series. Uranium is found in the earth’s crust often around two parts per million (ppm) and is a slightly radioactive metal [8]. That is, there is an average of one pound of uranium in every 500,000 pounds of earth. Traces of uranium are found almost everywhere. It is as common as tin, more abundant than gold, silver, or mercury and slightly less plentiful than cobalt, lead, or molybdenum. Uranium is present in virtually all rocks and soils as well as in rivers and sea water. Uranium is found in concentrations of about four ppm in granite, which makes up 60% of the earth's crust. Phosphate rocks, often used as fertilizers, may contain concentrations of uranium as high as 400 ppm (0.04%), while lower concentrations are found in sedimentary rocks, such as limestone. Uranium is also found in coal and hence in coal ash and other coal plant effluents. Natural fresh waters typically contain in the order of 0.024 to 200 Fg/l of uranium. Seawater shows concentrations of 2.0 to 3.7 Fg/l [9]. There are a number of areas around the world where the concentration of uranium in the ground is sufficiently high that extraction for use as nuclear fuel is economically feasible.

A typical person will contain about 100 -125 Fg of uranium. The daily uranium intake (largely from food ingestion) and excretion (in feces) in people is about 1.9 Fg. Bone contains a few thousand picograms (pg) of uranium per gram of bone ash; however, soft tissue concentrations are relatively low, in the order of a few hundred pg per gram of wet tissue [10].

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 oxides rapidly become coated with a black layer of oxide from air and moisture contact with their surface. Uranium is one of the most dense metals; it is about 65 % more dense than lead. Table 2.3 includes some of the properties of uranium.

The uranium (^{238}U) series includes ^{230}Th, which has a half-life of 80,000 years and is considered the most significant contributor to lung dose from inhaled uranium minerals [11]. Radium 226 is also an important member of this series. Its daughter ^{222}Rn (radon) can be described as a radioactive gas that diffuses out of the ground and into the atmosphere and hence its large contribution to environmental radioactivity.

Table 2.3. Properties of uranium [1]

Property or Characteristic	Value/Example
Origin	Uranium occurs in minerals such as pitchblende, uraninite, carnotite, autunite, uranophane, davidite and tobernite. It is also found in phosphate rock, lignite, and monazite sands, and can be recovered commercially from these sources.
Composition	Natural uranium normally contains approximately 99.2830 % ^{238}U by weight, 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. Melting point = 1132.3 ± 0.8 °C Boiling point = 3818 °C
Isotopes	Uranium has fourteen isotopes, all of which are radioactive.
Preparation	- Uranium can be prepared by reducing uranium halides with alkali or alkaline earth metals or by reducing uranium oxides by calcium, aluminum, or carbon at high temperatures. - The metal can also be produced by electrolysis of KUF_5 or UF_4, dissolved in a molten mixture of $CaCl_2$ and NaCl. High-purity uranium can be prepared by the thermal decomposition of uranium halides on a hot filament.

2.3. Thorium

Thorium makes up an estimated 12 ppm of the earth's crust. 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 and about as abundant as lead or molybdenum. Thorium-232 can be recovered commercially from the mineral monazite, which contains from three to nine percent ThO_2 along with most rare-earth minerals [12]. Thorium-232 disintegrates as illustrated in Figure 2.2. A particular characteristic of its decay scheme is the presence of thoron (radon 220 $T_{1/2}$=52 sec.), which is an alpha emitter that continues to decay into its progeny, as detailed in Table 2.4 [13]. Therefore, it is essential to have good ventilation areas where thorium is stored.

Table 2.4. Thoron and progeny [13]

Nuclide	Radiation	Half-life
^{220}Rn	"	55 sec
^{216}Po	"	0.15 sec
^{212}Pb	$	10.6 hr
^{212}Bi	$ (64 % to ^{212}Po) " (36 % to ^{208}Tl)	1 hr
^{212}Po	"	304 nsec
^{208}Tl	$	3.1 min
^{208}Pb	Stable	

Natural thorium can be irradiated with neutrons to produce the important isotope ^{233}U, a fissionable isotope that is rarely used. Table 2.5 includes some of the properties of thorium.

Table 2.5. Properties of thorium [1]

Property or Characteristic	Value/Example
Origin	Thorium can be extracted from mineral monazite, which contains from three to nine percent ThO_2.
Composition	Natural uranium is assumed to be all ^{232}Th. However, other isotopes do exist as a result from 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. - Dimorphic, with about 1% cerium oxide and other ingredients. - Powdered thorium metal is pyrophoric and should be carefully handled. Thorium turnings ignite when heated in air and burn brilliantly with a white light. - An important alloying element of magnesium, imparting high strength and creep resistance at elevated temperature. - 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 ^{o}C Boiling point . 4790 ^{o}C
Isotopes	^{227}Th (($T_{1/2}$=18.2 d), ^{228}Th ($T_{1/2}$=1.9 y), ^{229}Th ($T_{1/2}$=7340 y), ^{230}Th ($T_{1/2}$=8 x 10^4 y), ^{231}Th ($T_{1/2}$=25.5 h), ^{232}Th ($T_{1/2}$=1.4 x 10^{10} y), and ^{234}Th ($T_{1/2}$=24 d).
Preparation	The production of thorium metal has been accomplished by several methods: - Electrolysis of anhydrous thorium chloride in a fused mixture of sodium and potassium chlorides. - Reduction of thorium oxide with calcium. - Calcium reduction of thorium tetrachloride mixed with anhydrous zinc chloride. - Reduction of thorium tetrachloride with an alkali metal.

Work has been done on the usage of thorium as a source of nuclear power. Examples are the High-Temperature Gas-cooled Reactor (HTGR) and the Molten Salt Converter Reactor Experiment (MSRE). However, operating difficulties have delayed progress in this area of the nuclear field. The principal use of thorium has been in the preparation of Welsbach mantle, used for portable gas lights. Thorium is used to coat tungsten wire used 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. Since glasses containing thorium oxide have a high refractive index and low dispersion, they are used in high quality lenses for cameras and scientific instruments. 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 [14].

Dosimetrically, ^{228}Ra ($T_{1/2}$=6.7 years), ^{228}Th ($T_{1/2}$=1.91 years), and ^{224}Ra ($T_{1/2}$=3.64 days) are also important members of the thorium series. Except for parent ^{232}Th, the radionuclides from the thorium series are relatively short-lived; the daughters of freshly separated thorium will achieve equilibrium[3] in about 60 years. During this period, however, the radioactivity composition is constantly changing, along with the radiotoxicity, external dose rate, and related chemical and physical characteristics.

2.4. Radon

Naturally-occurring radiation accounts for approximately 80 percent of our exposure [4]. Most of our exposure to natural radiation is from indoor radon (55%), followed by radiation from outer space and from the earth's crust. Radon is a colorless, tasteless, and odorless gas that comes from the decay of radium found in nearly all soils. Levels of radon vary throughout the earth. 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 if there is no proper ventilation. When one breaths air containing a large amount of radon, the radiation from its progeny can damage the lungs.

Radon (^{222}Rn, $T_{1/2}$= 3.82 days), is a daughter product of radium (^{226}Ra), which in turn is derived from the longer-lived antecedent ^{238}U, as illustrated in Figure 2.4. Most of the actual dose would come from the decay products of radon, sometimes called radon daughters or radon progeny. Table 2.6 includes a list of the radon progeny, its type of radiation and half-life. These radon progeny are usually present 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.

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[3] Many radionuclides undergo successive transformations in which the original nuclide, called the parent, give rise to a radioactive product called the daughter. Examples of such transactions can be found in the natural occurring radioactive series. Radioactive equilibrium refers to the state which prevails in a radioactive series, when the ratios between the amounts of successive members of the series remain constant. For example, if the half-life of the parent is longer than that of the daughter, then after a certain period of time, a condition of equilibrium will be achieved. That is, the ratio of the daughter activity to parent activity will become constant.

Table 2.6. Radon and its progeny [13]

Nuclide	Radiation	Half-life
^{222}Rn	"	3.8 d
^{218}Po	"	3 min
^{214}Pb	$	26.8 min
^{214}Bi	$	19.7 min
^{214}Po	"	0.164 milliseconds
^{210}Pb	$	21 y
^{210}Bi	$	5 d
^{210}Po	"	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. The radiation levels can be measured with reasonable accuracy and precision. Several methods are available to accurately measure the presence of radon and its progeny. In a high radon area, it is prudent to determine its level and to take appropriate action if the level is found to be high [greater than 4-8 picocuries per liter (pCi/liter)]; for example, the increase of ventilation will reduce radon levels. Widely varying radon levels exist in different regions and are related to geological circumstances. The NCRP recommended safe level is 8 pCi/liter, whereas the EPA recommended safe level is 4 pCi/liter [15].

Radon measurement techniques can be classified in three categories: 1) grab sampling, 2) continuous active sampling, and 3) 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 [15].

Almost all measurements of radon levels in-or-outdoors are expressed as the concentration of radon in units of pCi/liter of air, or in SI units as becquerels per cubic meter (Bq/m^3). Radon progeny concentrations are often expressed in working levels (WL[4]). The correspondence between WLs and radon concentration in air in pCi/liter depends on the extent to which radon daughters, which impart dose to the tracheobronchial epithelium, are in equilibrium with the parent radon. At complete equilibrium, one pCi/liter of radon results in an exposure equal to 0.01 working level. The assumption is generally made that inside buildings, the radon decay product/radon equilibrium is about 50%. Consequently, inside buildings, 1 pCi/liter = 0.005 WL, or 1 WL= 200 pCi/liter.

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[4] The working level (WL) was introduced by Holaday et al. in 1957, as a measure of the concentration of radon progeny in uranium mine air that can be employed as a measure of exposure. A working level is defined to be any combination of short-lived radon progeny in 1 liter of air, under ambient temperature and pressure, that results in the ultimate emission of 1.3E5 MeV of alpha particle. This is about the total amount of energy released over a long period of time by the short-lived daughters in equilibrium with 100 pCi of radon [16].

A working level month (WLM) is defined as 170 hrs (2l.25 working days/month x 8 hrs/day) in a work place at one WL. Therefore, a 12 hour a day exposure in a home at one WL, corresponds to approximately 26 working level months per year (for example, 2.1 times the occupational exposure, assuming equal radon levels at home and in the work place). Exposure rate is typically given in working level months per year (WLM/year) [17].

2.5. Radiation from the Ground and Outer Space

Other than radon gas, we receive about eight percent of our exposure to natural radiation from other radioactive elements in the earth's crust, such as thorium and potassium [4]. Radiation levels from these sources vary in different areas of the Earth. Another eight percent of our radiation exposure comes from outer space. Our exposure to cosmic radiation depends in part on the altitude; a thicker atmosphere can filter out more cosmic radiation than a thinner atmosphere [18].

The CRC handbook of environmental radiation includes a list of nuclides that are found in the earth's crust, in units of µg of nuclide per gram of crust [9]. This list includes elements such as: ^{40}K, ^{50}V, ^{87}Rb, ^{115}In, ^{138}La, ^{142}Ce, ^{144}Nd, ^{147}Sm, ^{148}Sm, ^{149}Sm, ^{152}Gd, ^{174}Hf, ^{176}Lu, ^{204}Pb, thorium and uranium. Concentrations are given for different types of rocks to include: igneous rocks (subclassified as ultrabasic, basaltic, hi and low calcium granites, and syenites), sedimentary rocks (sub-classified as shales, sandstones and carbonates), and deep sea sediments, such as carbonates and clay. This CRC handbook also has estimates of natural radionuclides concentration in soils and in the waters of rivers and oceans, as well as in our diets and bodies.

Table 2.7 includes data on the radionuclides concentrations found in the oceans [9]. This table can be used to identify radionuclides that may be present at a site near or at a sea water shore, and that are naturally present in that environment.

Background radiation can be caused by a combination of terrestrial (from the ^{40}K, ^{232}Th, ^{226}Ra, ^{238}U, etc.) and cosmic radiation (photons, muons, etc.). The background radiation level is fairly constant over the world, being 8 to 15 µrad/hr; however, there are some areas that have higher levels. The higher radiation levels are most commonly caused by high concentrations of radioactive minerals in soil. One such mineral, monazite, is a highly insoluble rare earth mineral that occurs in beach sand together with the mineral ilmenite, which gives the sands a characteristic black color. The principal radionuclides in monazite are from the ^{232}Th series, but there is also some uranium and its progeny, ^{226}Ra [19].

Table 2.7. Natural radioactivity found in the ocean [9]

Nuclide	Activity*	Ocean		
		Atlantic 3.095E17 m^3	Pacific 6.549E17 m^3	All Oceans 1.3E18 m^3
Uranium	0.9 pCi/L (33 mBq/L)	3E8 Ci (11 EBq)	6E8 Ci (22 EBq)	1.1E9 Ci (41 EBq)
Potassium 40	300 pCi/L (11 Bq/L)	9 E10 Ci (3300 EBq)	2E11 Ci (7400 EBq)	3.8E11 Ci (14000 EBq)
Tritium	0.016 pCi/L (0.6 mBq/L)	5E6 Ci (190 PBq)	1E7 Ci (370 PBq)	2E7 Ci (740 PBq)
Carbon 14	0.135 pCi/L (5 mBq/L)	4E7 Ci (1.5 EBq)	8E7 Ci (3 EBq)	1.8E8 Ci (6.7 EBq)
Rubidium 87	28 pCi/L (0.11 Bq/L)	9E9 Ci (330 EBq)	1.9 E10 Ci (700 EBq)	3.6E10 Ci (1300 EBq)

*Activity is expressed the following units:

- picocurie per liter (pCi/L), which is 1E-12 curies per liter,
- becquerel per liter (Bq/L) or millibecquerel per liter (mBq/L), which is 1E-3 becquerels per liter,
- curie, exabecquerel (EBq), which is 1E18 becquerels, and
- petabecquerel (PBq), which represents 1E15 becquerels.

Cosmic radiation permeates all of space, the source being primarily outside of our solar system. The radiation is in many forms, from high speed heavy particles to high energy photons and muons. The upper atmosphere interacts with many of the cosmic radiations, and produces radioactive nuclides. They can have long half-lives, but the majority have shorter half-lives than the primordial nuclides. The most common cosmogenic nuclides are listed in Table 2.8 below.

Table 2.8. Most common cosmogenic radionuclides

Nuclide	Half-life	Source
^{14}C	5730 yr	- Cosmic-ray interactions - ^{14}N(n,p)^{14}C
Tritium (^{3}H)	12.3 yr	- Cosmic-ray interactions with N and O - Spallation from cosmic-rays - ^{6}Li(n,")^{3}H
^{7}Be	53.28 days	- Cosmic-ray interactions with N and O

Other cosmogenic radionuclides include the following: ^{10}Be, ^{26}Al, ^{36}Cl, ^{80}Kr, ^{14}C, ^{32}Si, ^{39}Ar, ^{22}Na, ^{35}S, ^{37}Ar, ^{33}P, ^{32}P, ^{38}Mg, ^{24}Na, ^{38}S, ^{31}Si, ^{18}F, ^{39}Cl, ^{38}Cl, and ^{34m}Cl.

2.6. Radioactivity in the Human Body

Humans are made up of chemicals, some of which contain radionuclides ingested daily with food and water. Table 2.9 includes some of the ICRP 30 estimates of the concentrations of radionuclides based on a 70 kg reference adult [20].

Table 2.9. Natural radioactivity found in the human body [20]

Nuclide	Amount in body	Activity of nuclide	Daily intake of nuclide
Uranium	100 :g	30 pCi (1.1 Bq)	1.9 :g
Thorium	30 :g	3 pCi (0.11 Bq)	3 :g
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 :g	0.4 :Ci (15 kBq)	1.8 :g
Tritium	0.06 pg	0.6 nCi (23 Bq)	0.003 pg
Polonium	0.2 pg	1 nCi (37 Bq)	~0.6 :g

2.7. Natural Radioactivity found in Building Materials

Radioactivity is also found in building materials. Table 2.10 includes a few common building materials and their estimated levels of uranium, thorium, and potassium. Most of the data included in this table was obtained from NCRP 94 [21].

Table 2.10. Estimated concentrations of uranium, thorium and potassium in building materials [21]

Material	Uranium		Thorium		Potassium (^{40}K)	
	ppm	mBq/g (pCi/g)	ppm	mBq/g (pCi/g)	ppm	mBq/g (pCi/g)
Granite	4.7	63 (1.7)	2	8 (0.22)	4.0	1184 (32)
Sandstone	0.45	6 (0.2)	1.7	7 (0.19)	1.4	414 (11.2)
Cement	3.4	46 (1.2)	5.1	21 (0.57)	0.8	237 (6.4)
Limestone concrete	2.3	31 (0.8)	2.1	8.5 (0.23)	0.3	89 (2.4)
Sandstone concrete	0.8	11 (0.3)	2.1	8.5 (0.23)	1.3	385 (10.4)
Dry wallboard	1.0	14 (0.4)	3	12 (0.32)	0.3	89 (2.4)
By-product gypsum	13.7	186 (5.0)	16.1	66 (1.78)	0.02	5.9 (0.2)
Natural gypsum**0**	1.1	15 (0.4)	1.8	7.4 (0.2)	0.5	148 (4)
Wood**0**	-	-	-	-	11.3	3330 (90)
Clay Brick**5**	8.2	111 (3)	10.8	44 (1.2)	2.3	666 (18)

- Chang et al, 1974 [22]
- Hamilton, 1970 [23]

2.8. Summary of Natural Radiation Sources

The following table includes the most important radionuclides that are found in natural sources of radiation.

Table 2.11. Summary of natural radiation sources

Nuclide	Radiation	Longest Half-life
^{3}H	\$	12.3 y
^{7}Be	γ	55 d
^{14}C	\$	5730 y
^{40}K	\$, γ	1E9 y
^{87}Rb	\$	1E10 y
^{232}Th and its daughters (^{228}Ra, ^{228}Ac, ^{228}Th, ^{224}Ra, ^{220}Rn and its daughters)	", \$, γ	1E10 y
^{220}Rn and its daughters (^{216}Po, ^{212}Pb, ^{212}Bi, ^{212}Po, ^{208}Tl)	", \$, γ	10.6 hr
^{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)	", \$, γ	1E8 y
^{238}U and its daughters (^{234}Th, ^{234}Pa, ^{234}U, ^{230}Th, ^{226}Ra, ^{222}Rn and its daughters)	", \$, γ	1E9 y
^{222}Rn and its daughters (^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po, ^{210}Pb, ^{210}Bi, ^{210}Po)	", \$, γ	21 y
^{241}Pu and its daughters (^{241}Am, ^{237}Np, ^{233}Pa, ^{233}U, ^{229}Th, ^{225}Ra, ^{225}Ac, ^{221}Fr, ^{217}At, ^{213}Bi, ^{213}Po, ^{209}Tl, ^{209}Pb)	", \$, γ	1E6 y
Other primordial radionuclides (^{40}K, ^{50}V, ^{87}Rb, ^{113}Cd, ^{115}In, ^{123}Te, ^{138}La, ^{142}Ce, ^{144}Nd, ^{147}Sm, ^{152}Gd, ^{174}Hf, ^{176}Lu, ^{187}Re, ^{190}Pt, ^{192}Pt, and ^{209}Bi)	", \$, γ	1E18 y
Other nuclides found in the earth's crust (^{115}In, ^{138}La, ^{142}Ce, ^{144}Nd, ^{147}Sm, ^{148}Sm, ^{149}Sm, ^{152}Gd, ^{174}Hf, ^{176}Lu, ^{204}Pb)	", \$, γ	1E17 y
Other cosmogenic radionuclides (^{10}Be, ^{18}F, ^{22}Na, ^{24}Na, ^{26}Al, ^{31}Si, ^{32}Si, ^{32}P, ^{33}P, ^{37}Ar, ^{39}Ar, ^{34m}Cl, ^{36}Cl, ^{38}Cl, ^{39}Cl, ^{35}S, ^{38}S, ^{80}Kr)	", \$, γ	1E6 y

References:

1. Bolz, R.E. and Tuve, G.L. *CRC Handbook of tables for applied engineering science*. Boca Raton, Florida: CRC Press, 1973, 2nd ed.. (Bolz RE, ed.)

2. Rohwer, P.R.and Wilcox, W.H. Radiological Aspects of Environmental Tritium. *Nuclear Safet*y, 1976; 17(216).

3. Elwood, J.W. Ecological Aspects of Tritium Behavior in the Environment. *Nuclear Safety*, 1971; 12(326).

4. BEIR: Health effects of exposure to low levels of ionizing radiation. Washington, DC: National Research Council, 1990.

5. Shleien, B., Slaback, J.L.A., and Birky, B.K. *The Health Physics and Radiological Health Handbook*, 3rd ed. Baltimore, Maryland: Williams & Wilkins, 1998. (Shleien, B., ed.)

6. ICRP: Radionuclide Transformations: International Commission on Radiological Protection, Pergamon, Oxford, 1983.

7. Harley, N.H. and Pastenack, B.S. *Potential carcinogenic effects of actinides in the environment*. Health Phys. 1979; 37(3): 291-300.

8. Web: URL: http://www.epa.gov/radiation/ionize.htm., 1997.

9. Klement, A.W. CRC Handbook of Environmental Radiation. Boca Raton, Florida: CRC Press, 1982. (Brodsky, A., ed. CRC Series).

10. ICRP: Recommendations of the International Commission on Radiological Protection : Pergamon, Oxford, 1977.

11. Harley, N.H. and Pastenack, B.S. *A model for predicting lung cancer risks induced by environmental levels of radon daughters*. Health Phys. 1981; 40: 307-316.

12. Bolch, E.W. 1995 Radioactive Waste Management Lecture. Gainesville, Florida: University of Florida, 1995.

13. Falo, G. A Direct Radon Detector [Dissertation]. University of Massachusetts Lowell; 1997.

14. Kathren, R.L. *Radioactivity in the environment: sources distribution, and surveillance*. Chur, Switzerland; NewYork: Harwood Academic Publishers, 1984.

15. NCRP: Measurement of radon and radon daughters in air. Bethesda: National Council on Radiation Protection and Measurements, 1988.

16. BEIR: Health risks of radon and other internationally deposited alpha-emitters. .
Washington, DC: National Research CouncilCommittee on the Biological Effects of Ionizing Radiations
National Academy of Sciences Press, 1988.
17. Cember, H. *Introduction to Health Physics*, Third ed. New York: McGraw-Hill, 1996.
18. EPA: External Exposure to Radionuclides in Air, Water, and Soil. Oak Ridge, Tennessee: Environmental Protection Agency, 1993.
19. NCRP: National Council on Radiation Protection, Public Radiation Exposure From Nuclear Power Generation in the U.S. Bethesda: National Council on Radiation Protection and Measurements, 1987.
20. ICRP: Limits for Intakes of Radionuclides by Workers. International Commission on Radiological Protection, Pergamon, Oxford, 1979.
21. NCRP: Exposure of the Population in the United States and Canada from Natural Background Radiation (Supersedes NCRP Report No. 25). Bethesda: National Council on Radiation Protection and Measurements, 1987.
22. Chang, T.Y., Cheng, W.L., Weng, P.S.: Potassium, uranium and thorium content of building materials of Taiwan. *Health Physics*, 1974; 27: 385-387.
23. Hamilton, E.I.: Relative radioactivity in building materials. American Industrial Hygiene Association, 1971; 32: 398-403.

Chapter 3. Sources from the Nuclear Fuel Cycle

The nuclear fuel cycle includes all activities associated with the production of electricity from nuclear reactions in reactors. Uranium is mined in a number of countries; it undergoes several processing operations and conversions before and after being used in a reactor. The heat generated in a nuclear reactor is used to produce steam and drive turbines, connected to electricity generators. The fuel that is removed from a reactor and has reached the end of its useful life, can be reprocessed to produce new fuel. In summary, the fuel cycle includes the following steps: mining, milling, conversion, enrichment, fuel fabrication, reactor operations, and disposal of waste. These steps are represented as a flow diagram in Figure 3.1. Figure 3.2 represents a global distribution of the uranium fuel cycle [1].

Figure 3.1. The uranium fuel cycle

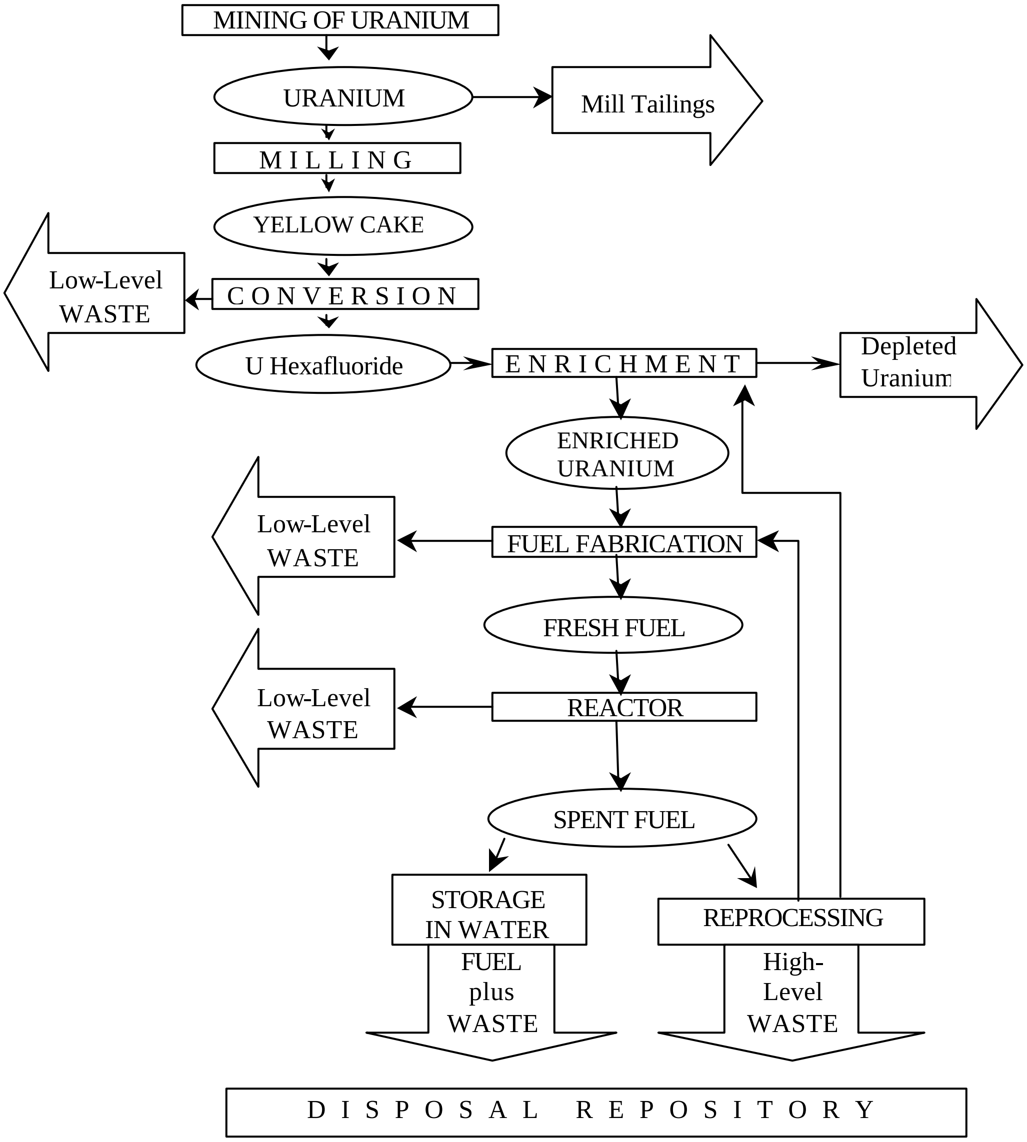
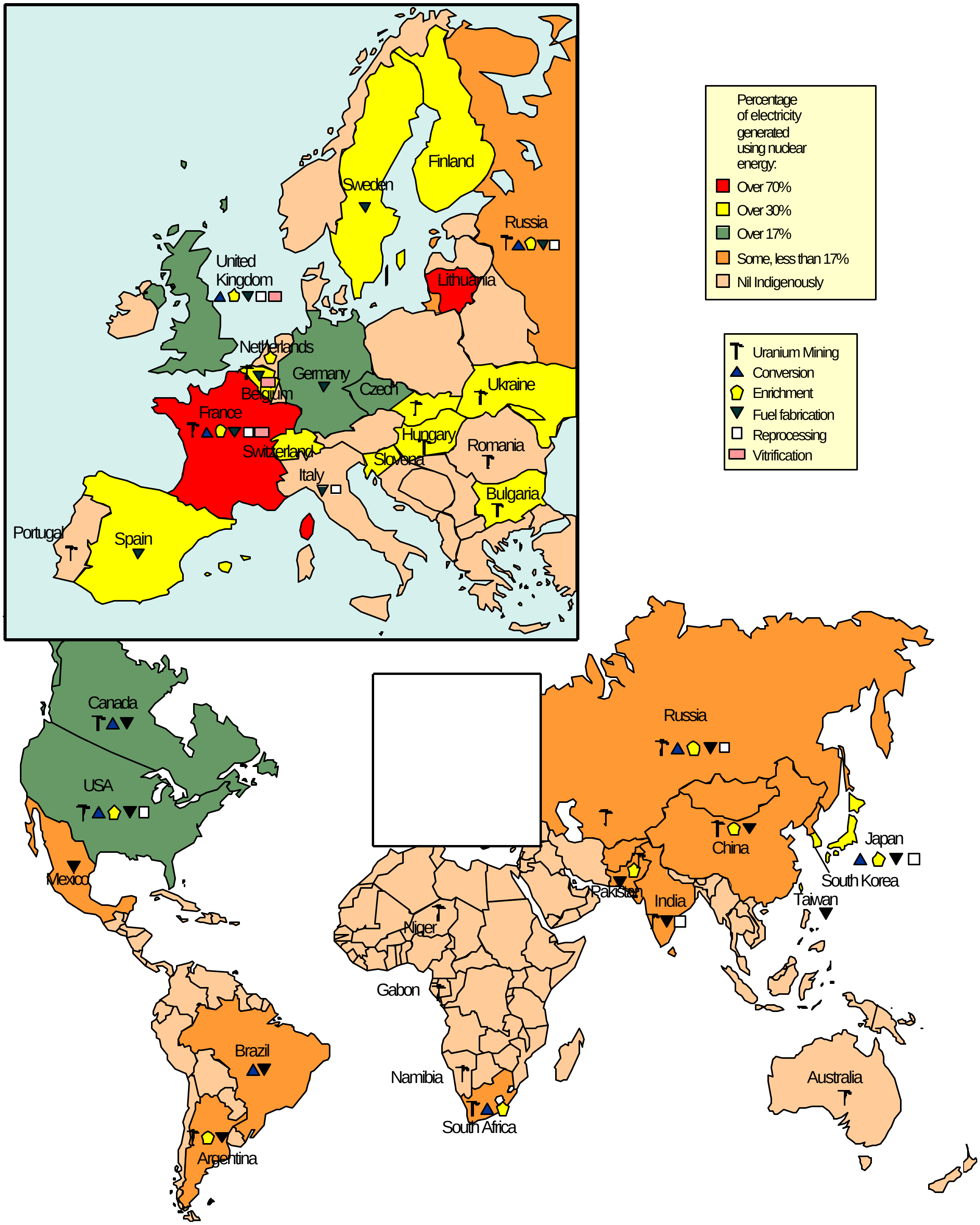


Figure 3.2. Uranium fuel cycle in the world (1998) [1]



3.1. The Mining of Uranium

Underground and open pit mining are used in the recovery of uranium. Open mining is used where deposits are close to the surface and underground mining is used for deep deposits, typically greater than 120 meters in depth. Open pit mines require larger openings on the surface than the size of the ore deposit because the walls of the pit must be sloped to guard against collapse (see Figure 3.3). As a result, the quantity of material that must be removed in order to access the ore is large. However, the most common method of mining uranium is the open-pit method [2].

Underground mines have relatively small openings to the surface and the quantity of material that must be removed to access the ore is considerably less than in the case of an open pit mine. In the case of underground uranium mines special precautions, consisting primarily of increased ventilation, are required to protect against airborne radiation exposure. Since there is variable concentration of uranium in mines, there is also variable concentration of radium and therefore, there is variable concentration of radon and its progeny. The following tables include the production and distribution of uranium and uranium mining activity in the world today. Table 3.1 is a summary of the uranium production in the world by region. [3]. Table 3.2 includes the estimated uranium recoverable resources in the world [1].

Table 3.1. World uranium production by 1997 [1]

Country or Area	Uranium Production (%)
Canada	34
Africa	21
CIS (Commonwealth of Independent States)	15
Australia	14
USA	7
Western Europe	4
Eastern Europe	3
Asia	2
Total	100

Table 3.2. Estimated recoverable resources of uranium [1]

Country	Tons U_3O_8	Percentage of world
Australia	894,000	25%
Kazakhstan	681,000	19%
Canada	507,000	14%
South Africa	335,000	9%
Namibia	291,000	8%
Brazil	281,000	8%
Russian Fed.	195,000	5%
USA	130,000	4%
World total	3,638,000	

In the solid state and chemically pure form, uranium is a gray, hard, and very dense metal. In nature it is found throughout the earth's crust in both granitic and sedimentary formations in various mineralogical forms. Uraninite (uranium oxide) is the most common primary uranium mineral. Coffinite (uranium hydrous silicate) and corrolite (potassium uranium vanadate) are also of economic interest. The most common form of uraninite is pitchblende, which is sometimes associated with colorful secondary uranium minerals derived from weathering.

The concentration of uranium needed to form an economic mineral deposit varies widely depending on its geological setting and physical location. Average ore grades at operating uranium mines range from 0.03%U to as high as 10% U but are most frequently less than 1% U [4]. Table is a list of locations of the largest deposits of uranium in the world.

Table 3.3. List of uranium mineral deposits around the world

Mineral	Location
Uranium silicate and copper (Cuprosklodowskite)	Musonoi, Shabba Copper belt, Zaire
Autunite crystals	Les Oudots, Sa^neet-Loire, France
Uranium and magnesium silicate (Sklodowskite)	Shinkolobwe, Zaire
Calcium and uranium silicate (α-uranophane)	Bois Noirs, Puyde-D^me, France
Uranium and barium vanadate (Francevillite)	Mounana, Gabon
Hydrated silicate of uranium and magnesium (Autunite)	Kerler, Morbihan, France
Uraninite, uranium oxide	Margnac, Haute-Vienne, France
Lead uraninite (Curite)	Shinkolobwe, Shaba Copper belt, Zaire
Hydrated calcium uranate (Becquerelite)	Shinkolobwe, Zaire
Potassium uranyl silicate (Boltwoodite)	R`ssing field, Namibia
Calcium and uranium silicate (β-uranophane)	Margnac, Haute-Vienne, France

3.2. 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, to sand-sized particles, thereby freeing the uranium minerals. It is then chemically concentrated. The concentration method varies from one mill to the next, depending on the characteristics of the ore. With few exceptions, the process is:

1) the uranium is dissolved by acidic or alkaline leaching of the ore. Diluted acid or alkali dissolves the freed uranium, allowing the uranium-bearing solution to be separated from the leached solids by a solid-liquid separation device,
2) the uranium is recovered, and
3) in the form of uranate of magnesium, sodium, ammonium or peroxide, is chemically precipitated.

The resulting concentrates look like a yellow powder or cake, hence the name "yellow cake." The concentrates contain approximately 75% uranium, or 750 kilograms per ton [5].

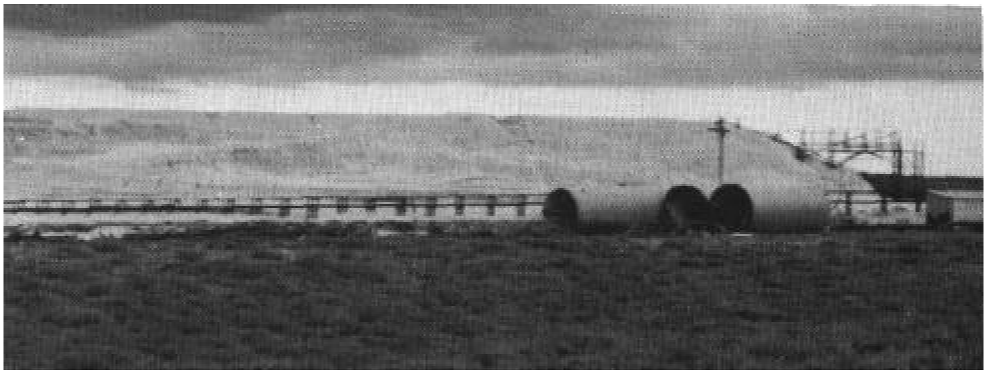
Figures 3.3 and 3.4 are pictures of a uranium open pit mine and annexed mill, and the interior of a mill. These pictures can assist in the physical identification of this type of plant, as mines and mills have been identified as sources of radiation within the uranium fuel cycle.

Figure 3.3. Open pit mining and annexed uranium mill (Mailhac-sur-Benaise, Haute-Vienne, France)

Figure 3.4. Internal view of a uranium mill

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 ^{238}U. Most of these elements are not removed in the extraction process of uranium. Generally, tailings leave the mill as liquid sludge and are allowed to dry. They are collected in piles within enclosures. Figure 3.5 is a picture of a typical tailing pile. Precaution is necessary to prevent the tailings from contaminating ground water 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 the material has been brought to the surface and is being converted into a new form, it can pose a hazard unless protective layers of earth are applied. The radon flux from tailings piles is often much higher than background levels. Placing a layer of material that promotes revegetation ultimately reclaims the mine sites. Monitoring of radiation levels is common after reclamation of land.

Figure 3.5. A mill tailings pile



3.3. 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, which can be enriched to produce fuel for the most common types of reactors.

Two different procedures, which involve the same basic chemistry, are used to convert the yellowcake (U_3O_8, shown in Figures 3.6 and 3.7) into uranium hexafluoride (UF_6). These are the wet and dry conversion processes. In each case, the essential steps are:

1) the reduction of U_3O_8 to UO_2 (uranium dioxide) by means of hydrogen produced by “cracking” (for example, strongly heating) ammonia gas,
2) the hydrofluorination of UO_2 to UF_4 (uranium tetrafluoride, a chemically stable blue-green compound), by heating in a stream of hydrogen fluoride gas, and
3) the conversion of UF_4 to UF_6 (uranium hexafluoride, a colorless solid at room temperature) by fluorine gas.

Figure 3.6. Picture of yellowcake of magnesium uranate after being filtered and pressed

Figure 3.7. Belt filtration of yellowcake (Société des Mines de Jouac, France)

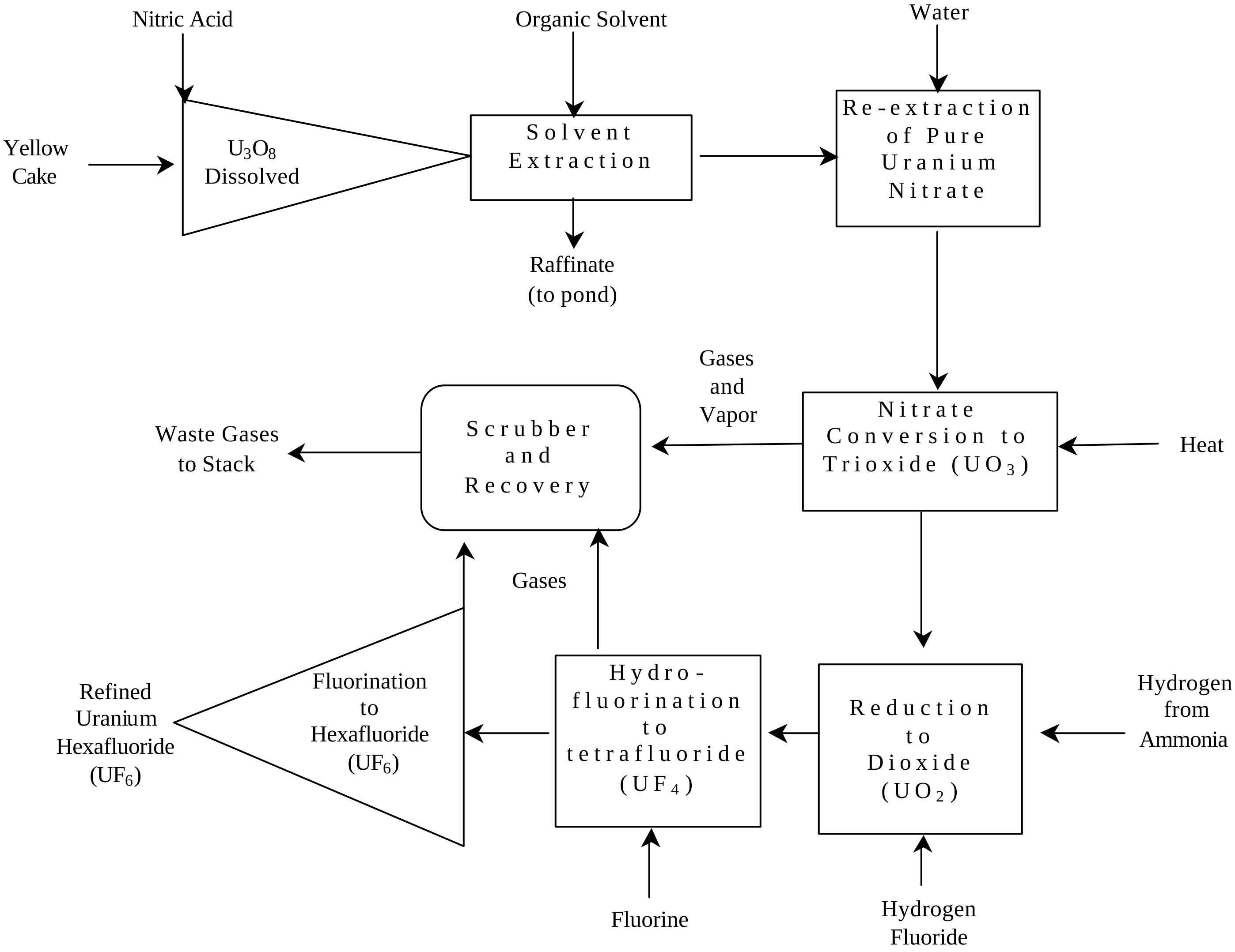
UF_6 sublimes at atmospheric pressure and it evaporates without melting at 56°C. The gaseous form is therefore used in the enrichment plants at temperatures below 100°C. UF_6 reacts with water, including vapor in the air, and must be transported in sealed containers. Figure 3.8 is an unusual picture of crystallized uranium hexafluoride as it forms white crystals that decompose in the presence of moisture.

Figure 3.8. Crystallized uranium hexafluoride

Figures 3.9 and 3.10 outline the wet and dry conversion processes for the production of UF_6. Figure 3.9 illustrates the "wet", solvent-extraction process. The yellowcake is digested with hot aqueous nitric acid, which dissolves the uranium (and impurities). Uranyl nitrate is extracted from the solution in water by means of an organic solvent (tributyl phosphate in hexane). The aqueous raffinate includes the impurities. Pure uranyl nitrate is then re-extracted from the organic solution by means of fresh water. The water is evaporated and the residue is heated to covert the uranyl nitrate into pure uranium trioxide (UO_3), which is then reduced by hydrogen to uranium dioxide. This is then heated, first in hydrogen fluoride gas and subsequently in fluorine to produce pure uranium hexafluoride [6]. Figure 3.10 illustrates the hydrofluoric process, which is a dry process. The yellowcake from the uranium mill is heated in a flow of hydrogen gas (and

nitrogen) obtained by cracking[5] ammonia gas. The resulting crude uranium dioxide is first converted into uranium tetrafluoride by means of gaseous hydrogen fluoride and then into hexafluoride by elemental fluorine gas. Distillation is then used in the purification of the crude uranium hexaflouride [6].

Figure 3.9. Illustration of the wet process for the production of uranium hexafluoride



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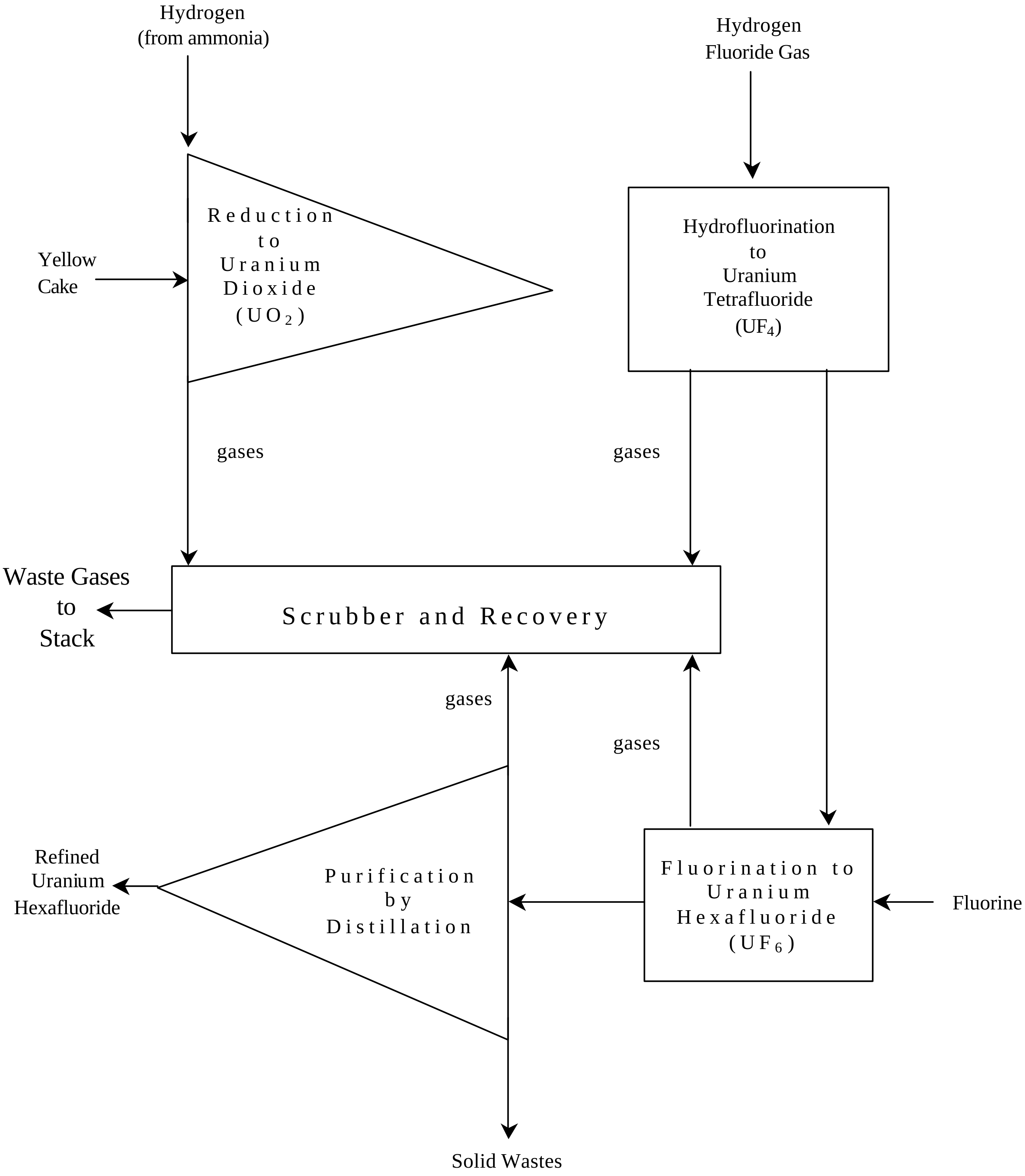
[5] Cracking ammonia gas refers to heating it strongly.

Figure 3.10. Illustration of the dry process for the production of uranium hexafluoride



3.4. Enrichment

A higher than natural concentration of ^{235}U (fissionable isotope of uranium), is required to run most common types of nuclear reactors[6]. This concentration is typically between 3.5 to 4.5 percent weight ^{235}U and is accomplished by enrichment. There are two enrichment processes in large-scale commercial use, each of which uses uranium hexafluoride as feed: gaseous diffusion and gas centrifugation [7]. Other less commonly used enrichment processes are the nozzle separation method and laser enrichment.

In the gaseous diffusion process, the uranium hexafluoride that resulted from the conversion process is used. Uranium hexafluoride is solid at room temperature, but it changes completely to vapor at 56.4 ^{o}C (133.5 ^{o}F) [8]. The vapor, like the solid, contains a mixture of ^{235}U hexafluoride and ^{238}U hexafluoride in the same molecular proportion as the two isotopes occur in nature. The uranium hexafluoride vapor is forced through a porous barrier containing a large number of very small holes. The hexafluoride molecules containing the ^{235}U (lighter isotope) travel more rapidly than those containing ^{238}U (heavier isotope). Therefore, the hexafluoride containing ^{235}U diffuses through the porous barrier; that is, the vapor that passes through the barrier first is richer in ^{235}U. A single barrier would result in a small amount of enrichment, but passing through a series or cascade of porous barriers can result in products with enrichment capabilities up to 90 percent. Figure 3.11 is a pictorial representation of a stage in this process. Enrichments of a few percent can be attained by using several hundred stages, whereas higher enrichment would require thousands of stages. Therefore, gaseous diffusion plants, as shown in Figure 3.12, cover large areas and require a considerable amount of power [9].

Gaseous diffusion plants use large volumes of water for cooling purposes and discharge heat to the surroundings. Liquid effluents from these plants are diluted to a considerable extent with clean water prior to discharge. 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.

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[6] A small number of reactors, notably the Canadian CANDU and the British Magnox reactors, do not require enriched uranium [1].

Figure 3.11. Pictorial representation of a stage of the gaseous diffusion process [10]

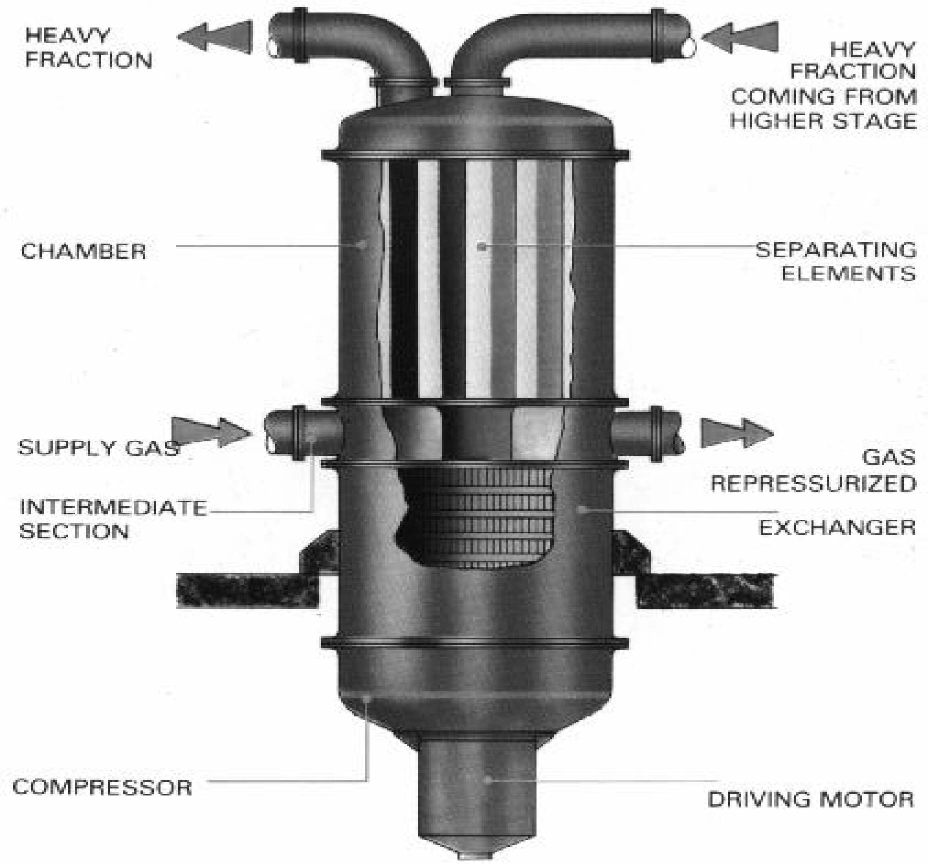
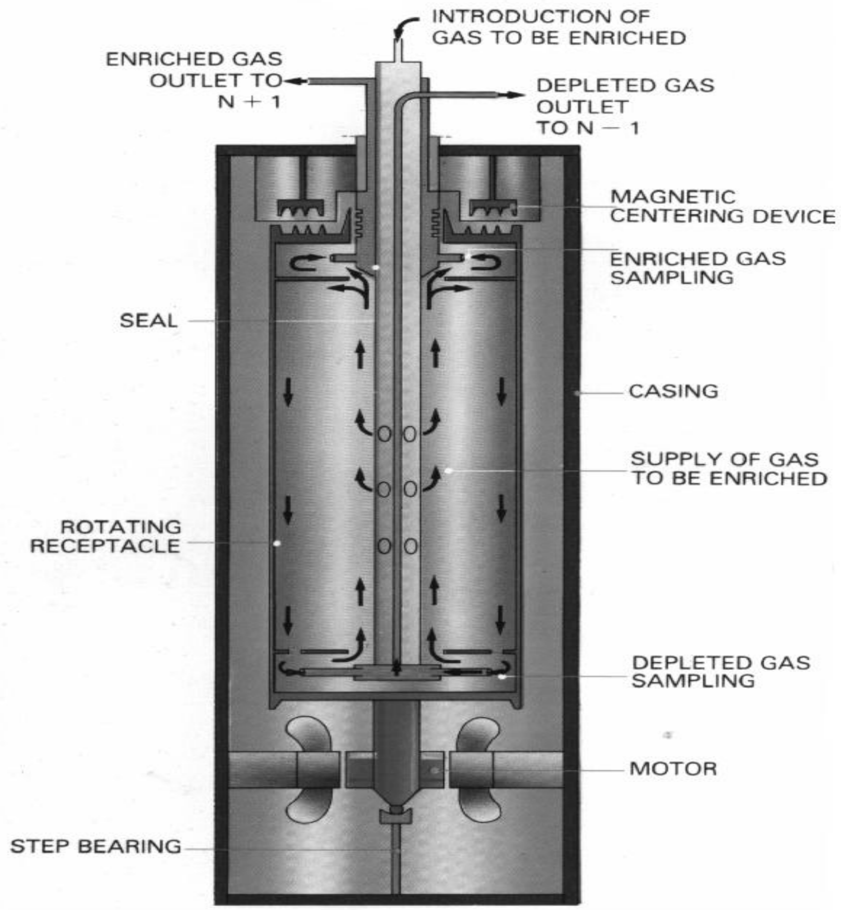


Figure 3.12. Picture of an enrichment gaseous diffusion plant (Tricastin, France)

The centrifuge method of isotope enrichment needs less than one-tenth the power required to operate an equivalent plant using gaseous diffusion. The centrifuge method is based on the fact the heavier molecules of uranium in uranium hexafluoride ($^{238}UF_6$) will tend to move outward in a high speed spinning centrifuge, whereas the lighter molecules ($^{235}UF_6$) will move inward toward the axis of rotation. Therefore, the product withdrawn from near the axis of the centrifuge is enriched in $^{235}UF_6$. Figure 3.13 is a representation of a stage of the enrichment process by the centrifuge method.

Figure 3.13. Stage of the enrichment process by centrifuge

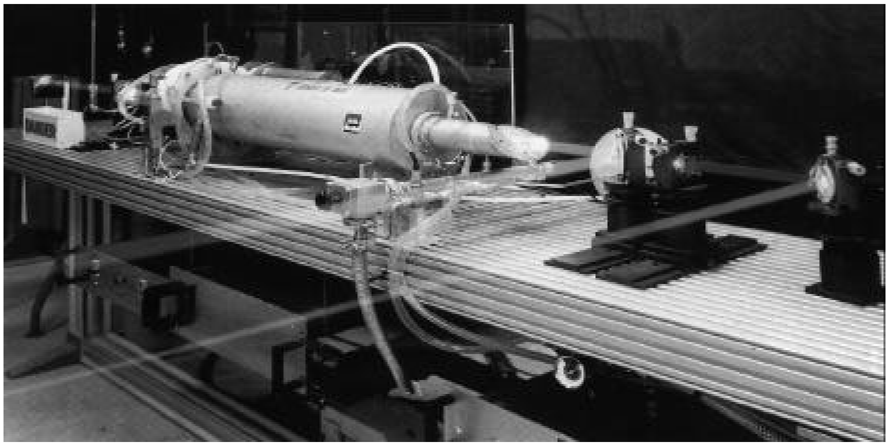


In the nozzle separation process a mixture of UF_6 and helium is exhausted through a curved nozzle arrangement. A separator splits the resulting stream into two. Being heavier, the depleted fraction is deflected further out. The inner, enriched stream is recovered for additional enrichment. The power consumption for this process is twice as high as for gaseous diffusion; the separation factor is somewhere between that of the gaseous diffusion and that for the centrifuge process [10]. This method was developed in Germany and used by plants in Brazil, Argentina and South Africa.

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 is used to selectively excite one or the other isotope. In the process of Molecular Laser Isotope Separation (MLIS), a laser is used to excite the molecules of uranium hexafluoride gas containing $^{235}UF_6$, diluted in helium at about 220°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 (AVLIS) 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 [10].

The laser separation processes are extremely promising; they require little power and involve only one separation step. These processes are used in the United States and France. Figure 3.14 shows a laser used for the uranium enrichment process. A copper vapor laser is shown as it 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.

Figure 3.14. Laser used for uranium enrichment



3.5. Fuel Fabrication

Fuel fabrication is the process in which the enriched uranium hexafluoride 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 1400 /C). The pellets are then 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 3.15 and 3.16 are pictures of UO_2 fuel pellets and fuel rods in the final stages of fuel fabrication.

Figure 3.15. Uranium fuel pellets

Figure 3.16. Uranium fuel rods

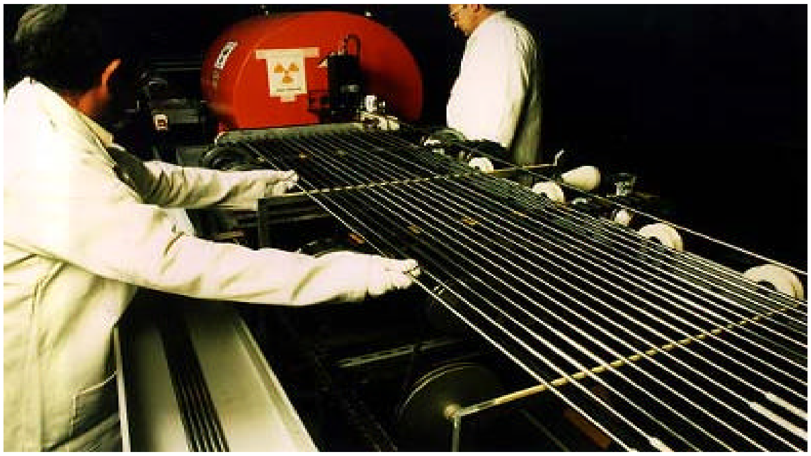
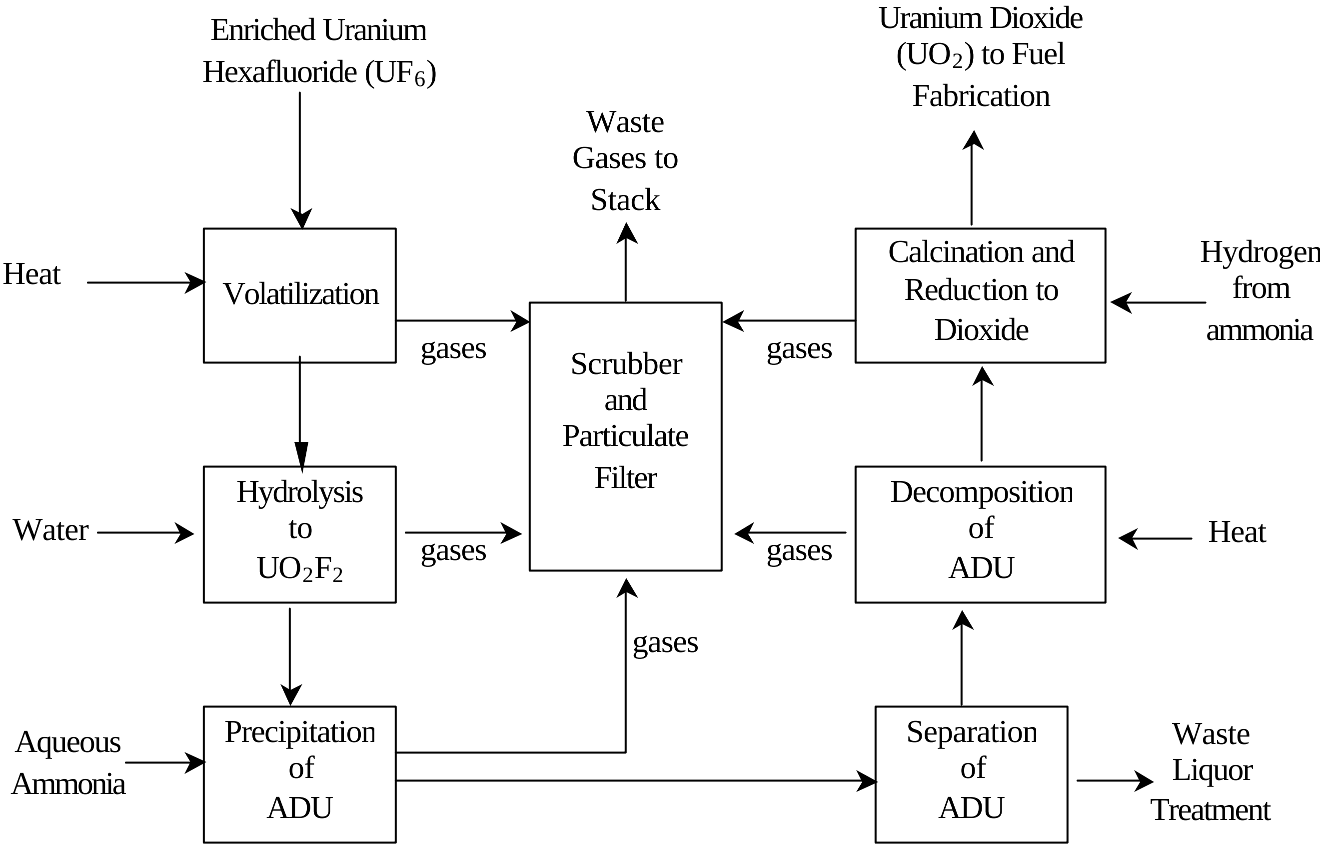


Figure 3.17 is a flow diagram of the production of uranium dioxide from uranium hexafluoride. Hydrolysis (the decomposition by water) of uranium hexafluoride to form uranyl fluoride (UO_2F_2) is the first stage in the production of uranium dioxide. An aqueous ammonia solution is then used to precipitate ammonium diuranate ($[NH_4]_2 U_2O_7$), commonly referred to as ADU. The solid ADU is then separated by a centrifuge or filter and dried by heating. The resulting dry solid is calcined and reduced in the presence of hydrogen from ammonia gas in order to yield uranium dioxide. The product, which has the same ^{235}U enrichment as the starting uranium hexafluoride, is powdered, compacted into small pellets (cylindrical pellets for most common reactor designs), and sintered until the required density is attained. Pellets are crushed to specified dimensions, cleaned, and loaded into zirconium-alloy tubes to form fuel rods, such as the ones used in light water reactors [11].

Figure 3.17. Production of uranium dioxide from uranium hexaflouride



Subsequent to passing through HEPA (high-efficiency particulate air) filters, gaseous effluents that originated in wet processes are scrubbed for the removal of chemicals and often “demisted” to separate water droplets. The filters are used in the fuel fabrication process, before discharging gaseous effluents to the atmosphere. These discharged gases have very low levels of radioactivity.

The chemical conversion of uranium hexafluoride to dioxide produces liquid waste that contains chemical impurities, including fluorides. Lime is used to treat the effluent in order to precipitate calcium fluoride that contains traces of uranium and some decay products. Calcium fluoride solids are usually buried at the plant site. The raffinate from the organic solvent extraction stage is the major effluent in the scrap recovery operation, and it is generally in a retention pond prior to discharge. However, the total amount of activity in this effluent is small because scrap recovery represents a relatively minor aspect of fuel production.

The liquid effluent may be more radioactive than expected from its ^{238}U content if several months have elapsed between the initial production of uranium hexafluoride and the conversion into dioxide. This happens because although thorium isotopes are essentially absent from the uranium hexafluoride when it is first produced from yellow cake, ^{234}Th (half-life of 24 days) is formed by the decay of ^{238}U [9]. The ^{234}Th amount increases with time until radioactive equilibrium is approached in about 6 months[7]. The ^{234}Th decays to ^{234m}Pa (half-life 1.18 min), which emits a photon to become ^{234}Pa (half-life 6.7 h), and then decays to ^{234}U (very long half-life of 2.47E5 years). Therefore, if several months have elapsed between the initial production of uranium hexafluoride and the conversion into dioxide, the liquid effluent may be more radioactive than expected from the ^{238}U content. However, once separated, these unsupported daughters will decay to very low levels after several months.

The product of gaseous diffusion is enriched in ^{234}U as well as in ^{235}U. The ^{234}U is not consumed during reactor operations and therefore, it remains in the spent fuel. The concentration of ^{234}U greatly exceeds the equilibrium value if the spent fuel is returned to the gaseous diffusion plant for re-enrichment of ^{235}U. Because ^{234}U has a much shorter half-life than ^{238}U, the activity of a given mass of uranium will increase if the spent fuel is recycled. The traces of fission products remaining in recovered uranium will also contribute to the increased activity.

Mixed-oxide (MXO) fuels are commonly made by mechanically mixing plutonium and uranium dioxide powders. The uranium dioxide used is produced in the manner described previously, using natural, rather than enriched uranium hexafluoride. Plutonium nitrate ($Pu[NO_3]_4$) solution is the starting point in the production of plutonium dioxide. This plutonium nitrate is the form in which plutonium is recovered from spent Light Water Reactor (LWR) fuel or from the fuel and blanket of a fast breeder reactor. Plutonium oxalate is generally precipitated from the nitrate solution. The oxalate is separated, dried, and calcinated to form the dioxide. The product is grounded and screened to yield a powder of the desired particle size. Figure 3.18 illustrates a block diagram of this process.

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 LWRs) 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 [13]. Figure 3.19 is a picture of MOX fuel pellets.

The scrap material from the MOX 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 calcined 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 MOX feed [14].

The dirty scrap is the small quantity that becomes contaminated with impurities during the fuel fabrication process and it requires chemical treatment. The oxides are dissolved in nitric acid with the addition of a small amount of hydrogen fluoride to facilitate dissolution. Liquid wastes containing plutonium from other sources of the operation may be added to the solution. Uranium and plutonium are then recovered as nitrates, either separately or together, by extraction with an organic solvent. Ammonia is added to the solution containing plutonium and uranium nitrates to

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[7] Roughly, seven half-lives are required for 99 percent of the equilibrium amount of any daughter to be attained from a long-lived parent, such as ^{238}U [12].

give a precipitate that consists of plutonium hydroxide and ammonium diuranate. This is separated, dried, and heated in hydrogen gas to generate the mixed oxides in pure form [13].

Figure 3.18. Block diagram of the production of mixed-oxide fuel fabrication

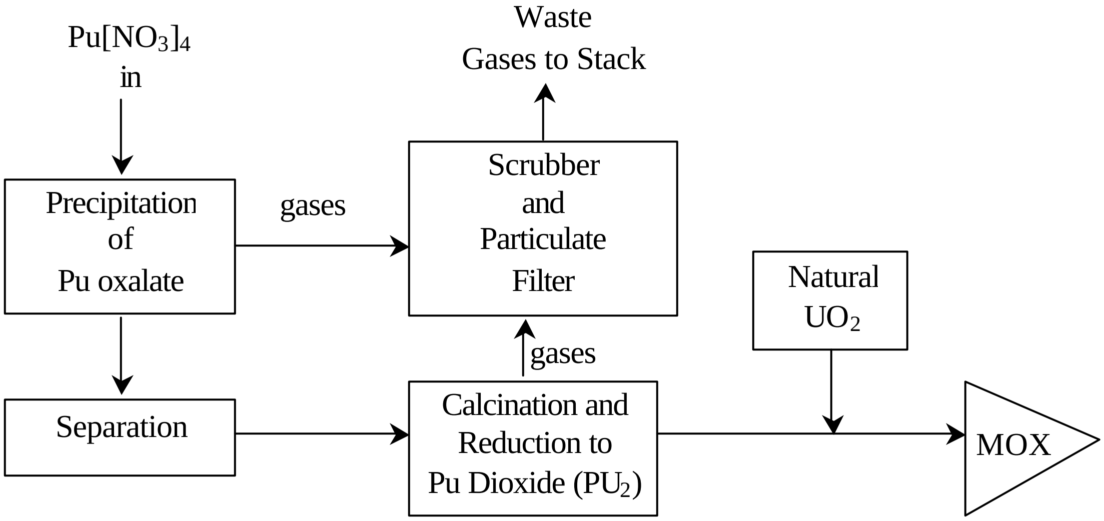
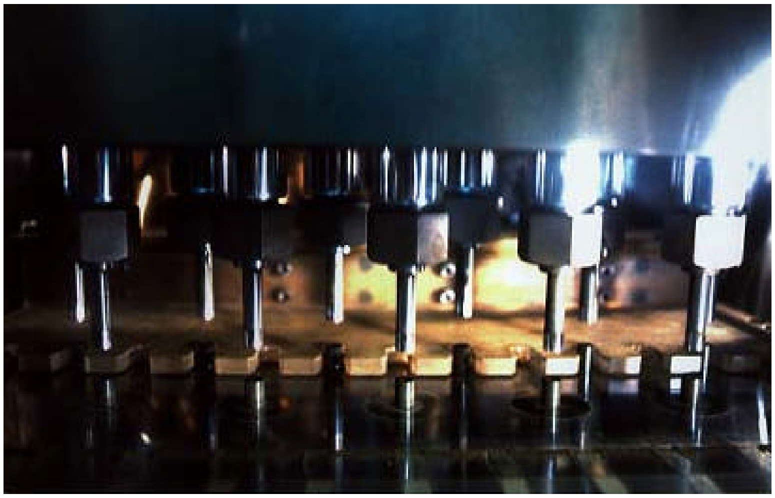


Figure 3.19. Mixed-oxide fuel pellets



All stages of the MOX 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, long-armed gloves, made of rubber or similar material and 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 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 MOX fuel production facilities are those from the treatment of dirty scrap. Liquid wastes containing plutonium are normally evaporated. The vapor may then 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 [13].

3.6. 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 fissioning 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.

3.6.1. 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. Figure 3.20 shows the basic fission mechanism. 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.

Figure 3.21 shows a chain reaction that is used in power reactors. 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, and so on. Figure 3.22 is a block diagram that illustrates the neutron irradiation process of ^{238}U.

Figure 3.20. Illustration of the fission process of ^{235}U

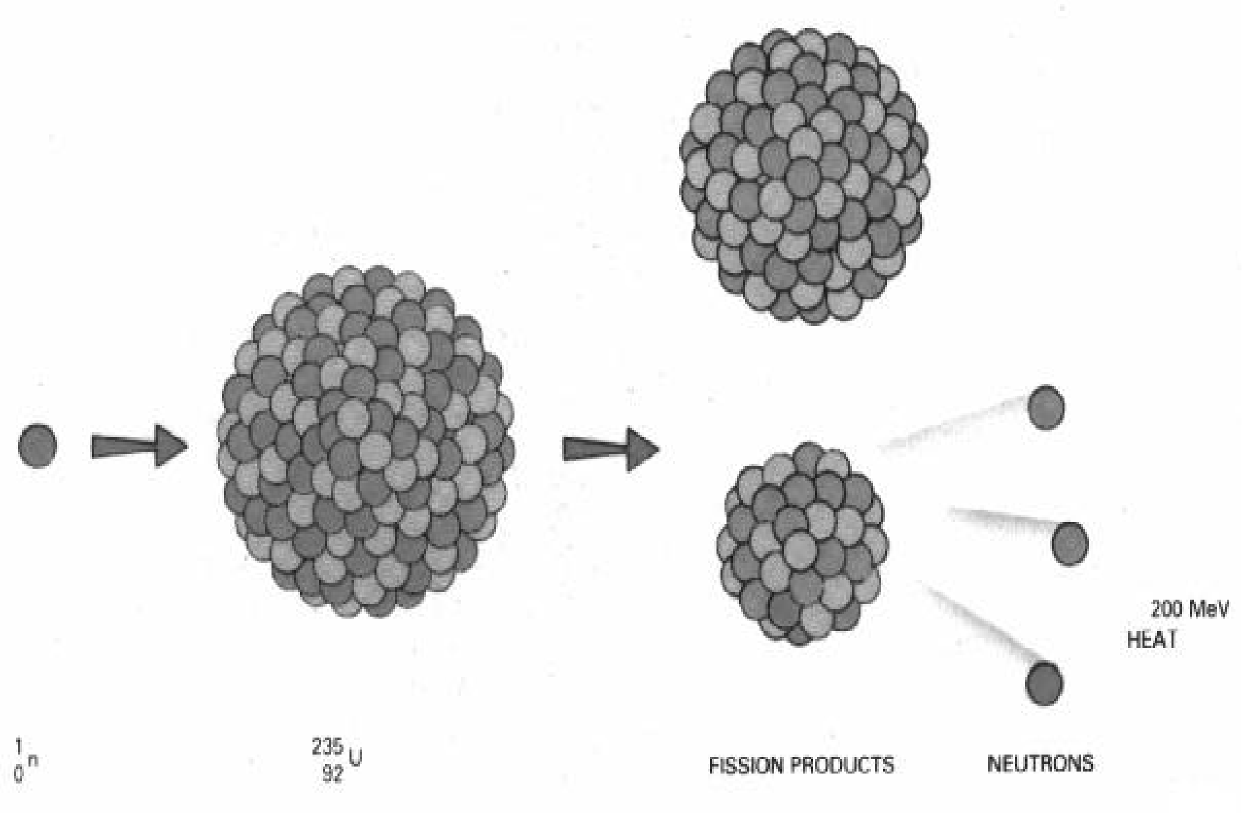


Figure 3.21. Illustration of the fission chain reaction

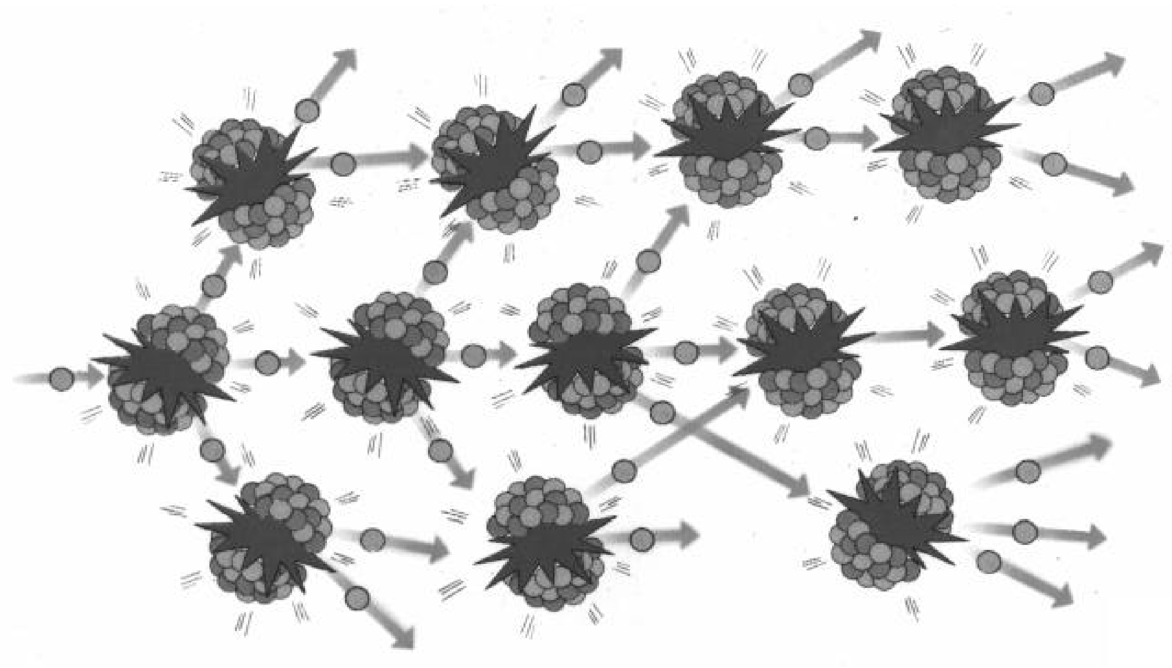
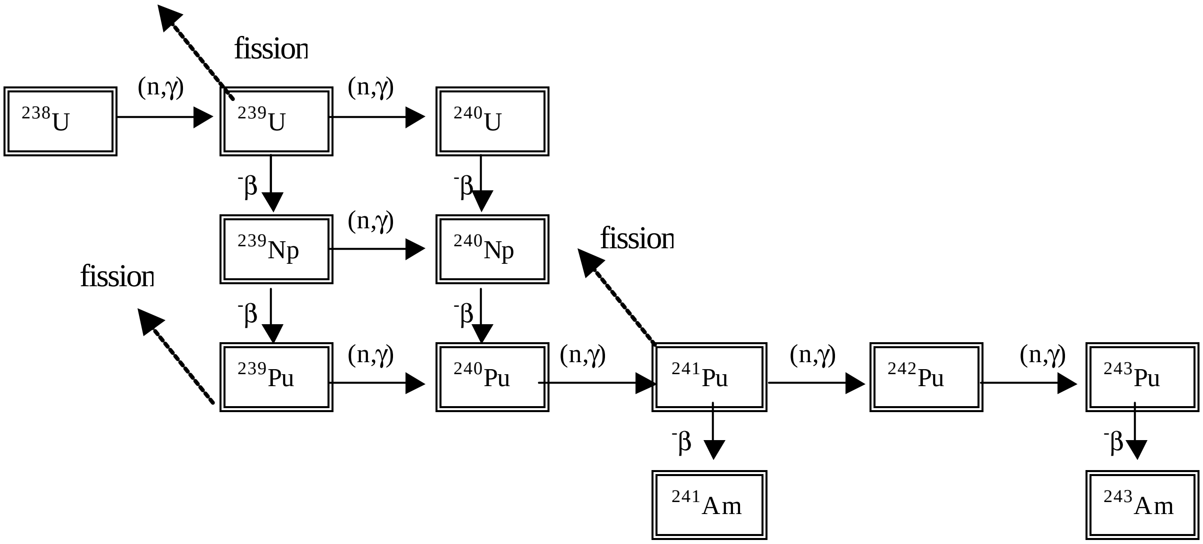


Figure 3.22. Neutron irradiation of ^{238}U



3.6.2. 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.

3.6.3. 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. The purpose of this distinctive profile is not to increase the air draft; rather, the double curve strengthens the concrete wall of the tower. This form makes it possible to reduce the thickness of the concrete to about 25 centimeters for a height of 160 to 180 meters and a diameter of 90 meters at the narrowest point. Figure 3.23 is a picture of a cooling tower. Figure 3.24 is a picture of an alternative cooling system used in nuclear power plants, the forced draft cooling system. Power plants can also have no distinctive cooling towers and use water from reservoirs in their cooling systems. An example is shown in Figure 3.25.

Figure 3.23. Picture of a hyperbolic cooling tower at a nuclear power plant (Grafenrheinfeld, Germany)

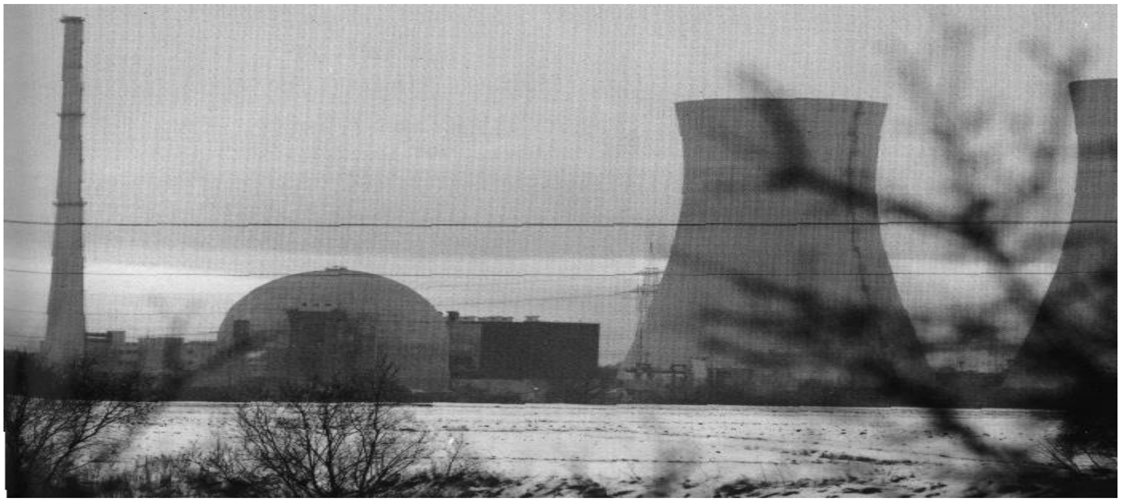


Figure 3.24. Picture of mechanical draft cooling towers at a nuclear power plant (Chinon, France)

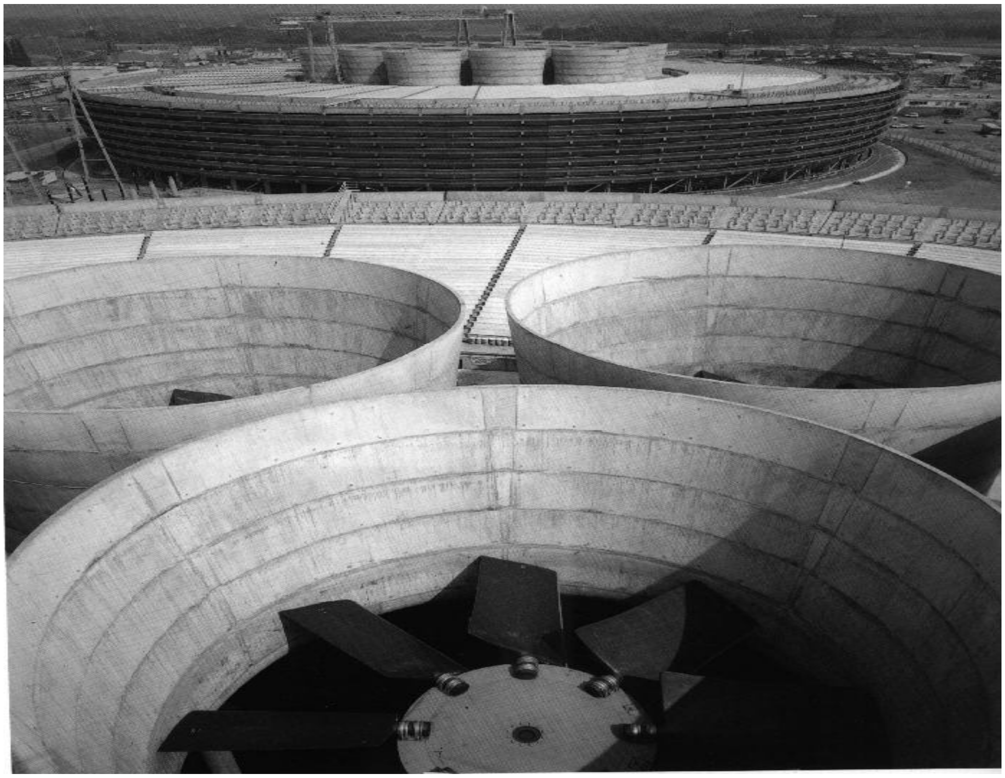


Figure 3.25. Nuclear power plant with no distinctive cooling tower (Saint-Alban, France)

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

1.) Main loop (primary), including major components.
2.) Reactor vessel.
3.) Reactor coolant.
4.) Reactor coolant purification system (including filters and demineralizers).
5.) Condensate purification system (Boiling Water Reactors, BWR).
6.) Radioactive liquid waste processing systems (including tanks, filters, demineralizers and evaporators).
7.) Spent reactor fuel.
8.) Radioactive gas waste processing systems (including tanks, compressors, charcoal bed absorbers, and filters).

The principles of using nuclear power to produce electricity are the same for all types of fission reactors. The fission process releases energy and continuous fission (the chain reaction) is maintained in the reactor core. A large amount of heat is released, which is transferred from the core via a coolant circulating through the reactor. Steam is produced either directly in the coolant, or indirectly via heat transfer to a secondary cooling system. This steam is used to drive the turbines that produce electricity. Typical reactor components (see Appendix B) are: reactor pressure vessel, fuel, moderator control rods, coolant, steam generator, and containment.

Other main components are the pumps and all other equipment that are part of the primary and secondary loops in most reactors. Demineralizers, turbines, condensers, dryers, shielding structures, water treatment systems, other systems, corresponding piping and many other systems are among these components.

3.6.3.1 Reactor Types

There are several types of reactors used for the production of electricity, most of these are covered in Appendix B. The components and their orientation determine the various operating characteristics of each type of reactor. Some 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 this type of operation. The type of fuel used and the amount that is replaced on refueling will also vary with reactor type. Table 3.4 summarizes the different type of reactors in the world today [15, 16]. This table also includes key information regarding the design of the reactors; that is, their type of fuel, moderator and coolant. This information is crucial in identifying possible sources of exposure when encountering any of these types of reactors. Moreover, this information can be used in the process of determining 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 3.4. 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	-	-	-

LWR: Light Water Reactor
PWR: Pressurized Water Reactor
REP: “RJacteur B Eau sous Pression” (PWR)
VVER: “Vode Vodjanie Energitcheskie Reactor” (Water-water power reactor)
HWR: Heavy Water Rector
CANDU: Canada Deuterium Uranium
EL4: “Eau Lourde” (Heavy water) Prototype no. 4
SGHWR: Steam Generating Heavy Water Reactor
GCR: Gas Cooled Reactor
UNGG: “Uranium Naturel Graphite Gaz” (Natural uranium, graphite, gas)
AGR: Advanced Gas Reactor
HTGR: High Temperature Gas-Cooled Reactor
LWGR: Light Water Graphite Reactor
RBMK: “Reactor Bolchoe Molchnastie Kipiachie” (High power boiling water reactor)
NPR: New Production Reactor
LMFBR: Liquid Metal Fast Breeder Reactor
FFTF: Fast Flux Test Facility [17]
FBR: Fast Breeder Reactor
OMR: Organic Moderated Reactor

3.6.3.2. 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 3.5.

Table 3.5. 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 3.6	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 and xenon, and some dissolved solid products can escape into the reactor water [18].

The most important fission products are those that are formed in the great majority of fissions. After a short period of time and as a result of radioactive decay, fission products constitute more than 300 radionuclides, all of which are radioactive [18]. Many of these have a short half-life and can be ignored because they are formed in very small portions. Table 3.6 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 as a result of fission. Tritium, although a fission product, is often considered separately because it 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.

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 as a result of corrosion and erosion of steel and other alloys used in the reactor vessel, pumps, piping, valves and steam generator.

Table 3.6. List of important fission products [9, 19]

Radionuclide	Radiation	Half-life
Gases		
^{3}H	$	12.3 yr
^{83m}Kr[8]	(	1.9 hr
^{85m}Kr[4]	$, (	4.4 hr
^{85}Kr	$, ((0.4%)	10.8 yr
^{87}Kr	$, (	1.3 hr
^{88}Kr	$, ((35%)	2.8 hr
^{133m}Xe[4]	(	2.3 d
^{133}Xe	$, ((37%)	5.3 d
^{135m}Xe[4]	(	16.0 min
^{135}Xe	$, (	9.1 hr
^{138}Xe	$, (	18.0 min
Solids		
^{88}Rb	$	18.0 min
^{89}Sr	$, ((0.01%)	52.7 d
^{90}Sr	$	28.0 yr
^{90}Y	$	2.7 d
^{91}Y	$, ((0.3%)	59.0 d
^{129}Te	$, ((20%)	70.0 min
^{131m}Te[4]	$ (82%), ((31%)	1.3 d
^{131}Te	$, ((68%)	25.0 min
^{133}Te	$	13.0 min
^{129}I	$, ((9%)	1.7E7 y
^{131}I	$, (	8.0 d
^{133}I	$, (	20.0 hr
^{135}I	$, ((37%)	6.7 hr
^{134}Cs	$, (	2.0 y
^{136}Cs	$, (	13.7 d
^{137}Cs	$, ((89%)	30.0 yr
^{138}Cs	$, ((73%)	32.0 min
^{140}Ba	$, (	13.0 d
^{140}La	$, (	1.7 d
^{144}Ce	$, ((13%)	284 d
^{144}Pr	$, ((2.5%)	17.0 min
^{147}Pm	$	2.6 y
^{151}Sm	$, ((4%)	87 y

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[8] These are metastable (higher-energies) states of the indicated radionuclide; they usually decay by emitting their extra energy as gamma rays.

Regardless of the high quality of the components, there is always activated corrosion products and neutron activated materials in reactors. In BWRs, corrosion and erosion in the turbine, turbine condenser, and feedwater heater can also contribute to the activation products because the condensed water is returned to the reactor vessel by way of the feedwater heaters. In PWRs, however, the condenser and feedwater are part of the secondary loop that includes the steam generator but not the reactor core; therefore, less activation products are found. Table 3.7 identifies the most significant activation products.

Table 3.7. List of most important activation products

Activation Product	Activity	Half-life
Gases		
^{13}N	$	10 min
^{16}N	$, (	7 sec
^{41}Ar	$, (	1.8 hr
Solids		
^{51}Cr	$, ((9%)	28 d
^{54}Mn	(	300 d
^{56}Mn	$, (	2.6 hr
^{58}Co	$ (15%), (	71 d
^{60}Co	$, (	5.3 yr
^{65}Zn	$, (	245 d
^{59}Fe	$, (	45 d

Activation products can also be 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[9]. 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, and ^{110m}Ag, ^{182}Ta, ^{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.

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[9] The activation of ^{85}Rb, an impurity in sodium coolant results in the production of ^{86}Rb.

Heat exchangers become a source of radiation exposure to personnel as water in the reactor coolant, reactor coolant cleanup and waste disposal systems flows through. 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. Examples of such areas include flanged dead legs, valves, bends in pipes (elbows), etc. As the radioactivity in these Acrud traps@ accumulates with time, the exposure rates increase resulting in Ahot spots@.

Traces of UO_2 may remain on the outside surface after fabrication of fuel elements. This is referred to as "tramp uranium" [9]. 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.

There are many ways that a person in the vicinity of a nuclear power plant could be exposed to radiation. The most important scenarios that represent sources of exposure from nuclear plants effluents are simplified in Table 3.8.

Table 3.8. Sources of exposure from nuclear plants effluents

Exposure	Example scenario
External	Submersion in air
	Immersion in water (swimming)
	Radiation from particles deposited on the ground
	Direct radiation from plant
Internal	Inhalation of air
	Ingestion of food (e.g., leafy vegetables, fish, etc.) and water
	Drinking milk from grazing cows

Table 3.9 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), iodine-131 and iodine-133 are very important sources of exposure. Cesium-134 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.

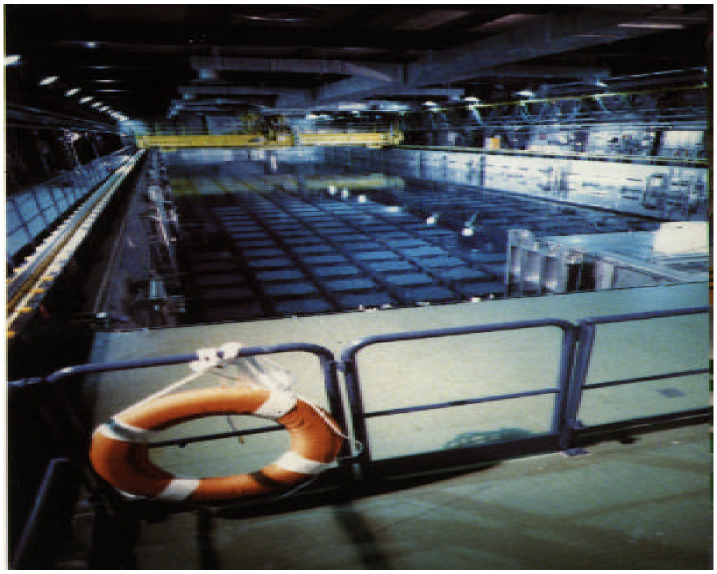
Table 3.9. Radiation exposure pathways from nuclear plants

Radiation from:	Effluent	Exposure Pathway	Critical Organ
Iodine isotopes	Airborne	Ground deposition (external)	Whole body
		Air inhalation	Thyroid
		Grass ÿ cow ÿ 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 ÿ cow ÿ milk	Whole body
		Grass ÿ cattle ÿ 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 tract
Direct radiation from plant		External	Whole body

3.7. 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. Figure 3.26 is a picture of a spent fuel pool. The Cerenkov effect can be observed in this picture as a result of the storage of spent fuel. High-energy electrons, traveling faster than light in water, emit a brilliant blue illumination as they are slowed down.

Figure 3.26. Spent fuel pool (La Hague, France)



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 radiolytic 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 [11].

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 days of cooling, the major contributors to the radioactivity of spent fuel are listed in Table 3.10. The values in this table are in curies and becquerels per metric ton (1000 kg) of uranium[10].

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[10] The uranium is assumed to be initially free of plutonium when charged to the reactor. The values in the table were calculated for a hypothetical LWR having a thermal power of 3300 MW and a specific fuel burnup of 2.85 x 10^{12} J (2.85 TJ, thermal) per kilogram of uranium in the original fuel. Other operating conditions will derive different activities; however, those in the table are fairly typical.

Table 3.10. Major contributors of radioactivity from spent fuel (LWR fuel) after 150 days cooling period [11]

Radionuclide	Radiation	Half-life	Activity	
			Bq/1000 kg U	Ci/1000 kg U
Fission Products				
^{89}Sr	$	52.7 d	3.6E15	9.6E04
^{90}Sr	$	28 y	2.8E15	7.7E04
^{95}Zr	$, (	65.5 d	1.0E16	2.8E05
^{95}Nb	$, (	35 d	1.9E16	5.2E05
^{106}Ru	$	368 d	1.5E16	4.1E05
^{134}Cs	$, (	2.05 y	7.7E15	2.1E05
^{137}Cs	$, (	30 y	4.1E15	1.1E05
^{144}Ce	$, (	284 d	2.8E16	7.7E05
^{147}Pm	$	2.62 y	3.7E15	9.9E04
Heavy-elements Isotopes				
^{238}Pu	", (	88 y	1.1E13	2.8E02
^{239}Pu	", (	24,400 y	1.2E13	3.3E02
^{240}Pu	", (	6,540 y	1.8E13	4.8E02
^{241}Pu	", $, (	14 y	4.1E15	1.1E05
^{242}Pu	", (	387,000 y	5.0E10	1.36
^{241}Am	", (	433 y	7.4E12	2.0E02
^{243}Am	", (	7,370 y	6.4E11	17.4
^{241}Cm	", (, sf*	162.5 d	5.5E14	1.5E04
^{244}Cm	", (, sf*	17.6 y	9.3E13	2.5E03

* 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, few fission products, namely, strontium, zirconium, niobium, ruthenium, cesium and some rare earth elements, are responsible for nearly all of the 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.

3.8. 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 is a process that uses liquid solvent extraction principles coupled with oxidation-reduction chemical reactions to chemically separate the various constituents of the spent fuel. 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.

The solvent-extraction process is based on the separation by the preferential solubilities of fission products, uranium, and the produced plutonium. This is accomplished by various counterflowing organic and aqueous solutions with the objective of separating Pu from U (^{238}U + ^{235}U) or U from Th, and all of these from the fission products. However, the process is difficult, as extremely high radioactive levels, due primarily to the fission products, require the use of large facilities with concrete shielding and remote handling equipment. In this process the highly active waste solutions pose a problem of handling, storage and ultimate disposal. Reprocessing facilitates recycling and produces a significantly reduced volume of waste. Reprocessing facilities vary in design but can be identified as large industrial complexes as shown in Figure 3.27. Figure 3.28 is a block diagram that represents the flow of the spent fuel reprocessing.

Figure 3.27. Picture of a fuel reprocessing facility (La Hague, France)

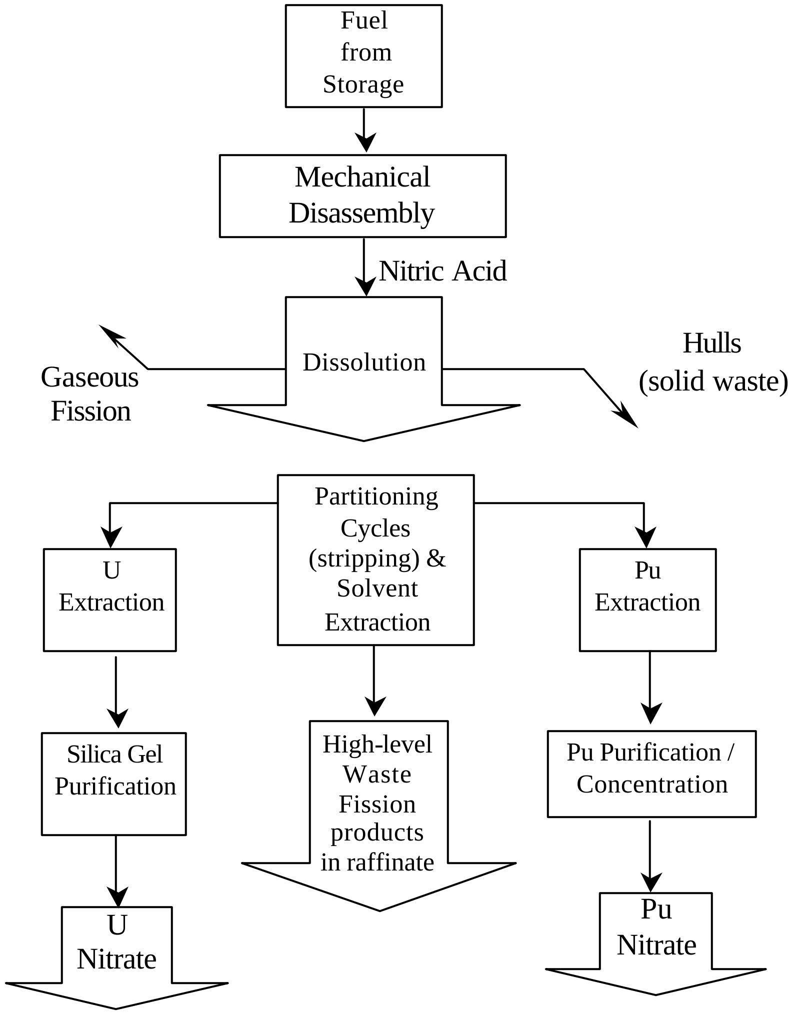
Reprocessing in the U.S. started with the plants in Hanford and Oak Ridge, built during World War II. Two other plants were built in the 1950's at Savannah River, South Carolina and at Idaho Falls, Idaho. These plants were constructed to meet military needs and were not intended for the processing of civilian fuel. Privately owned nuclear fuel reprocessing plants were built in West Valley, New York (plant went into operation in 1966 and shutdown in 1972) and in Morris County, Illinois and Barnwell, South Carolina (these plants never operated). Fuel reprocessing was prohibited in the U.S. in 1977 to avoid the diversion of Pu and the possible uncontrolled proliferation of nuclear weapons.

MOX fuel fabrication occurs at five reprocessing facilities in Belgium, France, Germany and UK, with two more under construction. The French plant, Melox, was the first large-scale plant of this type. Japan has also successfully implemented reprocessing.

Large quantities of fission products are produced in the reprocessing process and must be managed to avoid environmental contamination, which may occur during normal operations or as a result of an accident. In fission, ^{129}I (half-life of 1.7E7 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 of the thyroid dose to the general population [19].

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; for example, contamination of the skin. 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.

Figure 3.28. Fuel reprocessing flow chart



The five main steps in reprocessing can be described as follows:

1.) Mechanical disassembly. Fuel rods are fed to a mechanical shear and cut into small pieces.
2.) Dissolution. The uranium, plutonium and fission products are then dissolved into aqueous nitrate solution.
3.) Partitioning cycle. Uranium, plutonium and fission products are separated in a continuous solvent extraction process that uses the nitrated solution with an organic solvent containing tributylphosphate (TBP) in kerosene. Adjustments in concentrations result in an organic phase for the U and Pu, whereas the fission products remain in an aqueous phase. A reducing agent is used to reduce the valence state of plutonium and therefore separate it from the organic stream containing uranium. The waste is then composed of fission products, aluminum or other metals, and nitric acid. A scrub solution may be used to remove traces of fission products.
4.) Extraction and concentration cycles. The separated streams of uranium and plutonium undergo further solvent extraction to further purify the product and extract the U and Pu. The organic solutions are recycled and U and Pu solutions are concentrated by evaporation.
5.) Product preparation. Purified uranyl nitrate and plutonium nitrate solutions are the output of the previous steps. Uranium can be subject to further processing to produce either UF_6 as feed for isotope separation, or UO_2. Federal regulations in the United States require that Pu be converted to a solid prior to shipping.

Nuclear power reactors are shutdown 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 in a gaseous-diffusion (or other type such as centrifuge, laser, etc.) plant 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 [14]. The Pu can also be used in the fabrication of nuclear weapons.

The uranium from reprocessing, which typically contains a slightly higher concentration of ^{235}U than occurs in nature, can be reused as fuel after conversion and enrichment, if necessary. The plutonium can be made into MOX fuel, in which uranium and plutonium oxides are combined.

3.9. 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. Also included in this chapter is a description of the liquid and gas solid waste found in LWRs.

Radioactive waste from the nuclear fuel cycle includes waste with large amounts of radioactivity and waste with lower amounts. In order to manage this waste it is important to look at the half-lives of the radionuclides involved and their activity, as well as the physical state. Table 3.11 includes examples of radioactive wastes from the nuclear fuel cycle and their estimated activity[11] [20].

Table 3.11. 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	4×10^{6} - 4×10^{7} [10^{-4} - 10^{-3}]
	Liquid and Solid	U, ^{226}Ra, ^{230}Th, ^{210}Pb	2×10^{10} - 4×10^{10} [0.5 - 1]
Conversion and Enrichment	Liquid	^{238}U, ^{234}Th, ^{234}Pa, ^{226}Ra	4×10^{6} - 4×10^{7} [10^{-4} - 10^{-3}]
Fuel Fabrication	Liquid and Solid	U, Pu, Th	4×10^{6} - 4×10^{7} [10^{-4} - 10^{-3}]
Reactor Operations	Gaseous	^{13}N, ^{41}Ar, ^{89}Kr, ^{87}Kr, ^{135}Xe, ^{138}Xe	4×10^{11} - 4×10^{12} [10-100]
	Liquid and Solid	^{58}Co, ^{60}Co, ^{59}Fe, ^{51}Cr, ^{3}H	2×10^{12} - 4×10^{12} [50 - 100]
Waste Reprocessing	Gaseous	^{85}Kr, ^{133}Xe, ^{129}I, ^{131}I, ^{3}H	26×10^{13} [7×10^{3}]
	Liquid and Solid	Fission Products Pu, Am, Cm	22×10^{16} [6×10^{6}]

3.10. High-level Waste Reprocessing

Table 3.12 lists some of the most significant solid reprocessing high-level-waste nuclides [4]. These are usually produced from reactors (spent fuel), reprocessing activities, weapon production, and research activities. High level wastes are reprocessed in the same fashion as the reprocessing process described above by solvent extraction. Table 3.13 includes the typical composition of the liquid HLW from a LWR spent fuel.

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[11] Some of the waste is based on fuel that has been exposed 20,000 MWd/ton of U and others are based on fuel that has been further cooled for about 120 days.

Table 3.12. Radionuclides found in high level solid radioactive wastes

Radionuclide	Radiation	Half-live (years)
Fission Products		
Strontium-90	$	28
Technetium-99	$	2.1 x 10^5
Cesium-137	$, (	30
Transuranics		
Plutonium-238	"	89
Plutonium-239	"	2.4 x 10^4
Plutonium-240	", neutrons*	6.6 x 10^3
Americium-241	"	460
Americium-243	"	8.0 x 10^3
Curium-244	", neutrons*	18

* neutrons arise from spontaneous fissions.

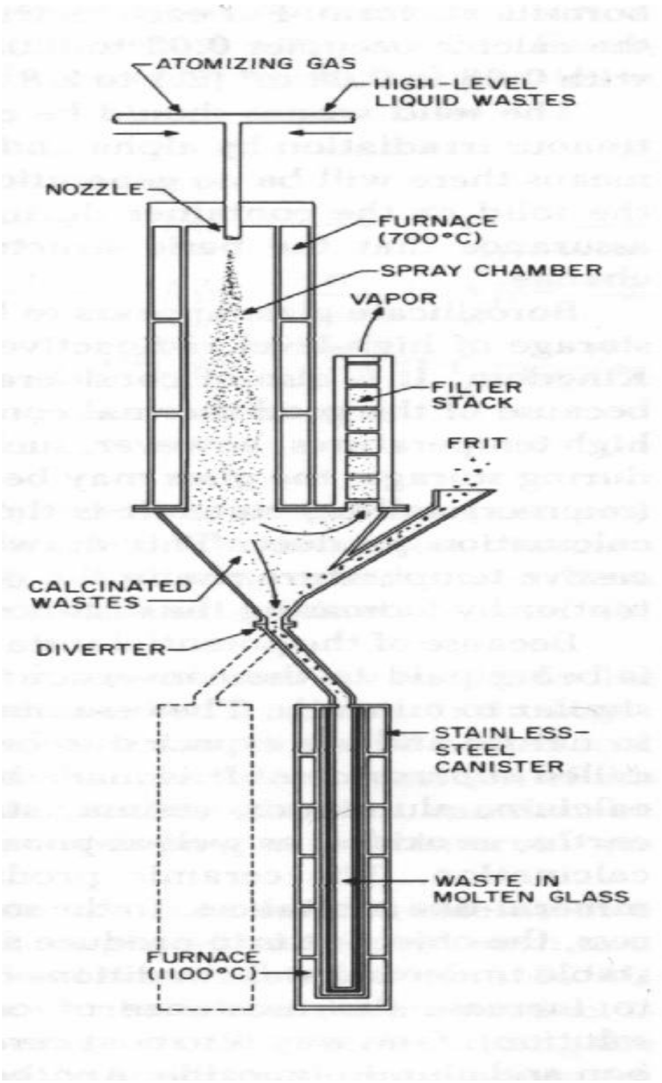
Table 3.13. Typical composition of high-level liquid waste from LWR fuel [11]

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 most common types of reprocessing are 1) drying and calcination, and 2) vitrification.In drying and calcination, the water is first removed, and the residual solid is heated to drive off volatile matter, producing calcine. If the high level solid wastes are to be stored in the calcine form, they must be heated to a temperature of about 900 ^{o}C (1650 ^{o}F) to cause complete decomposition of the nitrates. The high-temperature calcine, consisting mainly of oxides, can then be stored in sealed cylinders without the risk of developing a high internal gas pressure.

The two most common procedures used for drying and calcinating the concentrated high-level liquid reprocessing wastes are spray calcination and fluidized-bed calcination. Figure 3.29 represents spray calcination and vitrification of high level liquid radioactive wastes.

Figure 3.29. Spray calcination and vitrification of high-level liquid radioactive waste



In spray calcination, the liquid waste is sprayed through an atomizing nozzle into the tip of a cylindrical tower that is heated in a furnace. The walls of the cylinder are kept at a temperature of about 700 °C (1290 °F). As the spray descends, water is driven off the liquid droplets, and the resulting solid particles are calcinated. The product is collected in the stainless-steel canister at the bottom of the tower. Some of the powder is carried off with the vapors and gases generated during the drying and calcination phases.

In the fluidized-bed calcination process, the liquid waste is fed continuously into a calciner containing a bed of small nucleation particles, which may consist of the solid obtained by drying the waste. The bed is heated internally to 500 to 600 °C (930 to 1110 °C) by the combustion of kerosene in oxygen. A stream of air passing upward through the bed causes the particles to be "fluidized" so that they flow like a liquid. Contact between the hot particles and the incoming liquid waste causes drying and calcination to occur. Part of the calcine is deposited on the fluidized-bed particles, and part is in smaller particulate (or powder) form. Calcinated wastes can be retained in vented steel bins, and it is not necessary to decompose the nitrates completely by further heating. However, if the waste is to be stored in the calcine form it will be heated as mentioned above to cause the decomposition of nitrates. Alternatively, the calcine could be vitrified.

In the vitrification process, a glass forming frit, such as a mixture of borax and silica, is added to the calcinated waste (see Figure 3.29). The blend is heated to 1000 to 1100 °C (1830 to 2010 °F). Upon cooling, a glass-like (vitrified) borosilicate product is obtained. The canisters are then sealed for subsequent storage or permanent disposal. Storage at a vitrification plant is shown as an illustration in Figure 3.30.

Figure 3.30. Vitrification facility storage hall (COGEMA La Hague reprocessing plant, France)

The calcine (calcinated waste) from the calcination process contains a larger proportion of fission products and transuranic elements, and has a smaller total volume than the vitrified borosilicate form. Since the solid waste in the molten glass is not easily leachable, the radioactive material will be less likely to be dissolved in water than the calcinated waste, and escape to the environment.

Because of its good thermal conductivity and low leachability, borosilicate glass is the preferred form of solidification in many countries. At high temperatures, however, such as might develop from radioactive decay heat during storage, or in the event of a fire/explosion, the glass may become devitrified (change to a non-glassy, microcrystalline state). Therefore, it may become more leachable than the crystalline calcination product.

An alternative to vitrification, in which there is the potential instability of the product glasses to heat and radiation, is the conversion of high level wastes into ceramics, somewhat similar to minerals. These ceramics, formed at high temperatures, are crystalline in nature and expected to be stable. An example of this kind of ceramic waste product is called supercalcine, which is made by adding several different elements, including calcium, aluminum, cesium, strontium, molybdenum, zirconium, and rare earths, as oxides, as well as phosphate and silicate, to the liquid waste prior to calcination. This kind of ceramic material may contain as many as nine different mineral-like substances and should prove stable under natural conditions over geologic time with high resistance of ceramic particles to attack by water or salt solutions [5].

3.11. Disposal

There are three principles of radioactive waste disposal. These are 1) disperse and dilute, 2) concentrate and contain, and 3) delay and decay. These are followed throughout the nuclear fuel cycle and throughout the nuclear industry in general in order minimize the volume of the radioactive waste and its levels of radioactivity. Moreover, the ALARA (as low as reasonably achievable) principle influences the development of waste disposal plans.

Disposal of spent fuel, not destined for reprocessing, and the waste from reprocessing can be placed in repositories. A number of countries are carrying out studies to determine the optimum approach to the disposal of spent fuel and waste from reprocessing. The most commonly favored method for disposal being contemplated is placement into deep geological formations. An example of a repository or permanent disposal site is shown in Figure 3.31, a picture of the proposed radioactive waste disposal site at Yucca Mountain, Nevada.

Figure 3.31. A picture of the proposed radioactive waste disposal site at Yucca Mountain, Nevada

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 come in contact with 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 activity. The following figures are examples of the disposal of low and medium radioactive waste. Figure 3.32 is a cutaway of a low and medium level waste burial mound. In this example a mound covering 3,000 m^2 can accommodate 10,000 m^3 of waste packages. Its contents and its location in the mound identify each package. 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 observed to collect and monitor runoff. Figure 3.33 is a picture of a storage facility of low activity waste and Figure 3.34 is a picture of surface storage radioactive waste.

Figure 3.32. Cutaway of a low and medium waste burial mound (La Hague, France) [10]

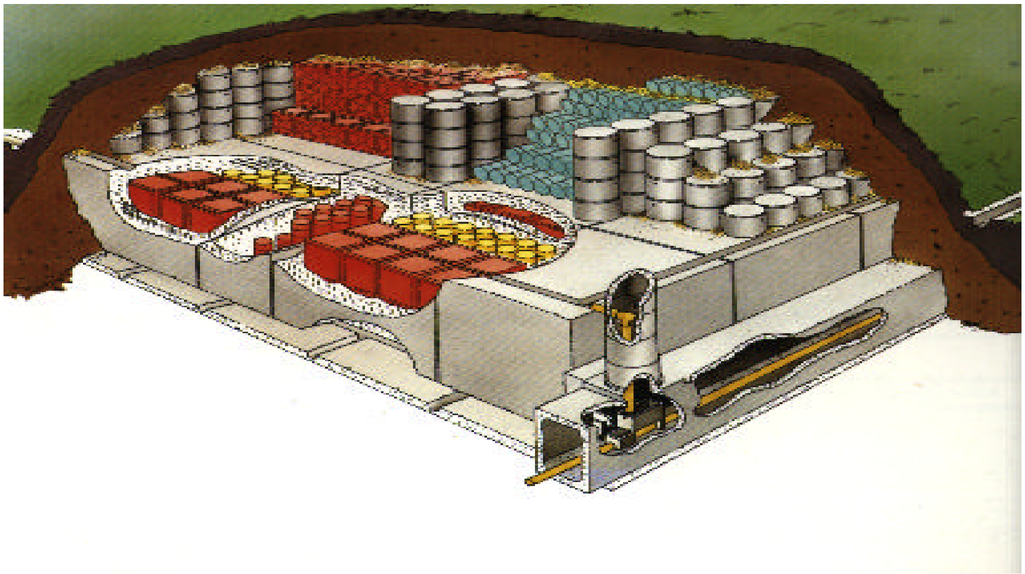


Figure 3.33. Storage of low activity waste (Asse mine, Germany)

Figure 3.34. Surface storage of radioactive waste (La Hague, France)

3.12. Summary of Radiation Sources from the Nuclear Fuel Cycle

The following table summarizes the sources addressed in this chapter throughout the entire fuel cycle.

Table 3.14. 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]	Precaution Level (Appendix A)
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)	", \$, γ	~1 E8 y	Gases ~1E7 [1E-3] Liquids and solids ~1E10 [1]	E-I
	^{238}U and its daughters (^{234}Th, ^{234}Pa, ^{234}U, ^{230}Th, ^{226}Ra, ^{222}Rn and its daughters)	", \$, γ	~1E9 y		E-I
	^{222}Rn and its daughters (^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po, ^{210}Pb, ^{210}Bi, ^{210}Po)	", \$, γ	21 y		E-I
Conversion	Same radionuclides as above. Radioisotopes are found in the conversion process and in the low-level waste.	", \$, γ	1E9 y	Gases ~1E7 [1E-3] Liquids and solids ~1E7 [1E-3]	E-I-U
Enrichment	Same radionuclides as above. Two main concerns are the enriched product containing ^{235}U and the depleted uranium (mostly ^{238}U) waste	", \$, γ	1E9 y	Gases ~1E7 [1E-3] Liquids and solids ~1E7 [1E-3]	E-I-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]	E-I
	Pu isotopes from the MOX fuel fabrication process, liquid waste and gases	α, β, γ, n	1E9 y		E-I-U

Process	Radionuclides	Radiation	Longest half-life	Approximate radioactivity level in Bq/ton U [Ci/ton U]	Precaution Level (Appendix A)
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, n	1E9 y	Gases ~1E12 [100] Liquids and solids ~1E12 [100]	X-E-I-U
	Fuel (core and spent fuel pool)				
	Same as above and mainly U and Pu isotopes, plus fission products and activation products	α, β, γ, n	1E9 y		X-E-I-U
	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		X-E-I-T
	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		X-E-I-T
	Neutron activation products (in systems, core components, reactor coolant system)				X-E-I
	Gases: ^{13}N, ^{16}N, ^{41}Ar	β, γ	2 hr		X-E-I
	Solids: ^{51}Cr, ^{54}Mg, ^{56}Mg, ^{58}Co, ^{60}Co, ^{59}Fe	β, γ	5.3 yr		X-E-I
Waste / Reprocessing	Most of radionuclides with longer half-lives	α, β, γ, n	1E9 y	Gases ~1E14 [1E3] Liquids and solids ~1E17 [1E6]	X-E-I-T

References:

1. Web: URL: http://www.uic.com.au/ : Uranium Information Centre, 1998.

2. Web: URL: http://www.uilondon.org/uihome.html, 1997.

3. Web: URL: http://www.uilondon.org/netpower.html, "Reactor status and the net power worldwide". London: Uranium Institute, 1998.

4. Bolch, E.W.: 1995 Radioactive Waste Management Lecture. . Gainesville, FL: University of Florida, 1995.

5. Schneider, K.J., and Platt, A.M.: Advanced Waste Management Studies, High-Level Radioactive Waste Management Alternatives. Richland, Washington: Battelle Pacific Northwest Laboratories, 1974.

6. Graves, H.W., Jr.: Nuclear Fuel Management. New York: John Wiley & Sons, 1979.

7. Cochran, R.G., and Tdoulfanidis, N.: The nuclear fuel cycle: analysis and management [Dissertation]. University of Florida; 1990.

8. Bolz, R.E., and Tuve, G.L.: CRC Handbook of tables for applied engineering science, 2nd Edition ed. Boca Raton, Florida: CRC Press, 1973. (Bolz, R.E., ed.)

9. Glasstone, S. and Jordan, W.H.: Nuclear Power and its Environmental Effects. La Grange Park, Illinois: American Nuclear Society, 1980.

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

11. Glasstone, S., Sesonske: Nuclear Reactor Engineering, Third Edition ed. New York: Van Nostrand Reinhold Co., 1981.

12. Evans, R.D.: The Atomic Nucleus, Original Edition ed. New York: McGraw-Hill, Inc., 1955.

13. NRC U: Final Genetic Statement on the Use of Recycled Plutonium in Mixed Oxide Fuel in Light Water-Cooled Reactors. Washington, DC: U.S. NRC, 1975.

14. ORNL, Finney BC: Correlation of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle - Nuclear Fuel Reprocessing. Oak Ridge, Tennessee: Oak Ridge National Laboratory, 1975.

15. Web: URL: http://www2.ijs.si/~icjt/npplist.html, 1997.

16. NRC U: Information Digest, NUREG-1350. Washington, DC: United States Nuclear Regulatory Commission, 1997.

17. DOE: Atoms to Electricity. Washington, DC: Department of Energy, 1987.

18. Lamarsh, J.R.: Introduction to Nuclear Engineering, 2nd Edition ed. Massachusetts: Addison-Wesley Publishing Company, 1983.

19. Eisenbud, M. and Gesell, R.: Environmental Radioactivity from Natural, Industrial and Military Sources, Fourth ed. New York: Academic Press, 1997.

20. Cember, H.: Introduction to Health Physics, Third ed. New York: MCGraw-Hill, 1996.

Chapter 4. Biomedical Sources

In addition to radiation sources from the nuclear fuel cycle, there are other sources of man-made radiation. The most common are sources used in the medical profession, including radiation from x-rays used for diagnosing or the treatment of patients, radioactive materials administered to patients in liquid or gaseous form, and treatments for cancer therapy. Biomedical sources of radiation are readily available at hospitals and some laboratories, which could present a hazard if exposure to individuals occurs or if they are dispersed to the surroundings. Examples of potential sources are the release of radionuclides from a nuclear medicine department due to a fire and the explosion of a source with the terrorist intention of dispersing it to the environment.

Medical facilities and irradiators may use large sources, which are made safe meeting appropriate shielding conditions. During hostile conditions such as a battle or an action of sabotage, shielding of such facilities may be breached and environmental release or exposure to personnel may be inevitable.

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

Looking at the medical uses of radiation one can identify many sources of possible radiation exposure. Radiation exposure can arise in the medical environment from materials (radionuclides) that spontaneously produce radiation, or from devices that produce x-rays, or radiation such as high-energy electrons, or from neutrons associated with high-energy photon beams. Radionuclides used in medicine are found as sealed or unsealed sources.[12] One can find unsealed sources in several locations within a hospital. These are in the 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 of radionuclides for therapeutic uses may also be found in the departments of endocrinology or radiation therapy. Relatively large doses are used for treatment of various pathological conditions.

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, such as injections of radioactive materials. Therapy is primarily the treatment of cancer. Therapy includes radiation from radiation-producing equipment, such as linear accelerators, other medical accelerators, radioisotope-generating machines, and radiation from brachytherapy sources.

4.2. Sources from Diagnostic Radiology

Radiation-producing devices produce x-rays by accelerating electrons through an electrical voltage potential and stopping them at a target. Many devices that use a high voltage and a source of electrons produce x-rays as an unwanted byproduct of device operation. These are

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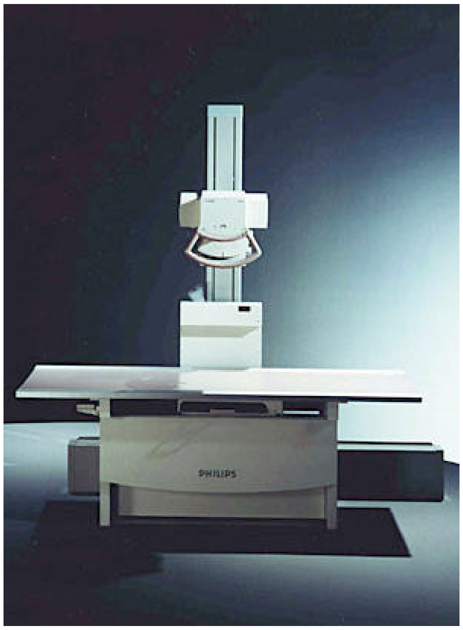
[12] A sealed source is defined as a source that contains radioactive material bonded or fixed in a capsule or matrix designed to prevent release and dispersal of the radioactive material under the most severe conditions, which are likely to be encountered in normal use and handling. The contrary applies to an unsealed source, which is a source that is not bonded.

called incidental x-rays (see section 4.2.4). Most x-ray devices emit electrons from a cathode, accelerate them with a voltage, and allow them to hit an anode, which emits x-ray photons.

4.2.1. X-ray Units

X-ray units are designed to produce x-rays when the exposure switch is engaged. As soon as the switch is released, or the pre-set exposure time is reached, x-ray production ends. Unless the equipment is operational at the moment of possible exposure, these machines present no potential harm to soldiers. However, it is important to be able to identify this type of equipment as they can be recognized as possible radiation sources. Figure 4.1 is a picture of an x-ray unit in a buckey table setting.

Figure 4.1. Picture of a typical x-ray unit and buckey table system



Diagnostic x-ray studies are performed primarily in the radiology departments in hospitals. However, these are also performed in operating rooms, intensive care units, coronary care units, special care nurseries, cardiac catheterization laboratories, emergency departments and even patient’s rooms.

4.2.2. Computed Tomography

Computed tomography is a diagnostic procedure in which a cross-sectional x-ray picture of a "slice" of the body is made. For this procedure, the patient lies still on a table, the x-ray machine rotates around the patient, and the table is moved horizontally, thus making it possible to take x-rays from several angles. The length of the procedure depends on the areas to be x-rayed. Sometimes a contrast material such as iodine is injected into the patient's vein; as a result, images produced during the procedure are sharply defined.

A computer then processes images from these x-rays. The final image, called a composite picture, is displayed on a cathode-ray tube (CRT), a device similar to a television picture tube and screen. This image can be recorded permanently on film. In addition, a CT scan can be stored on magnetic tape or disk.

Modern CT scanners use narrow x-ray beams that concentrate directly on the area or organs under study. Therefore, the amount of radiation received during a CT scan is minimized. As with regular x-ray units, CT scanners do not present a hazard unless they are operational, the soldier has no knowledge of its current maneuvering, and no shielding or distance is being applied. Figure 4.2 is a picture of a CT unit.

Figure 4.2. Picture of a CT Unit

4.2.3. Fluoroscopy

Fluoroscopy is the branch of diagnostic radiology that combines an x-ray unit and an image intensifier. Fluoroscopy allows the view on a screen of procedures, such as catheter placement and other diagnostic procedures, as they are being performed.

The image intensifier is an evacuated glass tube that contains four basic elements:
1.) the input phosphor or photocathode,
2.) the electrostatic focusing lens,
3.) an accelerating anode, and
4.) the output phosphor.

The x-ray beam passes through the patient and enters the intensifier tube. A fluorescent screen absorbs x-ray photons and converts the energy to light photons. The light photons strike the photocathode emitting photoelectrons. Because of the potential difference, the electrons are drawn from the cathode to the anode. These electrons are guided by electrostatic lenses that cause them to strike the output screen. Light photons are emitted which can then produce an image that can be observed. The output screen is attached to a viewing system of closed circuit televisions. This television/monitor system enables the radiologist to observe the fluoroscopic procedure [1]. Modern fluoroscopy allows for recording and computerized images. As in the case of plain-film x-rays (common x-ray exams) and CT scanners, fluoroscopy units are not a radiological hazard unless they are operational and the soldier is within the beam field of view (field irradiated).

4.2.4 Incidental Versus Intentional X-ray Devices

X-ray systems are divided into two broad categories: intentional and incidental. Table 4.1 defines the differences between these categories.

Table 4.1. Differences between incidental and intentional x-ray devices [2]

Type of x-ray device	Definition	Examples
Incidental	X-ray device produces x-rays that are not wanted or used as a part of the designed purpose of the machine. Shielding of an incidental x-ray device should preclude significant exposure.	computer monitors, televisions, electron microscopes, high-voltage electron guns, electron beam welding machines, electrostatic separators, and Jennings switches
Intentional	X-ray device that is designed to generate an x-ray beam for a particular use. Intentional x-ray devices are further divided into two subcategories: Analytical, and industrial.	x-ray diffraction, fluorescence analysis systems, flash x-ray systems, medical x-ray machines, industrial cabinet, and non-cabinet x-ray units

X-ray device related accidents occurred when proper procedures have not been followed during normal operations. Accidents can be precluded by simply having the devices turned off.[13] In the event that these are to be on, the three basic ways to reduce external doses (minimize time, maximize distance and shielding) can be applied. Lead, concrete, and steel are effective in shielding against x-rays.

4.3. Sources in Nuclear Medicine

Nuclear medicine is the branch of medicine that uses radiation from radioactive materials introduced in the body. This is done 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, such as x-rays, CT and fluoroscopy. Nuclear medicine uses radioactive materials, or radiopharmaceuticals, to diagnose and treat disease.

Tracers are used in nuclear medicine in the form of radiopharmaceuticals, which are attracted to specific organs, bones, or tissues. When radiopharmaceuticals are introduced into the body, they produce emissions. A special type of camera, a gamma or PET (positron emission tomography) camera, or a SPECT (single photon emission computed tomography) camera, is used to

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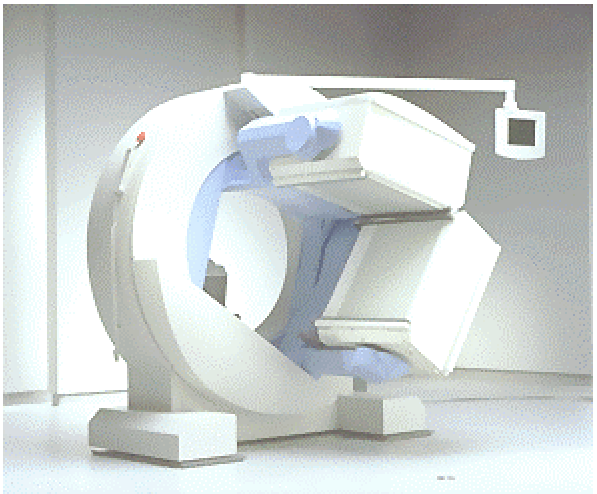
[13] Making sure that the device is not on should be the first immediate response to avoid possible exposure.

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 [3]. The gamma camera is not a source of radiation itself, unless it is contaminated with a radiopharmaceutical. However, since contamination of equipment is possible and gamma cameras are found in the proximity of radiopharmaceuticals and their generators, a pictorial representation is included below.

Figure 4.3. Gamma camera with dual head system



Most nuclear medicine tomography is performed with Anger camera systems having one to three detector heads mounted on a gantry to allow rotation around the patient for 180^o to 360^o angular sampling. These systems typically have an on-line computer and display system and permit the user to choose the display grid and reconstruction filter. The equipment itself is not a source unless it is contaminated. Figure 4.4 is a pictorial representation of a SPECT gamma camera and it is included in order to announce its possible proximity to radionuclides used in nuclear medicine. As the camera rotates about the patient, completing an arc of 180^o - 360^o, two-dimensional images are obtained at each scanning angle. Scan profiles from these projection images are used as input for the reconstruction algorithm to compute a tomographic image.

Figure 4.4. Picture of a SPECT gamma camera

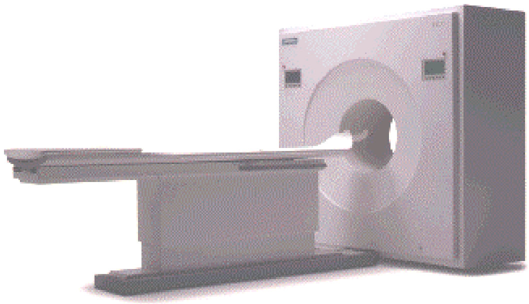


Figure 4.5 is a pictorial representation of a SPECT gamma camera (ORBITER), which provides positioning flexibility for most types of nuclear medicine procedures. Cardiac SPECT applications are commonly done with this type of camera.

Figure 4.5. Picture of an "ORBITER" SPECT gamma camera

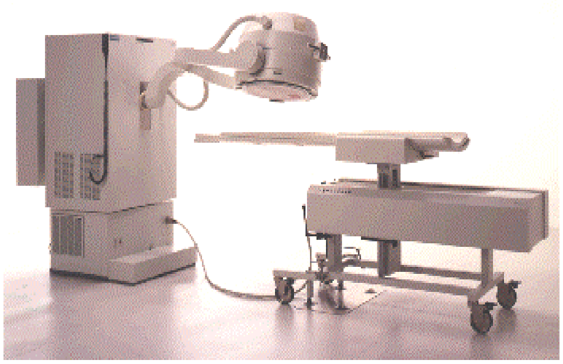
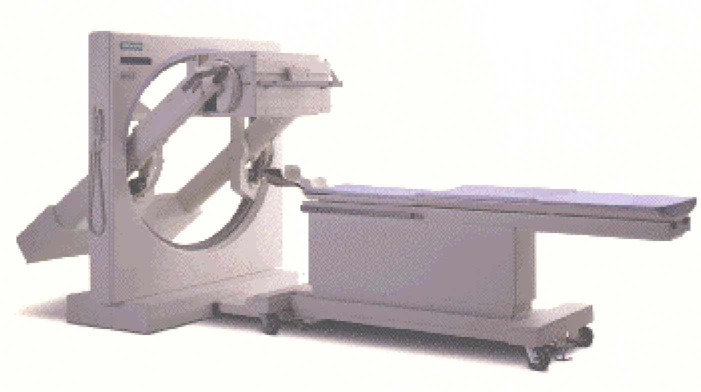


Figure 4.6 is an open system designed for whole body imaging procedures. This system is called the DIACAM system and it offers unique, energy-independent detector technology and a full range of collimation for higher image quality.

Figure 4.6. Picture of a DIACAM gamma camera



Computer image reconstruction techniques can be categorized as those based on ordinary gamma-ray emitters, for SPECT systems, and those based on annihilation photons from positron emitters, for PET systems. The fundamental physical difference between PET and SPECT is that PET uses an annihilation coincidence detector (ACD) system in the detection process. ACD is based on the fact that two 511 keV photons are emitted in opposite directions following the annihilation of a positron and an ordinary electron. Two detectors, oriented at 180° to each other are used to detect these photons. A coincidence circuit records only those pairs of events that are detected within a narrow time interval that is determined by the resolving time of the detectors and their associated electronics (typically 5-20 nanoseconds). Figure 4.7 is a picture of an actual PET scanner (ECAT scanner by Siemens).

Figure 4.7. A PET scanner unit

4.3.1. The Use of Radioisotopes in Nuclear Medicine

Nuclear techniques are used in every branch of medicine and especially in diagnosis. These procedures usually use isotopes to test the body basic functions. 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 it accumulates. For this reason, there are large numbers of specially developed isotopes for very specific diagnostic/imaging tasks.

Radioisotopes are also used in nuclear medicine in cancer treatment. In such treatment, the radiation is used very 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, just like medicine involving drugs or chemicals, generates some wastes, both in the process of making radioactive isotopes and in treating patients. That waste is no different from wastes from any other application of nuclear science and technology and it 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 4.2 lists these isotopes and includes their half-life, type of radiation, and application in the medical field, as well as their precaution levels (see Appendix A). 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. Fluorine-18 is becoming popular among the radionuclides used in nuclear medicine in the U.S. and other most commonly used are ^{57}Co, ^{58}Co, ^{51}Cr and ^{59}Fe. Table 4.2 also includes radioisotopes used in radiation therapy procedures, quality control and biomedical research.

Table 4.2. List of commonly used radionuclides in nuclear medicine, radiation therapy and biomedical research

Nuclide	Half-life	Radiation types	Application	Precaution level
^{26}Al	7.4E+5 y	\$+, γ (Mg x-rays)	QC	X-E-I
^{70}As	52.6 min	\$+, γ (Ge x-rays)	PET studies	X-E-I
^{71}As	65.28 hr	\$+, γ (Ge x-rays)	PET studies	X-E-I
^{74}As	17.77 d	\$+, \$-, γ (Ge x-rays)	PET studies	X-E-I
^{241}Am	458 y	", γ (Np L x-rays)	QC, osteoporosis detection, heart imaging	X-E-I
^{195}Au	183 d	γ (Pt x-rays)	Biomedical research	X-E-I
^{195m}Au	30.6 s	γ (Au x-rays)	Biomedical research	X-E-I
^{198}Au	2.7 d	\$-, γ	Brachytherapy	X-E-I
^{133}Ba	10.5 y	γ (Cs x-rays)	QC	X-I
^{75}Br	1.7 hr	\$+, γ (Se x-rays)	PET studies, SPECT, planar imaging	X-E-I
^{76}Br	16.2 hr	\$+, γ (Se x-rays)	PET studies	X-E-I
^{11}C	20.34 min	\$-, γ	PET studies, pain physiology and pathology, localization of epileptic focus, psychiatry and cardiology	X-E-I
^{14}C	5730 yr	\$-	Biomedical research, radiolabeling for detection of tumors	E-I
^{45}Ca	165 d	\$-	Biomedical research	E
^{47}Ca	4.56 d	\$-	Biomedical research	E
^{252}Cf	2.65 y	", γ (Cm L x-rays)	Radiation therapy, therapy for cervical cancer, melanoma, brain cancer treatment	X-I
^{55}Co	18 hr	\$+, γ (Fe x-rays)	PET studies, SPECT, planar imaging	X-I
^{57}Co	270 d	γ	QC, tracer to diagnose pernicious anemia	X-I
^{58}Co	71.3 d	\$+, γ (Fe x-rays)	QC, biomedical research	X-I
^{60}Co	5.26 y	\$-, γ	QC, therapy, biomedical research, sterilization of surgical instrumentation	X-E-I
^{51}Cr	28 d	γ	Red blood cells labeling, quantification of gastrointestinal protein loss, biomedical research	X-I
^{137}Cs	30 yr	\$-, γ	Radiation therapy, calibration studies, QC, blood irradiators	X-E-I
^{61}Cu	3.33 hr	\$+, γ	PET studies, SPECT	X-I

Nuclide	Half-life	Radiation types	Application	Precaution level
^{62}Cu	9.74 min	$+, γ	Cardiac perfusion studies, other cerebral studies	X-I
^{64}Cu	12.80 hr	$-, $+, γ	Genetic diseases affecting copper metabolism (Wilson's & Menke's diseases), other biomedical studies	X-E-I
^{67}Cu	58.5 h	$-, γ (Zn x-rays)	Radiation therapy, monoclonal antibodies	E-I
^{18}F	1.83 hr	$+, γ	PET studies for brain physiology and pathology, for localizing epileptic focus, psychiatry and neuropharmacology studies	X-I
^{52}Fe	8.2 hr	$+, γ	Used in PET studies and whole body imaging	X-I
^{55}Fe	2.6 y	γ (Mn x-rays)	Metabolic research, heat source	X-I
^{59}Fe	45.6 d	$-, γ	Ferrokinetic studies of iron metabolism (spleen), biomedical research	X-E-I
^{67}Ga	79.2 h	γ	Tumor imaging and localization of inflammatory lesions (infections)	X-I
^{68}Ga	68 min	$+, γ	PET studies, imaging of infection sites, study of thrombosis and arteriosclerosis	X-I
^{68}Ge	275 d	γ (Ga x-rays)	PET imaging, QC in nuclear medicine	X-I
^{3}H	12.3 yr	$-	D-T generators, Biomedical research and metabolic studies	E-T
^{166}Ho	1.2 d	$-, γ (Er x-rays)	Radiation therapy (intraarticular radiation synovectry)	X-E-I
^{120}I	81.0 min	$+, γ (Te x-rays)	PET studies	X-I
^{122}I	3.63 min	$+, γ (Te x-rays)	PET studies, brain blood flow studies	X-I
^{123}I	13.3 h	$+, γ	Diagnosis of thyroid function, brain, kidney and myocardial imaging	X-I
^{124}I	4.15 d	γ (Te x-rays)	PET studies, radiotracer used to create images of human thyroid	X-I
^{125}I	60 d	γ (X-rays)	Glomerular filtration rate of kidneys, deep vain thrombosis in the leg, radioimmuno assays, as an x-ray source for bone density measurements, brachytherapy and biomedical research	X-I
^{129}I	2.12 h	$+, γ (Te x-rays)	QC, check of radioactivity counters in labs	X-I
^{131}I	8.05 d	$-, γ	Thyroid functional imaging, thyroid therapy, liver function, renal (kidney) blood flow and urinary tract obstruction studies, biomedical research	X-E-I

Nuclide	Half-life	Radiation types	Application	Precaution level
^{110}In	4.9 hr	Weak β+, γ (Cd x-rays)	PET studies, detection of heart transplant rejection, antibody labeling	X-I
^{111}In	2.83 d	γ	Brain studies, infection and colon transit studies	X-I
^{113m}In	100 min	γ	Nuclear medicine, biomedical research	X-I
^{192}Ir	74.2 d	β-, γ	Brachytherapy	X-E-I
^{42}K	12.36 hr	β-, γ	Exchangeable potassium in coronary blood flow	X-E-I
^{77}Kr	1.19 hr	γ (Br x-ray, (γ w/ ^{77m}Br)	Blood flow studies	X-I
^{81m}Kr	13 s	γ	Pulmonary ventilation, lung imaging	X-I
^{85m}Kr	4.4 hr	β-, γ	Blood flow studies	X-E-I
^{99}Mo	67 hr	β-, γ	Generation of technetium 99m	X-E-I
^{13}N	9.9 min	β+, γ	PET studies for brain physiology and pathology, for localizing epileptic focus, psychiatry and neuropharmacology studies	X-I
^{22}Na	2.62 y	β+, γ (Ne x-rays)	QC in nuclear medicine	X-I
^{24}Na	14.96 hr	β-, γ	Electrolyte studies within the body	X-E-I
^{15}O	2.05 min	β+, γ	PET studies for brain physiology and pathology, for localizing epileptic focus, psychiatry and neuropharmacology studies, SPECT	X-I
^{32}P	14.3 d	β-	Treatment of polycythemia rubra vera (excess red blood cells)	E-I
^{33}P	24.4 d	β-	Molecular biology and generic research, labeling	E-I
^{103}Pd	17.0 d	γ (Rh x-rays)	Brachytherapy	X-I
^{226}Ra	1602 y	α, γ (Rn x-rays)	Brachytherapy, target isotope to make ^{227}Ac, ^{228}Th, ^{229}Th	X-I
^{81}Rb	4.7 h	β+, γ (Kr x-rays)	Pulmonary ventilation	X-I
^{82}Rb	75 sec	β+, γ	Myocardial perfusion imaging	X-I
^{186}Re	88.9 h	β-, γ	Palliation treatment, biomedical research	X-E-I
^{222}Rn	3.83 d	α, γ	Biomedical research	I
^{35}S	87.9 d	β-	Radiation therapy, biomedical research, nuclei acid labeling ^{32}P replacement, cellular dosimetry	E-I
^{75}Se	120.4 d	γ (As x-rays)	Formation of selenomethionine to study production of digestive enzymes, radiotracer used in biomedical research	X-E-I

Nuclide	Half-life	Radiation types	Application	Precaution level
^{142}Sm	72.5 min	$+, γ (Pm x-rays)	Tracer used in therapy	X-I
^{153}Sm	1.9 d	$-, γ	Palliation treatment	X-E-I
^{113}Sn	120 d	γ (In x-rays)	Generation of ^{113m}In	X-I
^{83}Sr	32.4 hr	$+, γ (Rb x-rays)	Tracer used in therapy	X-I
^{85}Sr	64 d	γ (Rb x-rays)	Bone formation and metabolic studies, brain scans	X-I
^{89}Sr	52 d	$-	Bone treatment, biomedical research	E-I
^{99m}Tc	6.02 h	γ	Most commonly used radionuclide in nuclear medicine, use 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.	X
^{201}Tl	74 h	γ (Hg X-rays)	Myocardial perfusion imaging, for diagnosis and location of myocardial infarction (heart muscle death)	X-I
^{234}U	2.47E5 y	", γ (Th L x-rays & daughter radiations)	Used in dental fixture	I-U
^{122}Xe	20.1 hr	γ (I x-rays)	PET studies	X-I
^{127}Xe	36.4 d	γ	Pulmonary ventilation studies	X-I
^{133}Xe	5.3 d	$-, γ	Pulmonary ventilation studies, SPECT imaging of brain	X-E-I
^{86}Y	14.7 hr	$+, γ (Sr x-rays)	PET studies	X-I
^{169}Yb	31.8 d	γ (Tm L x-ray, K x-ray)	Cerebrospinal fluid studies, gastrointestinal tract diagnosis	X-I
^{62}Zn	9.13 hr	$+, γ (Cu x-rays)	PET studies, production of ^{62}Cu	X-I
^{63}Zn	38.47 min	$+, γ (Cu x-rays)	PET studies	X-I
^{89}Zr	78.4 hr	$+, γ (Y x-rays)	PET studies	X-I

Most of the radioisotopes in the above table are isotopes produced in nuclear reactors or in atomic particle accelerators.

4.3.1.1. Reactor-produced Isotopes

Isotopes used in medicine can be byproducts of the fission reaction of ^{235}U. These include ^{133}Xe, ^{99}Mo, and ^{131}I and are produced in great quantity in nuclear reactors. The nuclear power industry considers these waste products; however, once they have been purified adequately, they are perfectly suitable for human use. Many other isotopes, which have commercial value, are produced in the nuclear reactors.

4.3.1.2. 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 E.

4.3.1.3. Radioisotope Generators [3]

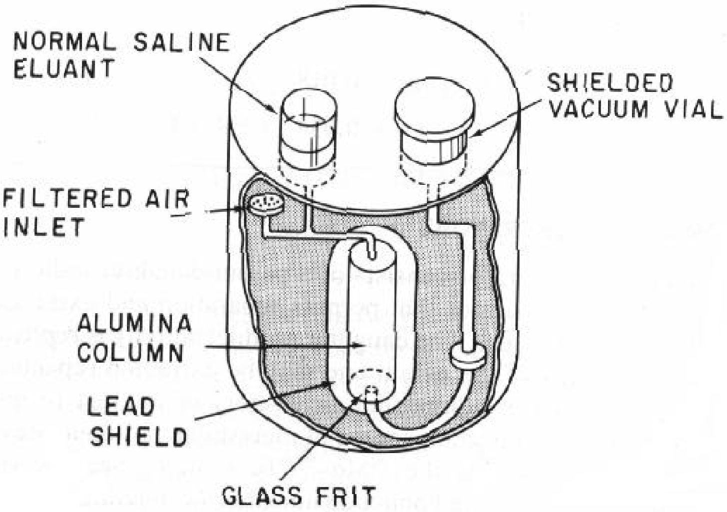
A generator is a self-contained system housing a parent/daughter mixture in equilibrium, which is designed to yield the daughter for some purpose by separating it from the parent. The principal utility is to produce certain radioisotopes (on-site) which, because of their short half-lives, cannot be shipped 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. Generators and the radioisotopes they use or produce are potential sources of radiation exposure or contamination. The following table includes some of the common radionuclide generators used in nuclear medicine.

Table 4.3. Common radionuclide generators used in nuclear medicine

Daughter	Decay Mode	Half-life	Parent	Half-life
^{68}Ga	\$+, EC	68 min	^{68}Ge	275 days
^{82}Rb	\$+, EC	1.3 min	^{82}Sr	25 days
^{87m}Sr	IT	2.8 hr	^{87}Y	80 hr
^{99m}Tc	IT	6 hr	^{99}Mo	66 hr
^{113m}In	IT	100 min	^{113}Sn	120 days

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 an Anger 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 agents. Figure 4.8 is a schematically representation of a ^{99}Mo - ^{99m}Tc generator. The ^{99}Mo activity in the form of molybdate ion, MoO$_4$, and is bound to an alumina (Al$_2$O$_3$) column. The ^{99m}Tc is chemically different; its activity is not bound by the alumina, and is eluted from the column with 5-25 ml of normal saline solution. Of the available ^{99m}Tc activity, 75-85 percent 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 that are commercially available are sterilized, well shielded and largely automated in operations. They are typically used for about one week and then discarded because of the natural decay of the ^{99}Mo [3].

Figure 4.8. Cross-sectional drawing of a ^{99}Mo-^{99m}Tc generator



4.3.2. Radiopharmaceuticals

Radio-pharmacological products or radiopharmaceuticals are molecules labeled (marked) with radioisotopes which, using their emitted radiation, are useful for medical diagnosis and therapy. Radiopharmaceuticals are radioactive drugs that, when used for the purpose of diagnosis or therapy, 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.

There is a significant difference between a radioisotope (a radionuclide whose chemical form is unknown) and a radiopharmaceutical whose chemical form is usually precisely known. For example, ^{123}I is a radioisotope with a characteristic physical half-life. Reference to a biological half-life or an effective half-life for ^{123}I is meaningless, since the chemical form is unknown. On the other hand, Na^{123}I is a compound with known biodistribution and clearance rates and is associated with both biological and effective half-lives.

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 4.4.

Table 4.4. Types of radiopharmaceuticals

Pharmaceutical type	Example
Prepared Products	^{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

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

4.4. 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.

Linear accelerators produce high-energy x-rays and/or high-energy electron beams. Like x-ray machines, these units do not produce a beam unless energized; therefore, there is minimal risk of radiation exposure to the soldiers encountering this type of equipment. However, equipment is identified in order to emphasize its lethal capabilities in the event they are operational and not controlled. Cutting the power supply will eliminate the continuous production of x-rays.

Rapidly dividing cells are particularly sensitive to damage by radiation. For this reason, some cancerous growths can be controlled or eliminated by irradiating the area containing the growth. This irradiation can be carried out using an external beam, for example a beam from a radioactive cobalt-60 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. This type of treatment is called brachytherapy.

Particle accelerators are used directly in radiation therapy or in the production of radioisotopes that are to be utilized in making radiopharmaceuticals. Appendix E includes a general introduction to particle accelerators and the possible radiations emanating from them.

4.4.1. 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. Commonly used radioisotopes were included in Table 4.2.

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, it is beta radiation that 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). Phosphorus-32 is used to control the excess of red blood cells produced in the bone marrow from a disease called Polycythemia vera [4].

4.4.2. Machines Using Radionuclides

Radionuclides such as ^{226}Ra, ^{137}Cs, and ^{60}Co have been used as sources of gamma rays for teletherapy[14]. These gamma rays are emitted from the radionuclides as they undergo radioactive disintegration. Of all the radionuclides, ^{60}Co has proved to be the most suitable and most commonly used for external beam radiotherapy. The reasons for its choice over radium and cesium are higher possible specific activity (curies per gram), greater radiation output per curie and higher average photon energy. Caution must be taken when handling teletherapy units because sources in the units may not be in the shielded position and may be a serious radiological hazard.

4.4.2.1. 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 [5].

Cobalt-60 beta decays to ^{60}Ni with the emission of beta particles (E_{max}=0.32 MeV) and two photons per disintegration of energies 1.17 and 1.33 MeV. These gamma rays constitute the useful treatment beam. The beta particles are absorbed in the cobalt metal and the stainless-steel capsules, resulting in the emission of bremsstrahlung x-rays and a small amount of characteristic x-rays. However, these x-rays of average energy around 0.1 MeV do not contribute appreciably to the dose in the source and the capsule. Other contaminants to the treatment beam are the lower-energy gamma rays produced by the interaction of the primary gamma radiation with the source itself, the surrounding capsule, the source housing, and the collimator system. The scattered components of the beam contribute about 10 percent to the total intensity of the beam [5].

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. Figure 4.9 is a picture of a cobalt-60 therapy unit.

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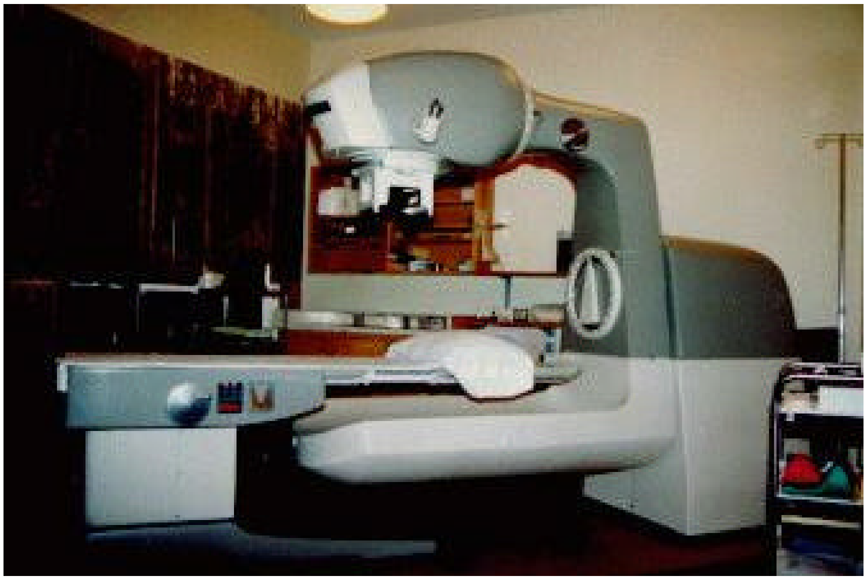
[14] Teletherapy is a general term applied to external beam treatments in which the source of radiation is at a large distance from the patients.

Figure 4.9. A Cobalt-60 therapy unit



4.4.2.2. 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 cobalt-60 sources[15] 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 [6]. The Gamma Knife has been successfully applied to various conditions, such as brain tumors, arteriovenous malformations (AVM)[16], and functional disorders. Figure 4.10 and 4.11 are pictures of a gamma knife unit and its helmet, which houses the cobalt-60.

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.

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[15] Information obtained from http://www.chw.edu/mha/Gamma/What.html

[16] Arteriovenous Malformations (AVMs) is the basic principle behind utilizing radiosurgery for vascular lesions is? radiation-induced injury to the walls of these abnormal vessels, causing a slow obliteration.

Figure 4.10. Picture of a Gamma Knife Unit [6]

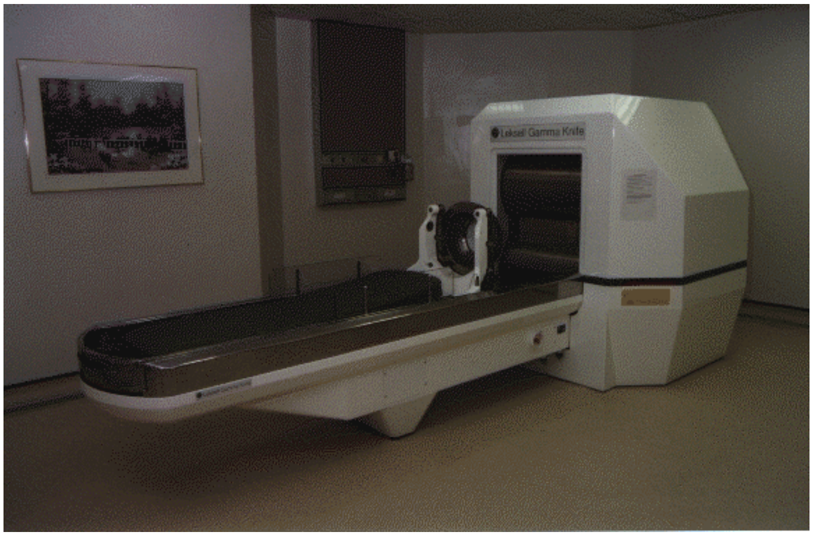
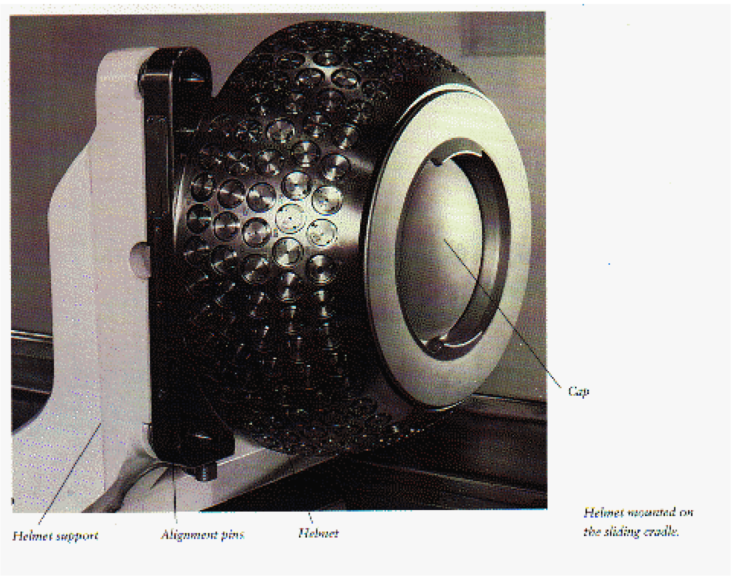


Figure 4.11. Close View of a Gamma Knife Helmet



4.4.3. Heavy Particle Beams

X-rays and electrons are the main radiation used in radiotherapy; however, heavy particle beams offer special advantages with regard to dose localization and therapeutic gain[17]. These particles include neutrons, protons, deuterons, alpha particles, negative pions[18], and heavy ions accelerated to high energies. Their use in radiotherapy is still experimental; however, one may find utilities that have acquired these modalities for clinical trials, and it is important to learn the risk associated with this type of equipment.

Deuterium-tritium (D-T) generators, cyclotrons, or linear accelerators produce high-energy neutron beams for radiotherapy. The bombarding particles are either deuterons or protons and the target material is usually beryllium, except in the D-T generator in which tritium is used as the target.

Neutrons are indirect ionizing, like x-rays and gamma rays, but interact with matter differently. In the elastic interactions (billiard ball type collisions), the energy is redistributed after the collision between the colliding particles. The energy transfer is very efficient if the colliding particles have the same mass, as it is in the case of a colliding neutron with a hydrogen nucleus. On the other hand, the neutron loses very little energy when colliding with a heavy nucleus. Thus, the most efficient absorbers of a neutron beam are the hydrogenous materials such as paraffin wax or polyethylene. Lead, which is a very good absorber for x-rays, is a poor shielding material against neutrons.

Dose deposited in tissue from a high-energy neutron beam is predominantly contributed by recoil protons. Because of the higher hydrogen content, the dose absorbed in fat exposed to a neutron beam is about 20% higher than in muscle. Nuclear disintegrations produced by neutrons result in the emission of heavy charged particles, neutrons, and gamma rays and give rise to about 30% of the tissue dose. Such diverse secondary radiation produced by neutron interactions complicates neutron dosimetry from clinical beams.

4.4.4. 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 sources are fabricated 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. In a permanent implant, sources of shorter half-lives are left permanently in the implanted tissues. Examples are ^{198}Au and ^{125}I seeds.

Intracavitary brachytherapy is mostly used for cancers of the uterine cervix, uterine body, and

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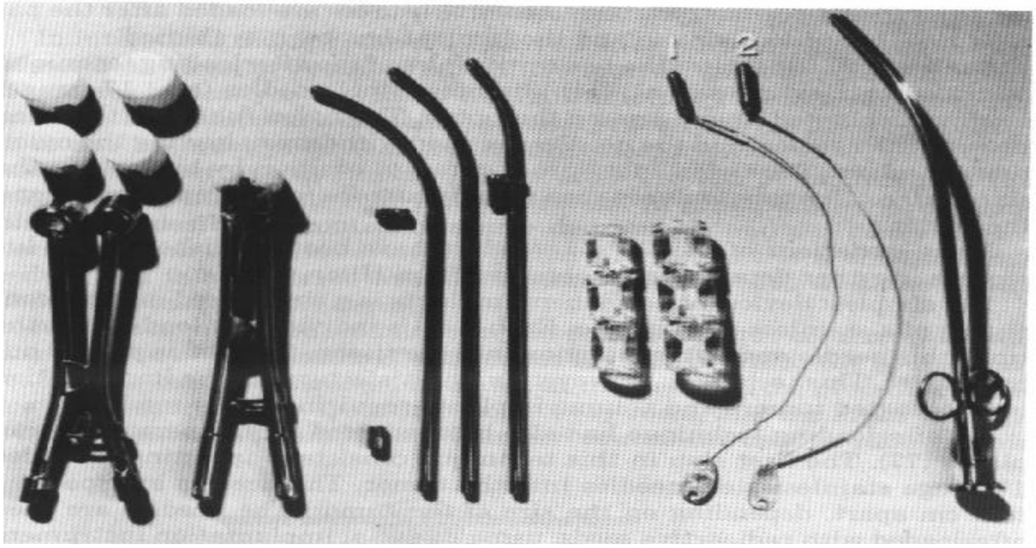
[17] Therapeutic gain refers to having a greater effect on tumor than on normal tissue.

[18] The existence of pi mesons was theoretically predicted by Yukawa in 1935, when he postulated that protons and neutrons in the nucleus are held together by a mutual exchange of pi mesons or "pions". A pion is 273 times more massive than an electron and may have positive or negative charge, or be neutral [5].

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. Figure 4.12 illustrates a Fletcher-Suit applicator set. The tandem and the ovoids are made of stainless steel and then secured to hollow handles to permit afterloading of the source [5].

Figure 4.12. The Fletcher-suit applicator set



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 rapidly increasing [7].

Artificial radioisotopes offer special advantage in some situations because of their gamma ray energy, source flexibility, source size, and half-life. Table 4.5 lists the most commonly used sources for brachytherapy with their relevant physical properties.

Table 4.5. Most common radionuclides used in brachytherapy

Radionuclide	Half-life	Photon Energy (MeV)	HVL (mm Lead)	Exposure rate constant, ' $[R\cdot cm^2/mCi\cdot hr]$
^{60}Co	5.26 years	1.17, 1.33	11.0	13.07†
^{103}Pd	17.0 days	0.021 avg.	0.008	1.48†
^{125}I	60.2 days	0.028 avg.	0.025	1.46†
^{137}Cs	30.0 years	0.662	5.5	3.26†
^{192}Ir	74.2 days	0.136 - 1.06 (0.38 avg.)	2.5	4.69†
^{198}Au	2.7 days	0.412	2.5	2.38†
^{222}Rn	3.83 days	0.047-2.45 (0.83 avg.)	8.0	10.15*
^{226}Ra	1600 years	0.047 - 2.45 (0.83 avg.)	8.0	8.25*‡ $R\cdot cm^2/mg\cdot hr$

* In equilibrium with daughter products
† Unfiltered
‡ Filtration by 0.5 mm Pt

4.4.4.1. Cobalt-60 Sources

Cobalt-60 is rarely used in brachytherapy, but it has been used for this purpose in the past. Sources of ^{60}Co are usually fabricated in the form of a wire that is encapsulated in a sheath of platinum, iridium, or stainless steel. The sources can be used to replace ^{226}Ra in intracavitary applications. Curie-sized cobalt sources have been used in a unit called the Cathetron. This is a remote-loading device and provides high-dose rates for intracavitary therapy.

4.4.4.2. Palladium-103 Sources

Palladium-103 seeds have recently become available for use in brachytherapy. Their clinical applications are similar to those of ^{125}I. Having a shorter half-life than ^{125}I, ^{103}Pd may provide a biological advantage in permanent implants as the dose is delivered at a much faster rate. Common ^{103}Pd seed models consist of laser-welded titanium tubes that contain two graphite pallets plated with ^{103}Pd[19].

4.4.4.3. Iodine-125 Sources

Iodine-125 has gained a wide use for permanent implants in radiotherapy [8]. Common seed models are designated 6701, 6702 and 6711 and manufactured[20] with identical size and encapsulation but different active source design. The earlier model 6701 is now obsolete. Figure 4.13 shows the most current seed designs. The encapsulation consists of a 0.05 mm thick titanium tube welded at both ends to form a cylindrical capsule of dimensions 4.5 x 0.8 mm. The model 6702 seed contains ion-exchange resin beds, which are impregnated with ^{125}I in the form of the iodine ion. The model 6711 seed contains a silver wire with the active material, silver iodine (AgI), adsorbed on its surface and can be radiographed to view seed position as well as

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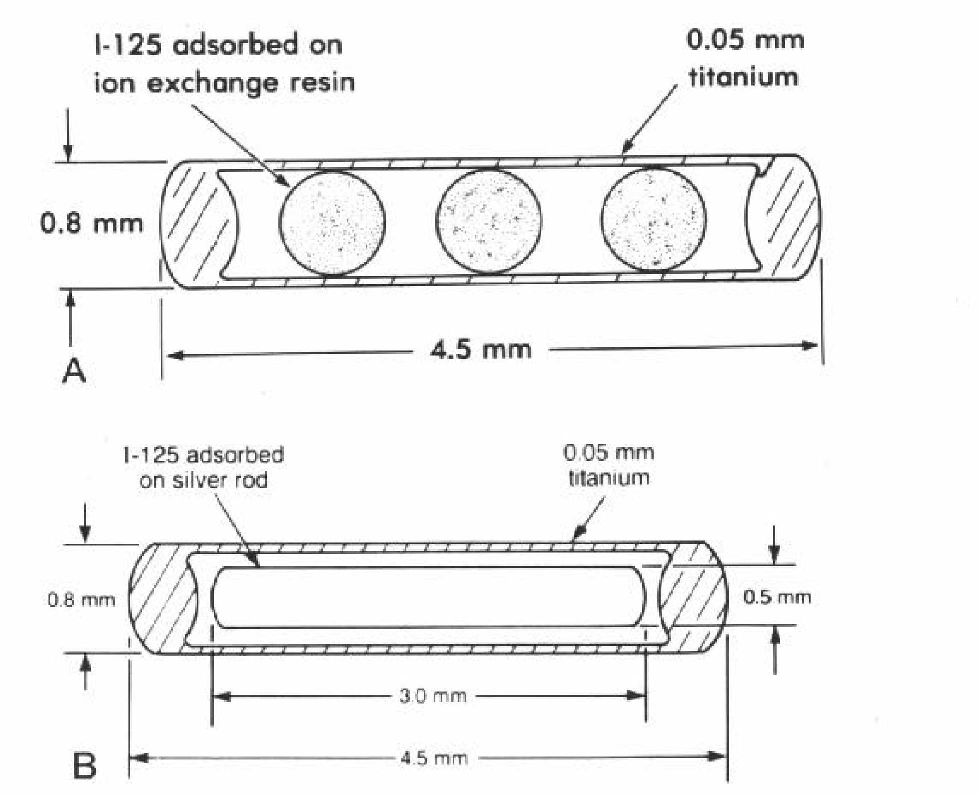
[19] An example is the model 200, manufactured by Theragenics Corp., Norcross, Georgia.

[20] Models 6701, 6702 and 6711 are manufactured by Medical Products Division/3M, New Brighton, Minnesota.

orientation.

Figure 4.13. Iodine-125 seeds Model 6702 (A) and Model 6711 (B)



Iodine-125 decays exclusively by electron capture to an excited state of ^{125}Te, which spontaneously decays to the ground state with the emission of a 35.5 keV photon. Characteristic x-rays in the range of 27 to 35 keV also are produced due to the electron capture and internal conversion processes. Titanium encapsulation serves to absorb liberated electrons and x-rays with energies less than 5 keV. Model 6711 emits two additional photons at 22.1 keV and 25.2 keV energies. These are fluorescent characteristic x-rays produced by the interaction of ^{125}I photons with the silver wire. The presence of titanium end welds causes the dose distribution around iodine seeds to be highly anisotropic.

4.4.4.4. Cesium-137 Sources

Cesium-137 is a gamma-emitting radioisotope that is used as a radium substitute in both interstitial and intracavitary brachytherapy. Cesium-137 is supplied in the form of insoluble powders or ceramic microspheres, labeled with ^{137}Cs, and doubly encapsulated in stainless-steel needles and tubes. These sources require less shielding than the radium sources and are less hazardous in the microsphere form. These sources can be used for about 7 years without a replacement, allowing for radioactive decay adjustment in the treatment planning.

Cesium-137 transforms to ^{137}Ba by $\$^-$ decay but 93.5% of the disintegrations are followed by gamma rays from the ^{137}Ba metastable state. The beta particles and low-energy characteristic x-rays are absorbed by the stainless-steel material, so that the clinical source is a pure gamma emitter.

The gamma rays from cesium have nearly the same penetrating power as radium gamma rays in tissue [7]. However, doses at oblique angles are different between cesium and radium sources. Not only is the attenuation of gamma rays in steel and platinum quite different, but also cesium emits monoenergetic gamma rays and radium emits gamma rays of a wide energy range [9].

4.4.4.5. Iridium-192 Sources

Iridium-192 sources used in brachytherapy are made of an alloy of 30% Ir and 70% Pt. They are fabricated in the form of thin flexible wires, which can be cut to the desired lengths. Nylon ribbons containing iridium seeds 3 mm long and 0.5 mm in diameter, spaced with their center 1 cm apart, are also commonly used. Both wires and seed ribbons are suitable for the afterloading technique. Sources can be used in non-permanent implants, similar to radium and cesium because the half-life is long compared with the average treatment time.

4.4.4.6. Gold-198 Sources

Gold-198 is used in seeds or “grains” for interstitial implants. They are used in the same way as radon seeds have been used for permanent implants. The beta rays of 0.96 MeV maximum energy are absorbed by the 0.1 mm thick platinum wall surrounding the seed. A gold seed is typically 2.5 mm long with an outer diameter of 0.8 mm. Because of its lower gamma ray energy, personnel protection problems with gold are easier to manage than those of radon. Moreover, radon seeds continue to exhibit low-level gamma activity for many years due to bremsstrahlung, arising from high-energy beta particles emitted by its long-lived daughter products.

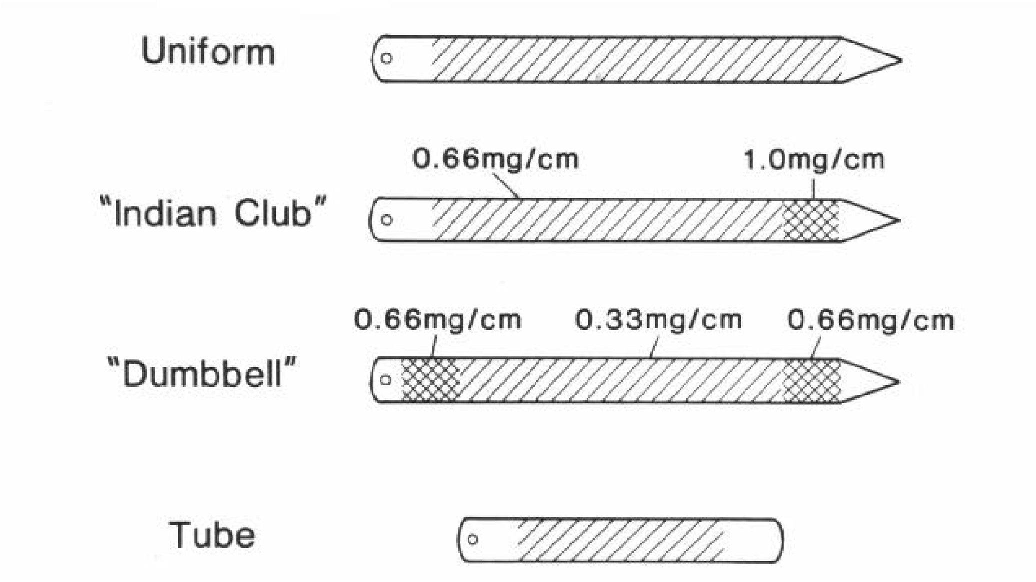
4.4.4.7. Radium and Radon Sources

Radium is a member of the uranium series. Radium disintegrates with a half-life of 1600 years to form radon, the inert gas that in turn disintegrates into its daughter products. The average energy of the gamma rays from radium in equilibrium with its daughter products and filtered by 0.5 mm of platinum is 0.83 MeV [10]. Filtration of 0.5 mm platinum is sufficient to absorb all the alpha particles and most of the beta particles emitted by radium and its daughter products. Only gamma rays are used for therapy.

Radium is placed in a sealed container, in which it achieves secular equilibrium with its daughter. The radium source used in brachytherapy uses mostly radium sulfate or radium chloride mixed with an inert filler and loaded into cells about 1 cm long and 1 mm in diameter. These cells are made of 0.1- to 0.2 mm thick gold foil and are sealed to prevent leakage. Radium sources are manufactured as needles or tubes in a variety of lengths and activities. Figure 4.14 illustrates the three types of radium sources used in interstitial and intracavitary therapy for implants. These are needles with uniform linear activity, needles with higher activity at one end (Indian club), and needles with high activity at both ends (dumbbell). Uniform linear activities needles may be "full intensity" (0.66 mg/cm) or "half-intensity" (0.33 mg/cm). Needles also are constructed with linear activities of 0.5 and 0.25 mg/cm. Tubes for intracavitary and mold therapy are usually furnished in multiples of 5 mg of radium filtered by 1mm platinum.

Leakage of radon gas from a radium source represents a significant hazard if the source is broken. The sources are, however, doubly encapsulated to prevent such an occurrence. Spontaneous rupture of a sealed radium source due to pressure buildup of helium gas (from alpha particle disintegration) is considered unlikely.

Figure 4.14. Illustration of different types of radium needles



Radon gas has been used in brachytherapy by sealing it into small hollow gold tubes that can be used instead of radium seeds. The gamma activity of radon may be the same as that of radium because radon is down the line in the radium's decay series and therefore, both radium and radon share daughters. Radon has become less popular because other isotopes are more convenient and less dangerous [11].

4.5. Summary of Biomedical Radiation Sources

Some of the most important radiation sources that are used in nuclear medicine, radiation therapy, and biomedical research are illustrated in Table 4.6.

Table 4.6. Summary of biomedical radiation sources and most commonly used radionuclides in nuclear medicine, radiation therapy and biomedical research

Source	Radiations	Half-life	Application	Precaution level
X-rays	(	n/a	X-ray equipment, CT, fluoroscopy, linear accelerator (Not a hazard, unless functional)	X
Nuclear Medicine equipment	All	n/a	Nuclear medicine diagnostic equipment, such as Gamma Cameras	X-E-I
Isotopic generators	All	n/a	Generators of radioisotopes to be used in nuclear medicine as radiopharmaceuticals; for example, the ^{99}Mo-^{99m}Tc generator	X-E-I
Therapy Units	(	n/a	Radiation therapy units, such as ^{60}Co or ^{137}Cs therapy units.	X
Brachytherapy Equipment	All	n/a	Equipment used in the application of brachytherapy	X-E-I
^{198}Au	$-, (	2.7 d	Brachytherapy	X-E-I
^{18}F	$+, (	1.83 hr	PET studies for brain physiology and pathology, for localizing epileptic focus, psychiatry and neuropharmacology studies	X-I
^{67}Ga	(	79.2 h	Tumor imaging and localization of inflammatory lesions (infections)	X-I
^{123}I	$+, (	13.3 h	Diagnosis of thyroid function, brain, kidney and myocardial imaging	X-I
^{125}I	(	60 d	Glomerular filtration rate of kidneys, deep vain thrombosis in the leg, radioimmunoassays, as an x-ray source for bone density measurements, brachytherapy and biomedical research	X-I
^{131}I	$-, (	8.05 d	Thyroid functional imaging, thyroid therapy, liver function, renal (kidney) blood flow and urinary tract obstruction studies, biomedical research	X-E-I
^{111}In	(	2.83 d	Brain studies, infection and colon transit studies	X-I
^{99}Mo	$-, (	67 hr	Generation of technetium 99m	X-E-I
^{32}P	$-	14.3 d	Treatment of polycythemia rubra vera (excess red blood cells)	E-I
^{226}Ra	", (Rn x-rays)	1602 E	Brachytherapy, target isotope to make ^{227}Ac, ^{228}Th, ^{229}Th	X-I
^{99m}Tc	(	6.02 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.	X
^{201}Tl	(	74 h	Myocardial perfusion imaging, for diagnosis and location of myocardial infarction (heart muscle death)	X-I
^{192}Ir	$-, (	74.2 d	PET studies	X-I
^{127}Xe	γ	36.4 d	Pulmonary ventilation studies	X-I
^{133}Xe	$-, γ	5.3 d	Pulmonary ventilation studies, brain SPECT	X-E-I

References:

1. Rollo, F.D.and Richardson, R.L.*: Basic electronics. Basic science principles in nuclear medicine*. St. Louis, Missouri: C. V. Mosby Co., 1977.

2. Web: URL: http://www.chw.edu/mha/Gamma, 1997.

3. Sorenson, J.A.and Phelps, M.E.: *Physics in Nuclear Medicine*, 2nd ed. Philadelphia: W.B. Sounders Company, 1987.

4. Quimby, E.H., Feitelberg, S.and Gross, W.: *Radioactive nuclides in medicine and biology*, 3rd ed. Philadelphia, Pennsylvania: Lea & Febiger, 1970.

5. Khan, F.M.: *The Physics of Radiation Therapy*, 2nd ed. Baltimore: Williams & Wilkins, 1984.

6. Web: URL: http://www.gammaknife.com.sg/technica.htm, 1997.

7. Meisberger, L.L., Keller, R.J.and Shalek, R.J.: The effective attenuation in water of gamma rays of gold 198, iridium 192, cesium 137, radium 226,and cobalt 60. *Radiology* 1968; 90(953).

8. Hilaris, B.S.: *Handbook of interstitial brachytherapy*. Acton, Massachusetts: Publishing Science Group, 1975.

9. Krishnaswamy, V.: Dose distribution about 137Cs sources in tissue. *Radiology* 1972; 90(953).

10. Attix, F.A.: *Introduction to radiological physics and radiation dosimetry*. New York: John Wiley & Sons, 1986.

11. Johns, H.E.and Cunningham, J.R.: *The Physics of Radiology*, 4th ed. Springfield, Illinois: Charles C. Thomas Publishers, 1983.

Chapter 5. Sources of Radiation from Army Commodities and Foreign Materiel

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 their threat.

Table 5.1 indicates all of the 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 TB 43-0116, Identification of Radioactive Items in the Army, as well as AST-1500Z-100-93, Identification Guide for Radioactive Sources in Foreign Materiel [1, 2]. The TB includes item 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. Section 5.2 summarizes these sources.

Table 5.1. Army radioactive commodities, major radiation energies, and main progeny

Isotope	Half-life	Major Radiation E (MeV) and (Intensity%)	Main Progeny	Half-life	Major Radiation E (MeV) and (Intensity%)	Use of Materiel
^{3}H	12.3y	$\$^{-}$, 0.0186	^{3}He	stable	N/A	Meter faces, dials, compasses, watches, collimators, telescopes, fire control devices, rifle sights, radioluminous devices
^{14}C	5730y	$\$^{-}$, 0.156	^{14}N	stable	N/A	Source
^{60}Co	5.258y	$\$^{-}$, 1.55(0.12),0.314	^{60}Ni	stable	N/A	Wave tube, spark gap, surge arr., omni wave, calibration source, rad calib
^{63}Ni	92y	$\$^{-}$, 0.0659	^{63}Cu	stable	N/A	CAM, expl. Detonator
^{85}Kr	10.76y	$\$^{-}$, 0.67; (, 0.514(0.41)	^{85}Rb	stable	N/A	Exciter, spark gap, omni wave, check source
^{90}Sr	28 y	$\$^{-}$, 0.546	^{90}Y	64.0h	$\$^{-}$, 2.27	Rad calibration source, marker, det. Unit
^{90}Y	64.0h	$\$^{-}$, 2.27	^{90}Zr	stable	N/A	Ice detector (foreign)
^{131}I	8.065d	$\$^{-}$, 0.806(0.6), 0.606; (, 0.364(82)	^{131}Xe	stable	N/A	Radiation source
^{137}Cs	30.2y	$\$^{-}$, 1.176(7), 0.514	^{137m}Ba	2.60m	(, 0.662(89)	Spark igniter, density probe, calibration source
^{133}Ba	10.7y	(,0.356(69), 0.080(36), 0.302(14)	^{133m}Ba	14.6m	(, 0.107(40)	Radiation source
^{147}Pm	2.62y	$\$^{-}$, 0.224	^{147}Sm	1E11y	", 2.23	Luminous dials, sights
^{204}Tl	3.81y	$\$^{-}$, 0.766(97.9)	^{204}Pb	1E17y	", 2.6	Depth gauge
^{210}Pb	22y	$\$^{-}$, 0.061(19), 0.015	^{210}Bi	5.01d	$\$^{-}$, 1.16	Arrestor
^{210}Bi	5.01d	$\$^{-}$, 1.16	^{210}Po	138.4d	", 5.31	Radiation source
^{226}Ra	1602y	", 4.60(5), 4.78	^{222}Rn	3.82d	", 5.49	Toggle switches, knobs, meters, watches, luminous dials, sights
^{232}Th	1.4E10y	", 3.95(23), 4.011	^{228}Ra	6.7y	$\$^{-}$, 0.055	Thermal optics, combustor (M1 tank), check source

Isotope	Half-life	Major Radiation E (MeV) and (Intensity%)	Main Progeny	Half-life	Major Radiation E (MeV) and (Intensity%)	Use of Materiel
^{234}Pa	6.75h	\$$^{-}$, 1.13(13), 0.53	^{234}U	2.5E5y	", 4.72(28), 4.77	Radiation source
^{235}U (1)	7.1E8	", 4.21(5.7), 4.58(8), 4.37 (18), 4.4(57); (,0.110(2.5), 0.163(5), 0.205(5), 0.143 (11), 0.302(52), 0.185(54)	^{231}Th	25.6h	\$$^{-}$, 0.026(2), 0.218(13), 0.140(40); (, 0.085(10)	DU component
^{238}U (2)	4.5E9y	", 4.15(25), 4.20	^{234}Th	24.1d	\$$^{-}$, 0.103(21), 0.193	Radiation source
DU*	6.5E15y	", 4.20 {see below}	-	-	", and weak x-ray and beta from daughters	AP munitions, armor, radiation shields, aircraft counter weights
^{239}Pu	2.4E4y	", 5.16 ((from U x-ray)	-	-		Rad calibration source
^{241}Am	458y	", 5.44(13), 5.49; (, 0.060(36)	^{237}Np	2.1E6y	", 4.65(12), 4.78; (, 0.030(14), 0.086(14)	density and moisture tester, chem. Detector
Am/Be						Radiation source (neutrons)

* 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.

Note: 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 to be radioactive (e.g., self-luminous dials and sights).

5.1. Main Sources in Army Commodities

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

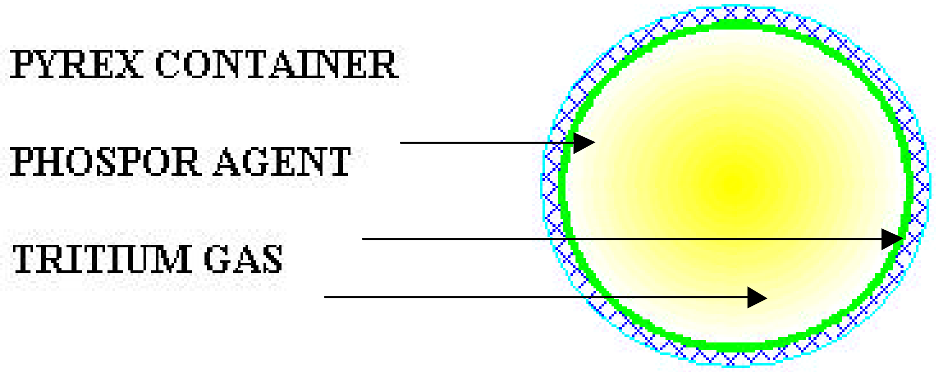
5.1.1. Tritium (^{3}H)

Tritium is the heaviest isotope of hydrogen and the only one that is radioactive. Section 7.8.3 covers the principal physical characteristics of tritium. Tritium and tritium devices used in the military are identified to illustrate the potential for accidents that result in unnecessary exposure to a soldier.

Tritium that is used in military applications is contained in a Pyrex glass tube, which has been lined with a phosphor, as shown in Figure 5.1. The interaction between the phosphor and the beta particles from tritium gas produces visible light. The amount of tritium to be 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 and 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. In all cases, the equipment and its carrying case should have warning labels attached to it [3].

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.

Figure 5.1. The tritium light source



In its gaseous state, tritium is not absorbed by the skin to any significant degree, as it dissipates quickly into the atmosphere. 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), both through inhalation and absorption through the skin. The radioactive water that enters the body is chemically identical to ordinary water and is distributed throughout the body tissue. In addition, tritium that has plated out on a surface or combined chemically with solid materials may be a contact hazard.

Figure 5.2 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.

Figure 5.2. Typical radioactive material data plates

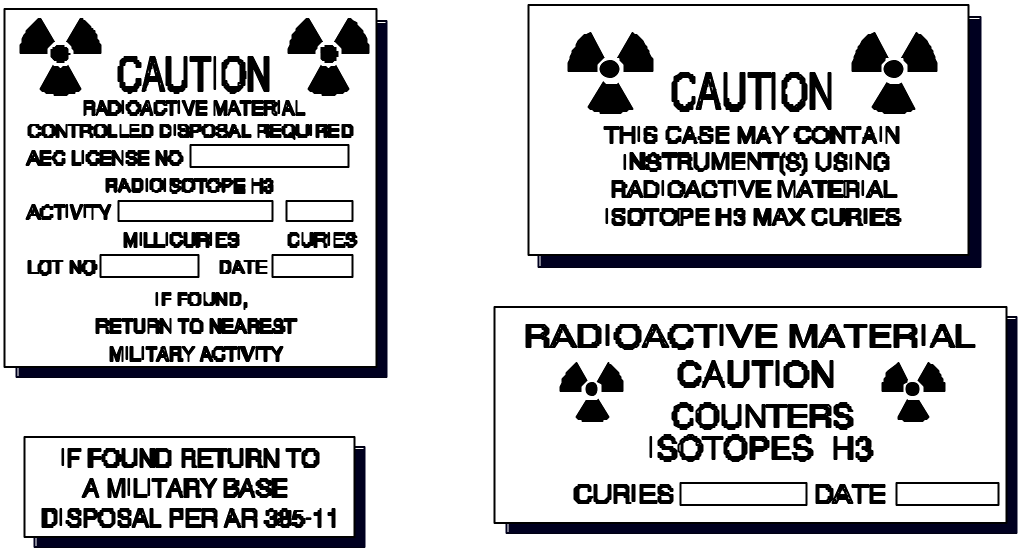


Table 5.2 includes a list of devices that contain tritium. The following pictures are illustration of these devices.

Table 5.2. List of some Army devices containing tritium and corresponding activity [4]

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
	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

Figure 5.3. The M1A1 Collimator (total activity = 10 Ci)

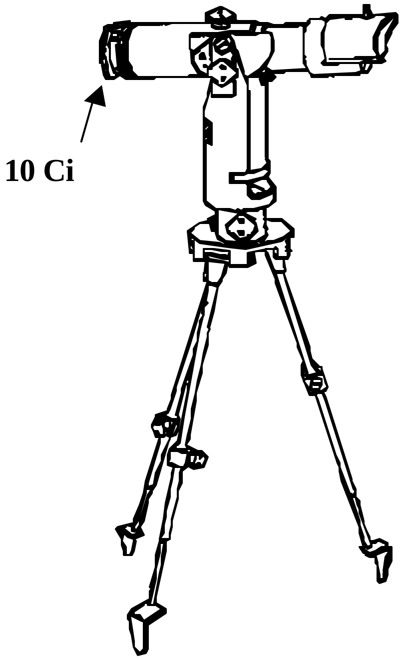
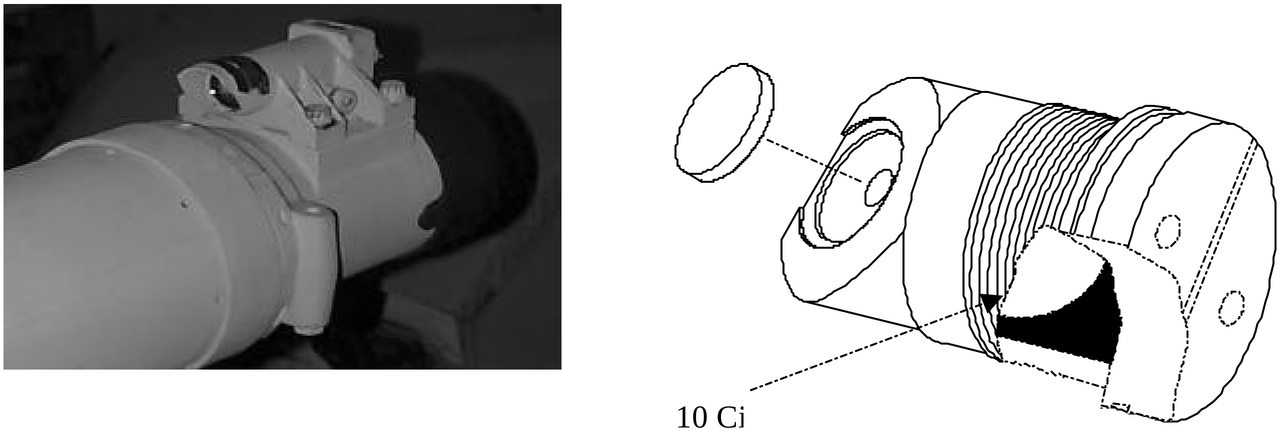


Figure 5.4 shows the infinite collimator found in all M1 series tanks with its respective NSN numbers. The Muzzle Reference Sensor (MRS) is located on the end of the main gun tube of all M1 series tanks and has a beam-splitter assembly, which contains a 10-curie tritium light source. This light source is completely contained within the beam-splitter and poses no external radiation threat unless the Pyrex vial is broken. If there is no apparent illumination when viewed in subdued light, the source may be leaking. If the beam-splitter is still mounted in the MRS, the entire MRS should be double bagged. To avoid or minimize contamination it is recommended not to remove the beam-splitter assembly from the MRS if there is no illumination.

Figure 5.4. The Infinity Collimator (Muzzle Reference Sensor, MRS) for M1 series tanks and beam-splitter (the beam-splitter is the same for all three MRS, with total activity of 10 Ci)


The MRS

The beam-splitter

Figure 5.5. The M58 and M59 Aiming post lights [M58 contains a 5.0 curie tritium source (RED) and M59 contains a 9.0 curie tritium source (Green)]

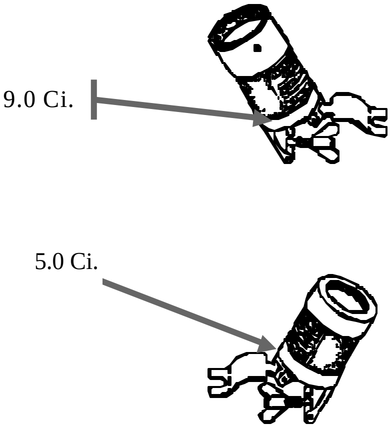


Figure 5.6. M64A1 Sight Unit w/ M9 Elbow Telescope (total activity = 6.69 Ci)

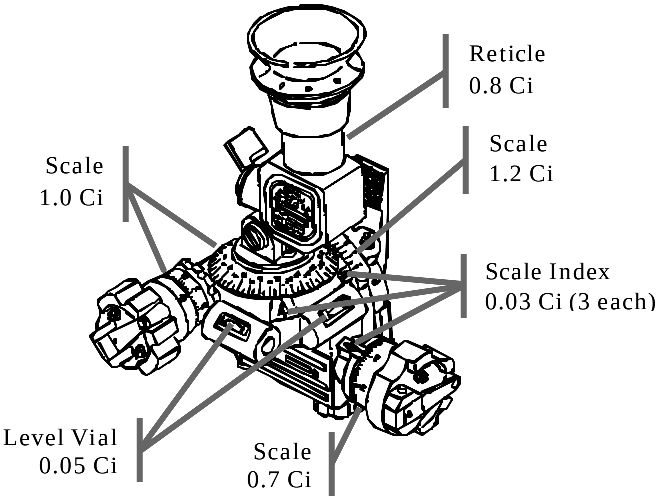


Figure 5.7. The M67 Sight Unit (total activity = 5.76 Ci)

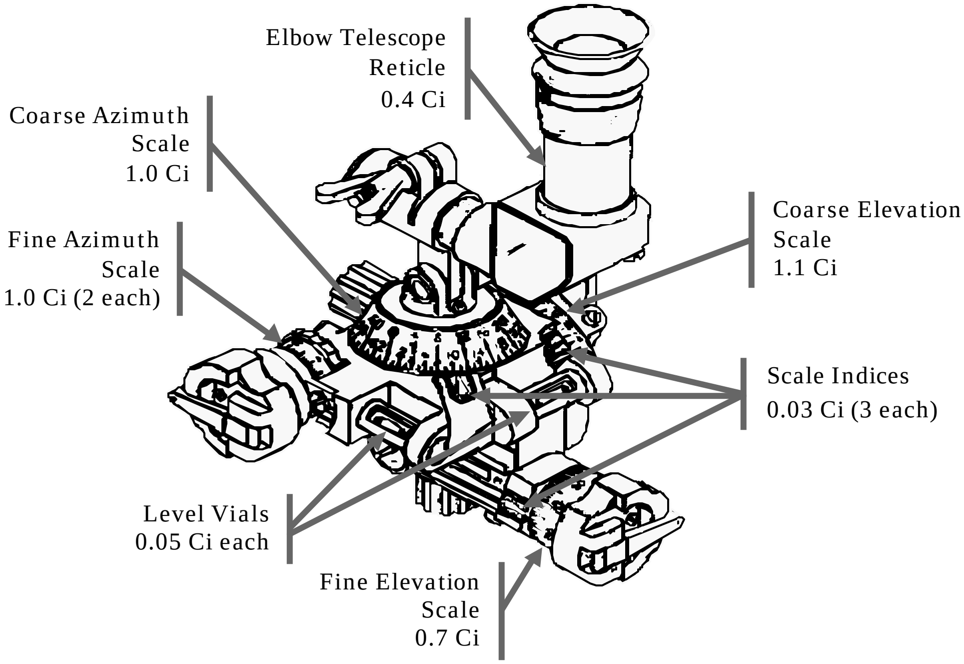


Figure 5.8. The M114A1 Elbow Telescope (total activity = 5.6Ci)

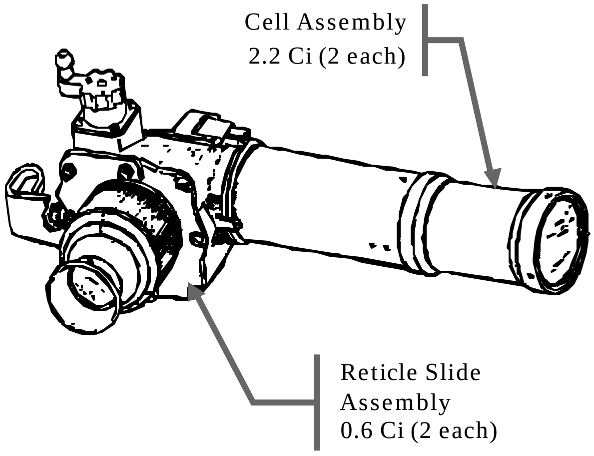


Figure 5.9. The M137 Panoramic Telescope (total activity = 5.1)

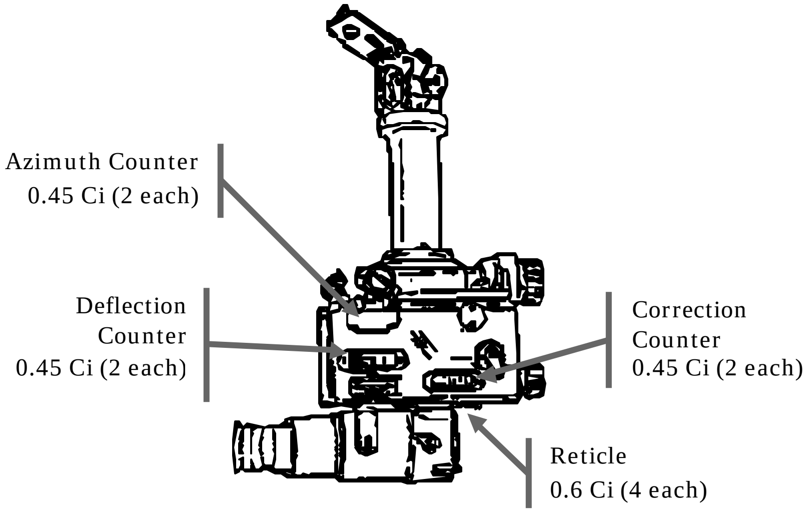


Figure 5.10. The M137A1 Panoramic Telescope (total activity = 5.1 Ci)

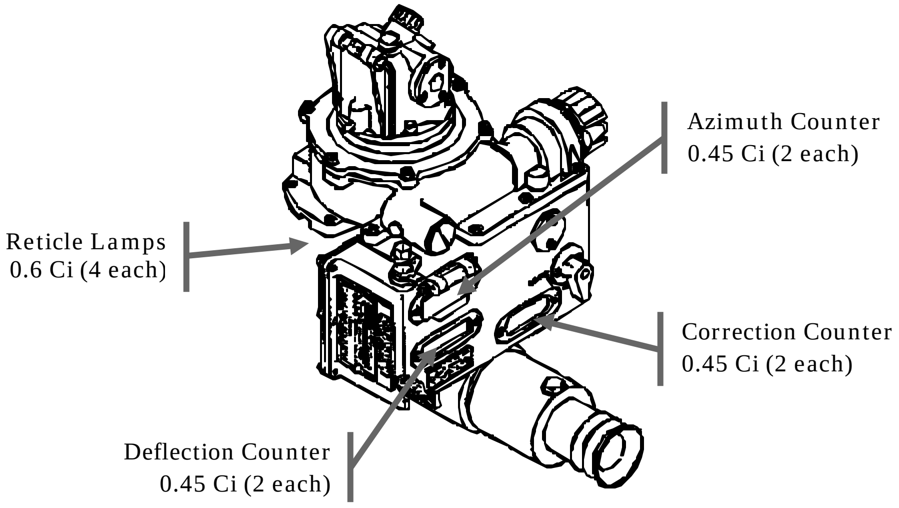


Figure 5.11. The M138 Elbow Telescope (total activity = 4.4 Ci)

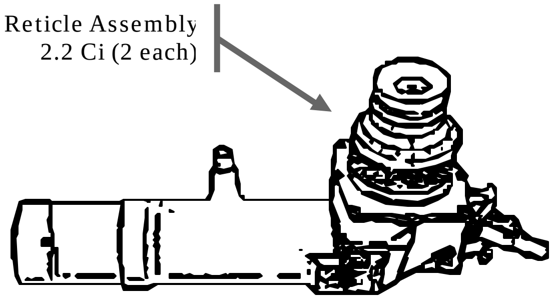


Figure 5.12. The M113A1 Panoramic Telescope (total activity = 4.6 Ci)

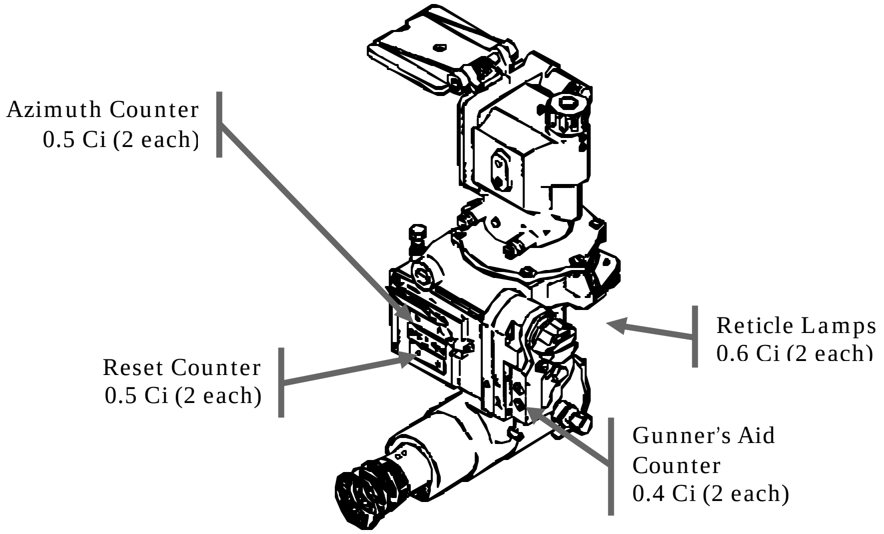


Figure 5.13. The M224 Mortar, 60mm, Range Indicator (total activity = 3.23 Ci)

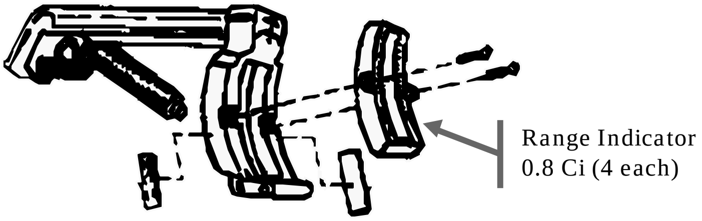
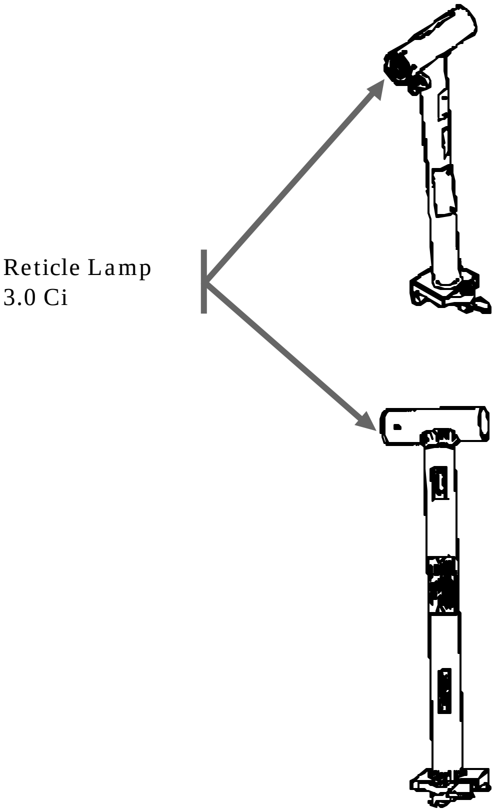


Figure 5.14. The M139/M140 Alignment Devices (light source contains 3.0 Ci of tritium)[21]



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[21] 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.

Figure 5.15. The M187 Telescope Mount and Quadrant (total activity = 2.65Ci)

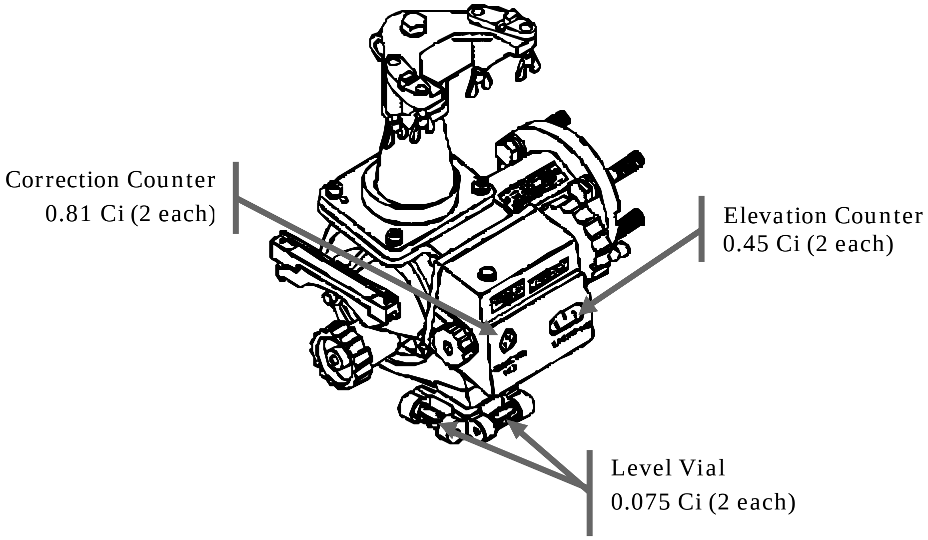


Figure 5.16. The M14A1 Fire Control Quadrant (total activity = 2.15 Ci)

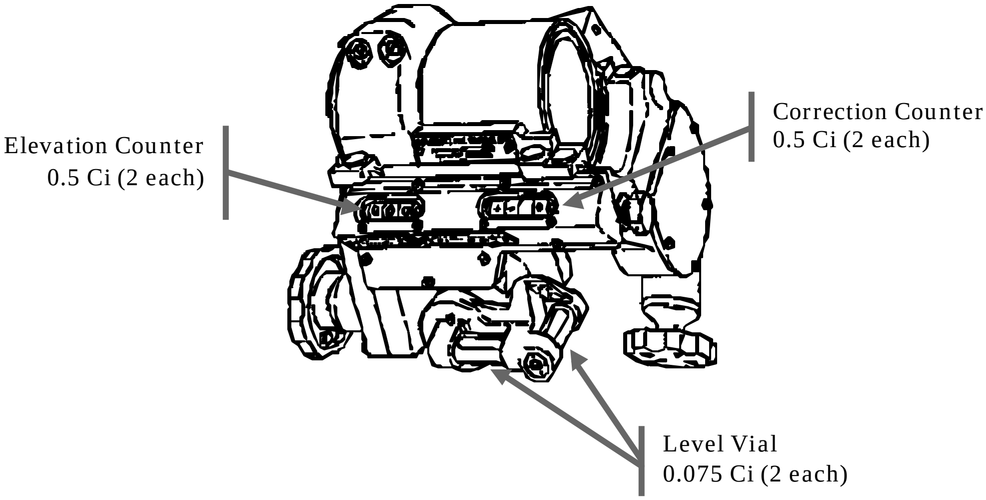


Figure 5.17. The M18 Fire Control Quadrant (total activity = 1.95 Ci)

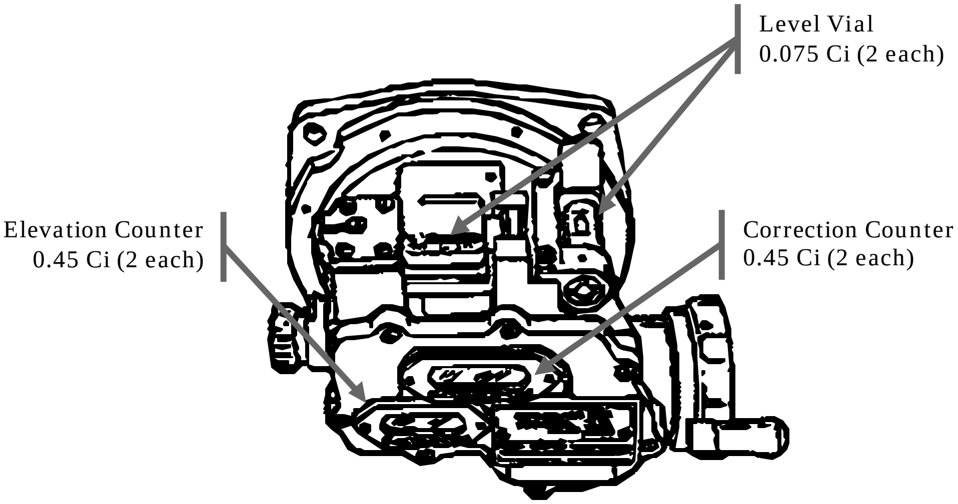


Figure 5.18. The M17 Fire Control Quadrant (total activity = 1.875 Ci)

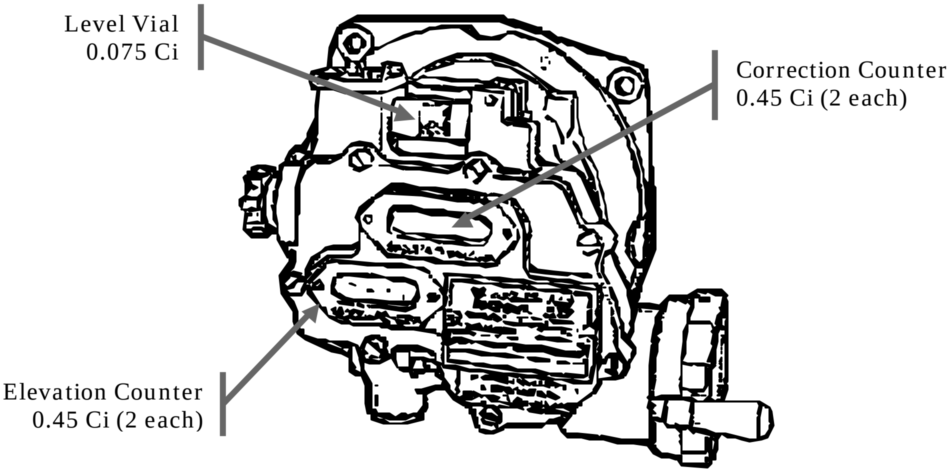


Figure 5.19. The M90A2 Straight Telescope (total activity = 1.6 Ci)

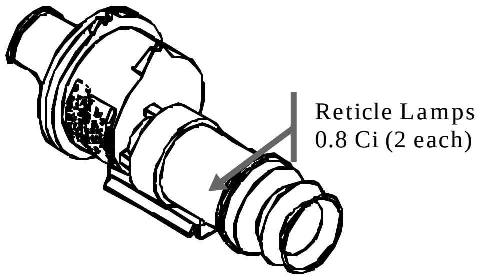


Figure 5.20. The M134A1 Telescope Mount (total activity = 0.15 Ci)

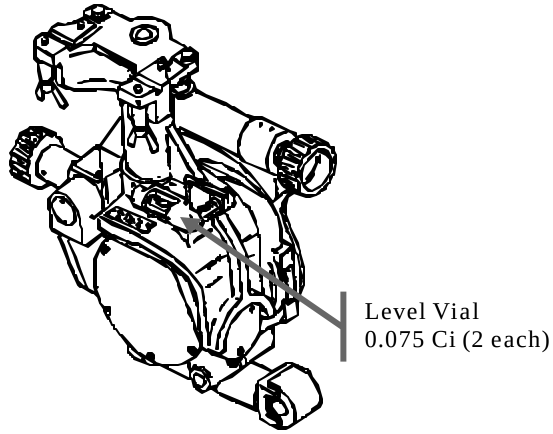


Figure 5.21. The M171 Telescope Mount (total activity = 0.15 Ci)

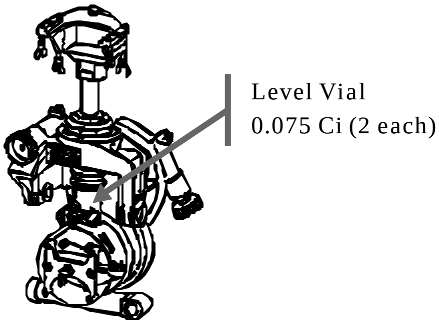


Figure 5.22. The M1A2 Gunner's Quadrant (total activity = 0.075 Ci)

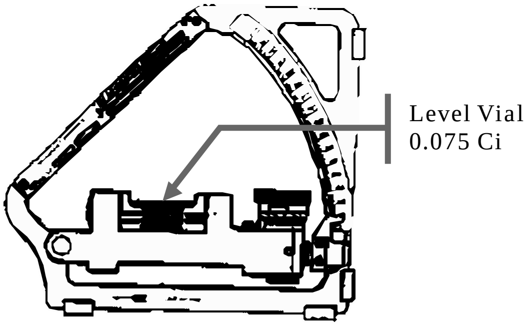


Figure 5.23. The M11 Pistol, 9mm - DARA 12-93-01 (total activity = 0.054)

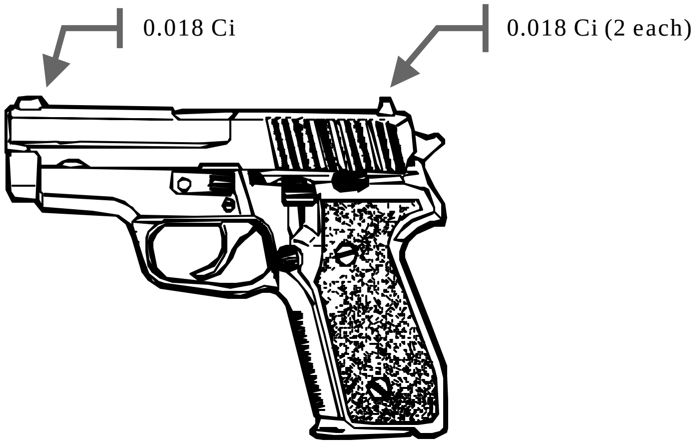
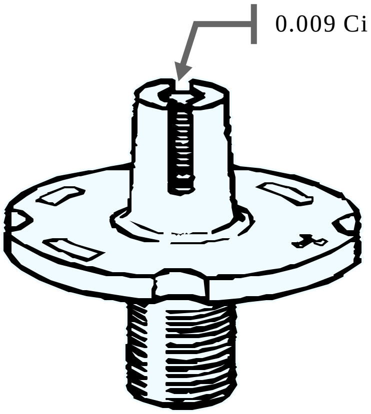


Figure 5.24. The M16A1 Rifle Front Sight Post (total activity = 0.009 Ci)[22]



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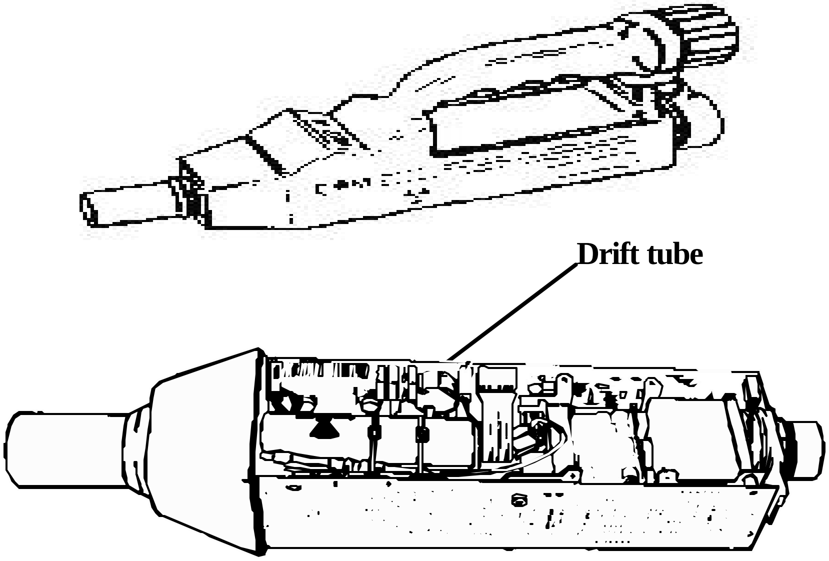
[22] This is no longer in use. It any is found it should be removed and turned into the RPO/RSO as LLRW.

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

Nickel-63 is a pure beta emitter (^{63}Ni emits betas only; 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) uses this isotope. The ^{63}Ni is used to ionize air molecules as they pass through the detector. The drift tube module consists of 10 millicuries of ^{63}Ni plated on a brass foil cylinder inside a Teflon housing that is installed in a larger aluminum alloy cylinder.

Figure 5.25. The Chemical Agent Monitor (CAM)



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

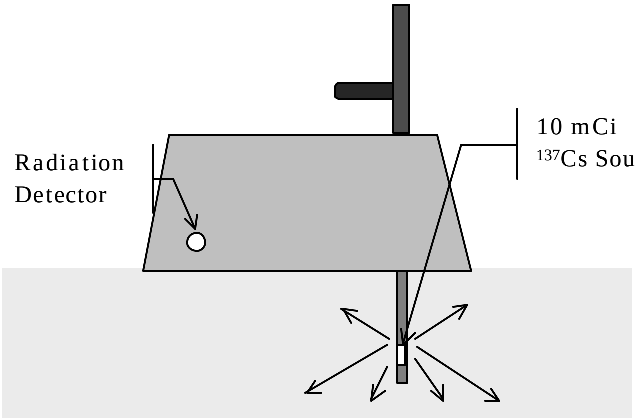
Cesium 137 emits a negative beta particle and becomes ^{137}Ba, which in turn decays by emitting gamma rays of a single energy (0.662 MeV). The fixed spectrum emission requires less shielding than other radionuclides and is ideal for soil density determination. The density and moisture tester (Campbell 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 form ^{137}Cs are virtually totally shielded by the stainless-steel. The density of soil is measured by the techniques of backscatter or transmission.

Backscatter refers to the technique of placing the source on the surface of a flat material. This technique measures only the top 2 inches of soil and is very sensitive to surface roughness or quality of site preparation.

Transmission is the technique of drilling a small hole in the ground and then inserting the radioactive source in the ground via the movable source rod. This permits measurement to specific depths to 12 inches and is not sensitive to surface roughness. It is very accurate and is the preferred method of density measurement for soils.

Figure 5.26 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 5.26. Illustration of the density and moisture tester



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

Promethium 147 has a half-life of 2.64 years and is a beta particle emitter used in luminous paints. The only weapon system that uses this element is the M72 series, 66mm, 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[23]. In the early 80's 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, M72, M72A1, and M72A2 still remain in use for training and in storage, and therefore are identified in this technical guide. Figures 5.27 to 5.29 illustrate a LAW, the range markers and the sight post that contains the ^{147}Pm.

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[23] The ^{147}Pm located in the front sight, on 16A1 is obsolete and should be removed and turned in as rad waste to the RPO/RSO.

Figure 5.27. Light Antitank Weapon (LAW)

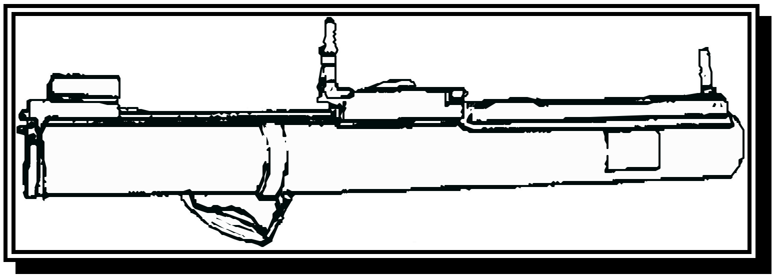


Figure 5.28 Illustration of ^{147}Pm on the 100th and 15th range markers

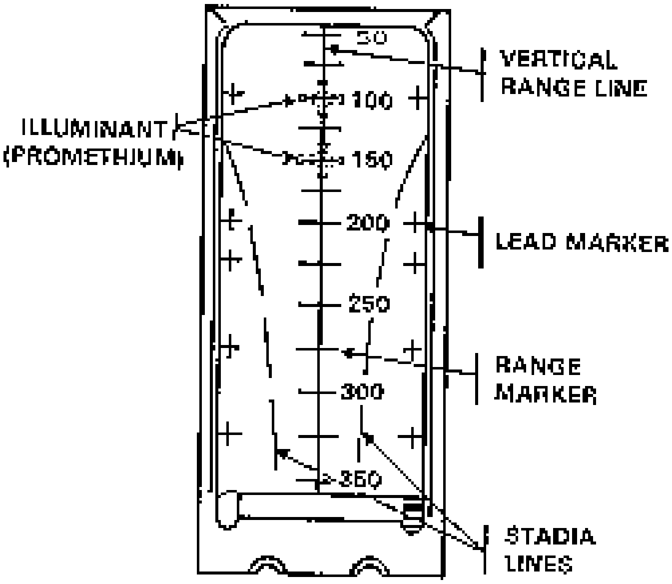
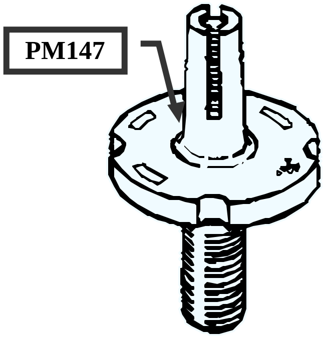


Figure 5.29 M16A1 Rifle Front Sight Post (no longer in use)



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

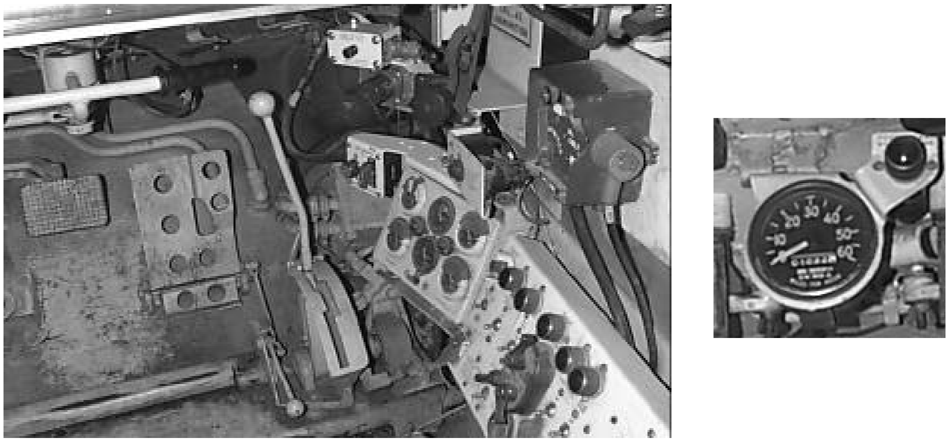
Radium-226 is primarily an alpha emitter, but it also emits some low energy beta and gamma radiation. Radium-226 was used on the faces and pointers of dials and gauges of instrument panels in tactical and combat vehicles. These items are no longer in DoD storage depots and have not been procured since 1969. Non-radioactive 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 (Tank-Automotive and Armament Command) 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 TM 3-261. REFER TO TB43-0216 FOR ADDITIONAL GUIDANCE."* Gauges and dials themselves that contain ^{226}Ra and are not marked or labeled in any way that would indicate that they are radioactive, should be reported immediately.

The easiest way to tell whether an unmarked dial or gauge contains radium or some other radioactive material is to check with a 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 [3].

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

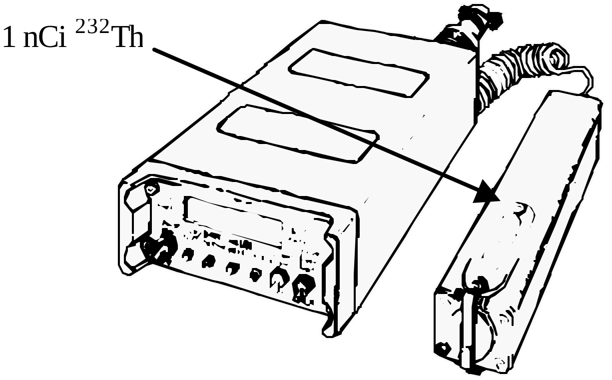
Figure 5.30. View of dials and gauges containing ^{226}Ra inside a combat vehicle



5.1.6. 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 *Welsback* lantern mantle used in portable gas lanterns.

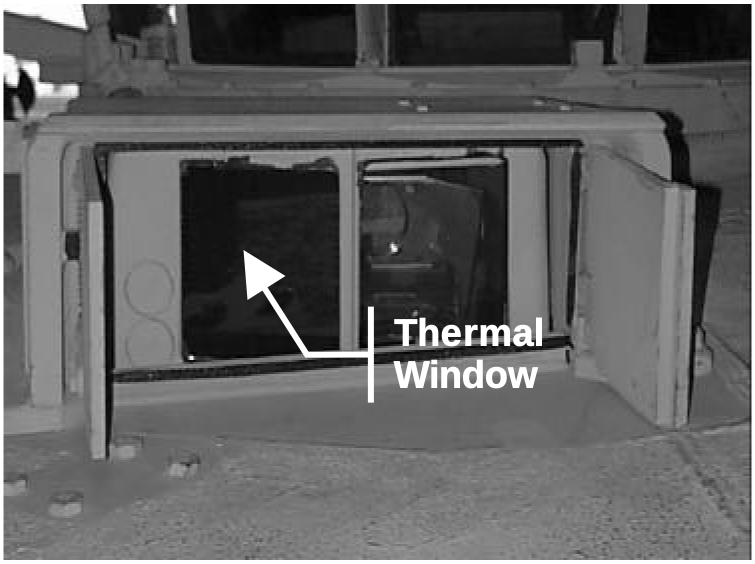
Figure 5.31. Source found in radiac instrumentation



The AN/VDR-2 radiac set uses a 1 nanocurie ^{232}Th source. The check sources of the AN/PDR-54 and the AN/PDR-77 radiac sets contain 0.1 microcuries of ^{232}Th.

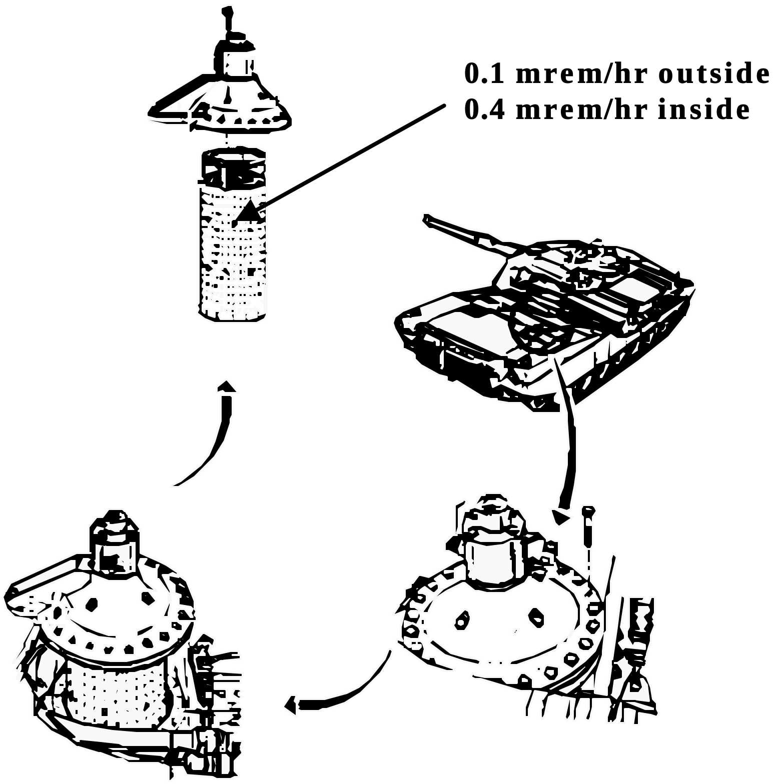
Thermal optics have a multi-layer infrared anti-reflective coating that contains ^{232}Th as a fluoride compound (thorium tetrafluroride). This hard coating is covered with a protective layer of non-radioactive compound, which prevents direct contact with the thorium surface. Care should be taken in the handling of these optical components to avoid inhalation and/or ingestion of any particles inadvertently chipped or scratched. Figure 5.32 is a picture of a thermal window that contains ^{232}Th.

Figure 5.32. Picture of thermal window containing ^{232}Th fluoride



Natural thorium oxide evenly dispersed in simple nickel thorium alloy is used in the combustor liner for the M1 Abrams series tank turbine engine. The ^{232}Th is used because the alloy can withstand a great amount of heat without physical damage. The combustor is a non-repairable component; the only maintenance function allowed is to replace it with a new one. Combustor liners separated from vehicle engines must be tagged or labeled with the words "RADIOACTIVE MATERIAL - TH 232" and otherwise labeled IAW MIL-STD-129. Surveys of the combustor indicate that the radiation exposure rates are 0.1 mrem/hr on the outside surface and 0.4 mrem/hr on the inside surface. No regular monitoring of the item in the turbine engine is required. The thorium-nickel alloy presents no external radiation hazard when handling and installing the combustor liner. Figure 5.33 illustrates the location and expected dose rates of this component.

Figure 5.33. Thorium nickel alloy in combustor liner



Thorium coated optic are also found in many night vision devices, such as the ANTAS 4 series.

5.1.7. Depleted Uranium (DU)

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 a 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 (DU) because it is "depleted" in this isotope. Table 5.3 is a comparison between the composition of DU and natural uranium. DU has a lower content of ^{235}U than natural uranium and it is less radioactive than natural or enriched uranium

Table 5.3. Comparison between the uranium composition of DU and natural uranium [4]

Uranium Isotope	Natural Uranium	Depleted Uranium
^{234}U	0.0057%	0.0005%
^{235}U	0.7204%	0.2500%
^{238}U	99.2739%	99.7495%
Total	100%	100%

As identified in Chapter 2, 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 one curie of radioactivity from DU, it would require a single piece weighing 6,615 pounds.

Depleted uranium 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 non-nuclear 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). Depleted uranium ammunition is not used for training.

The Abrams tank family (M1, IPM1, M1A1,and M1A2) includes an improved hull armor envelope that contains no DU. However, the newest M1A1 tanks, dubbed "Heavies", have depleted uranium packets "molded" into the left and right frontal turret armor. Figure 5.34 shows the location of this armor. The front slope of the turret has a radioactive signature, a little less than "0.5 mrem/hr". Tanks with this material are identified by a "**U**" at the end of the turret serial number as illustrated in Figure 5.35. The M1A2 tanks also contain these DU packets in the turret armor package.

Figure 5.34. Illustration of the armor package containing DU

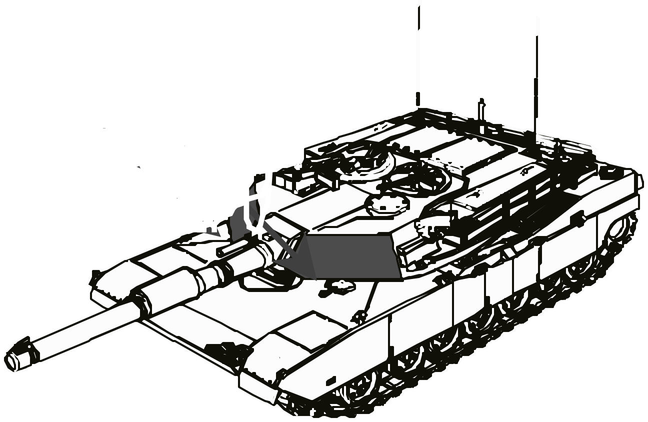
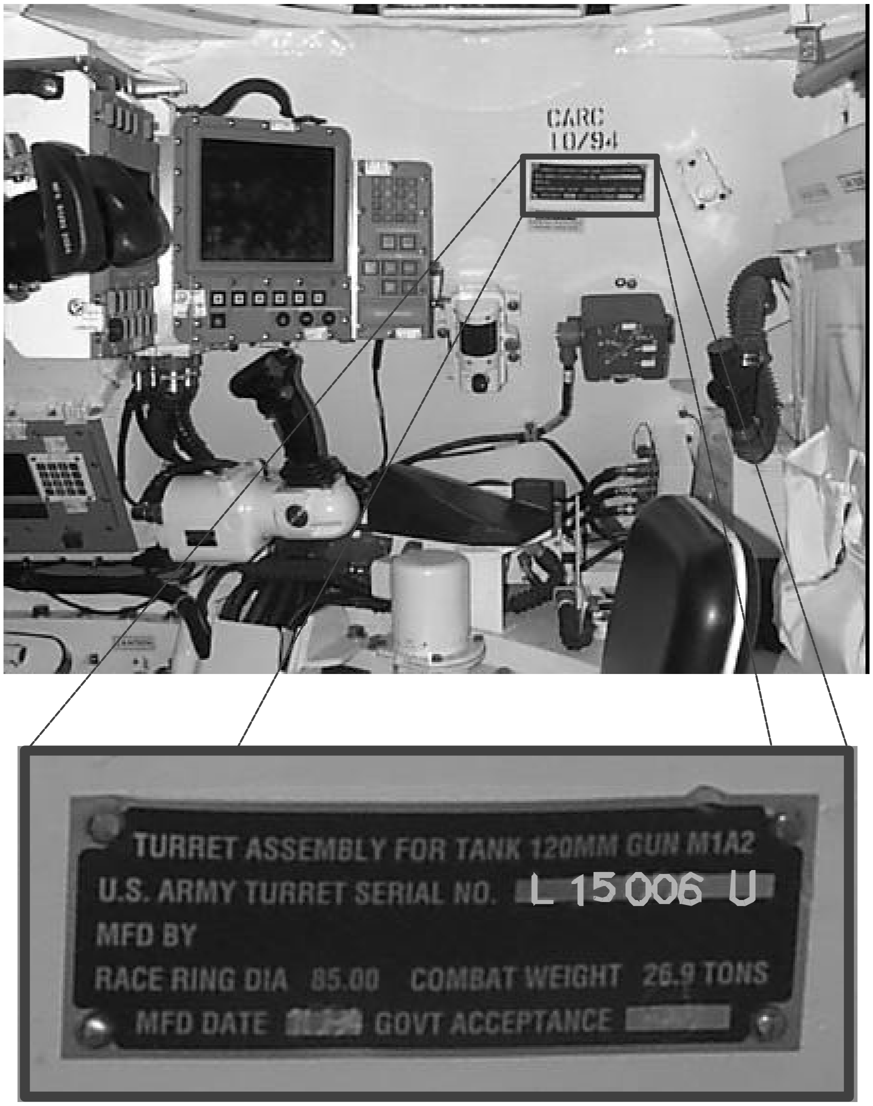


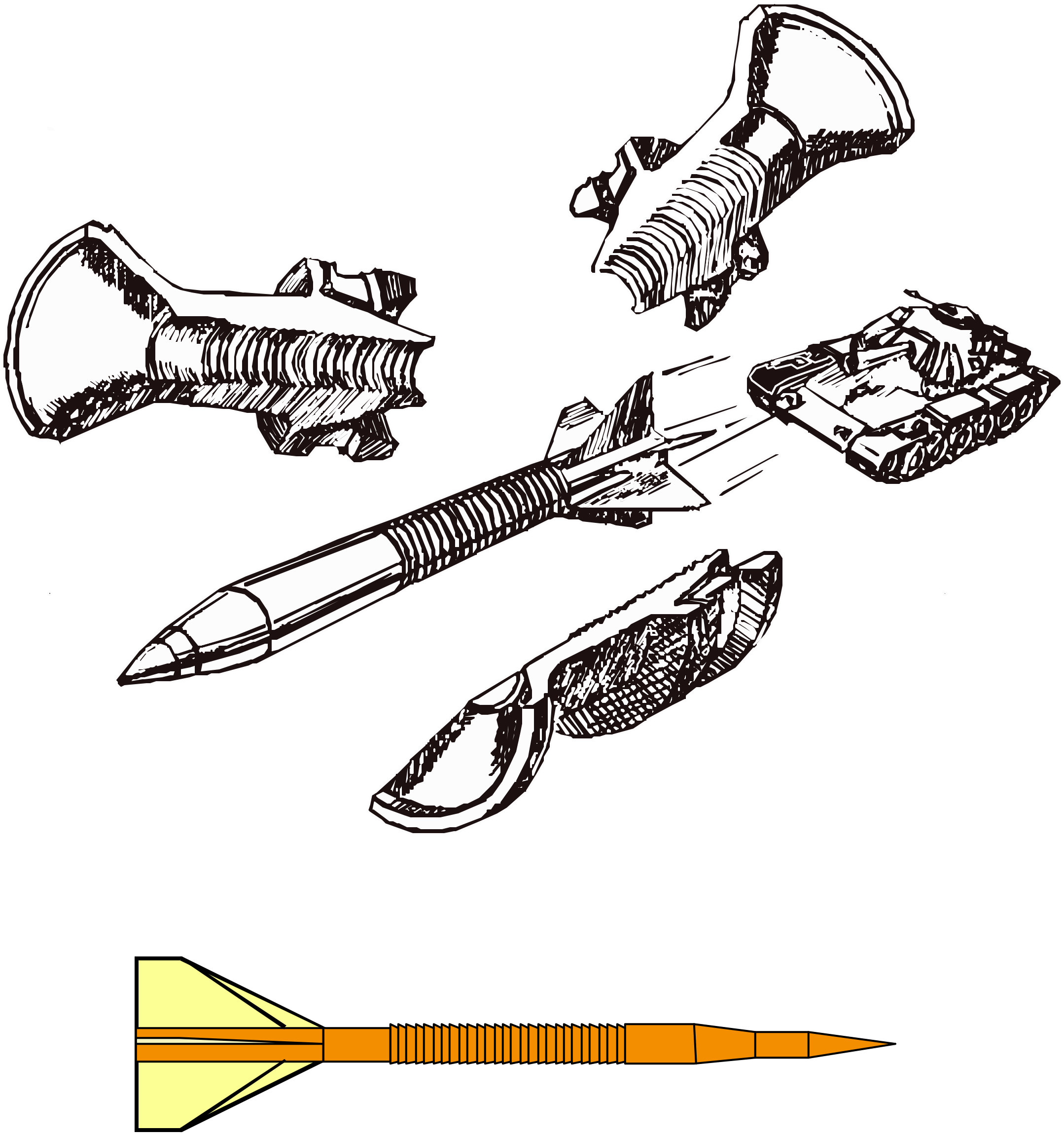
Figure 5.35. Radioactive signature identified by a "U" at the end of the turret serial number



TURRET ASSEMBLY FOR TANK 120MM GUN M1A2
U.S. ARMY TURRET SERIAL NO. L 15006 U
MFD BY
RACE RING DIA 85.00 COMBAT WEIGHT 26.9 TONS
MFD DATE [redacted] GOVT ACCEPTANCE [redacted]

Depleted uranium 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. Figure 5.36 illustrates this type of ammunitions.

Figure 5.36. Authorized DU ammunitions



The design and material composition of these cartridges represents a departure from previous generations of armor-piercing ammunitions. These rounds employ kinetic energy subprojectiles composed of monolithic (staballoy) depleted uranium cores. The design and material configurations warrant special emphasis during the life cycle of these cartridges. For general military applications, DU ammunition may only be fired during war emergency. All peacetime firings are prohibited except on ranges, which are approved and licensed by the NRC and/or have host nation agreement. The following tables include a list of DU ammunitions and their typical characteristics.

Table 5.4. 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 5.5. 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. The following sections are representative of the DU ammunitions from Table 5.4

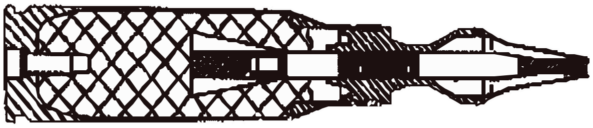
5.1.7.1. The M1919, 25mm APFSDS-T ammunition

The 25mm Armor-Piercing, Fin Stabilized Discarding Sabot with tracer (APFSDS-T) M919 has been designed and developed to replace the currently fielded M791 cartridge as the service armor piercing round for the Bradley. The M919 uses a high length/diameter ratio, depleted uranium penetrator and high energy propellant to achieve improved terminal ballistic characteristics. Figure 5.37 is an illustration of the M1919.

Hazard classification testing was conducted in 1988 at Nellis Air Force Base. Environmental sampling showed no indication that DU oxide had become airborne during the burn test (setting a pallet of ammo on fire). Essentially all of the oxide produced was insoluble when analyzed using a simulated lung fluid test. Only 0.1 to 0.2 percent of the oxide was small enough to be inhaled.

Radiological assessment of the M919 cartridge for external radiation levels was conducted in 1989. The components of the M919 effectively shielded out the predominant alpha and beta radiation. The gamma radiation penetrated the projectiles and the shipping containers. The highest radiation measurement was at the center of the shipping container. Radiation levels at the surface of a single shipping container, measured with field use exposure rate instruments, had a maximum reading of 0.6 mR/hr. This exceeds the surface exposure rate criteria of 0.5 mR/hr for shipping DU ammunition as excepted material. All other criteria are satisfied by the M919 shipping package.

Figure 5.37. The 25mm, M1919 APFSDS-T

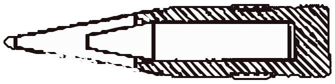


COLOR	MUZZLE VELOCITY
Black w/white obturator	4659 feet/second

5.1.7.2. The 30mm, API-T and API

Figure 5.38 represents the 30mm, API-T and API. The current production API has a boat tail and a shortened windscreen. The projectiles have an aluminum body that holds a DU penetrator and a hollow aluminum windscreen. Upon impact with the target, the windscreen and body are stripped away allowing the penetrator to continue through the target. Target friction produces a large amount of heat providing incendiary effects.

Figure 5.38. The 30mm, API-T and API



5.1.7.3. The 25mm, AP

The 25mm Armor Piercing incendiary cartridge, the PGU-20/U is used against armored targets, and it functions with a DU penetrator. This cartridge is only used by the U.S. Navy/U.S. Marine Corps. The color marking is red and black.

5.1.7.4. The 20mm, AP and DS

The MK 149 is an inert subcaliber saboted round. The projectile consists of a DU penetrator surrounded by a discarding sabot and an aluminum pusher plug assembly. The pusher plug has a nylon rotating band swaged into a circumferential groove near its aft end. The assembly (MK 149 cartridge) and the M61A1 gun (MK15 Phalanx Weapon System) are equipped with a linkless ammunition handling system and serves as a close-in weapons system (CIWS).

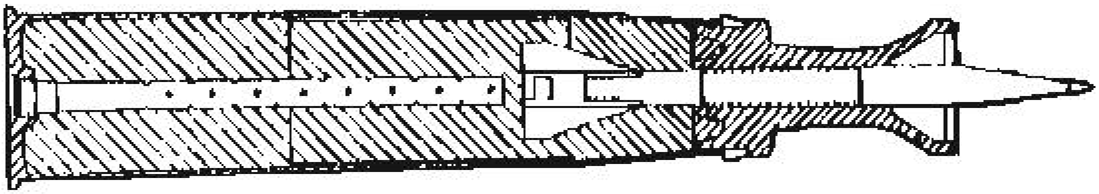
5.1.7.5. The 105mm, APFSDS-T

Figure 5.39 illustrates this type of ammunition. The 105mm kinetic energy rounds consist of three models, M774, M833, and M900. These are armor-piercing antitank ammunition and are intended for use in the 105mm, M68 gun in the M60 tank and are loaded and fired in the normal manner. The projectile is fin stabilized in flight. In order that only minimal spin is imparted to the projectile when the obturator engages the gun tube rifling, the plastic seal under the obturator produces approximately 80% slippage. Target penetration is effected strictly by the high kinetic energy of the subprojectile impacting the target. The subprojectile consists of a monolithic staballoy (depleted uranium) core, which is fitted with a steel tipped aluminum windscreen and an aluminum fin assembly. Table 5.6 includes the basic material composition of the 105 mm APFSDS-T.

Table 5.6. The basic material composition of the 105 mm APFSDS-T ammunition components

COMPONENT	MATERIAL
Fin	Aluminum (anodized)
Windshield	Aluminum (anodized) w/ steel tip
Sobot	Aluminum (anodized)
Penetrator	Staballoy (depleted uranium)
Bourrelet	Steel
Sabot Seal	Rubber (Silicon)
Obturator	Nylon
Sealing Band	Polypropylene
Bourrelet Screws	Steel

Figure 5.39. The 105mm, APFSDS-T

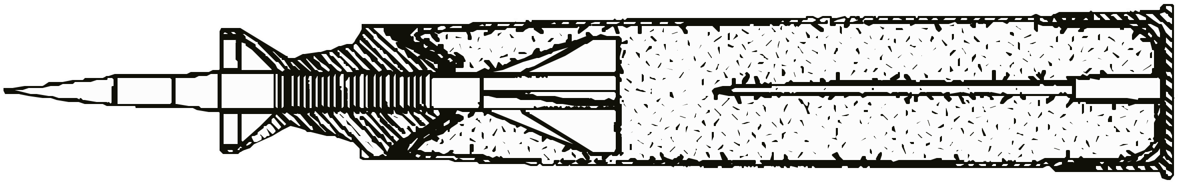


5.1.7.6. The 120mm, APFSDS-T

Figure 5.40 illustrates the 120mm DU armor-piercing fin stabilized discarding sabot-tracer (APFSDS-T). This 120 mm M829 series DU APFSDS-T is the primary anti-armor 120mm ammunition for the smooth bore M256 cannon in service with the M1A1 and M1A2 Abrams tanks. This second-generation kinetic energy projectile is capable of penetrating the frontal slope of all fielded armor systems and its high technology penetrator and sabot design provides a munition that is accurate at all combat ranges. Its primary function is the destruction of threat tanks and armor fighting vehicles. Target penetration is affected strictly by the high kinetic energy of the DU core when it impacts. Like other DU munitions, these are identifiable by their black color with white markings on the projectile (pointed) end.

M829 series ammunition is loaded and fired in the normal manner. This ammunition will not be fired over the heads of friendly troops unless adequate cover protects troops, as the discarded sabot may strike them.

Figure 5.40. The 120 mm, SU APFSDS-T



5.1.7.7. The 155mm, Area Denial Artillery Munitions (ADAM) and the Mine, Antipersonnel, M86 Pursuit Deterrent Munitions (PDM)

The Area Denial Artillery Munitions (ADAM) is used for rapid, remote emplacement of point or tactical minefields used to restrict personnel movement. ADAM is a wedge shaped mine that fits efficiently into a 155mm projectile. When the projectile reaches the target area, 36 mines are expelled and shortly after impact with the ground they release trip lines and arm themselves. If not triggered by one of the trip lines or if the battery reaches a level that impairs their proper functioning, the mines will detonate at a predesignated self-destruct interval. When the mine detonates, a small charge propels the kill mechanism upward and then the kill mechanism detonates to optimize its effect against personnel. The ADAM and PDM are not of the kinetic energy “penetrator” type design. These munitions contain an extremely small amount of DU and are not categorized as “DU ammunition”. It is identified as a munition containing radioactive material (DU).

The resin that forms the body of the ADAM mine wedge contains a small amount of DU in the “hardener” portion of the resin. The DU is less than 0.15% (0.024 oz) of the total resin and is present only as a chemical agent that allows the resin to cure at less then 160°F in less then 12 hours. These cure characteristics are required to efficiently produce the mine and to protect the electronic components during manufacture.

The M86 PDM is a hand-emplaced anti-personnel mine used by ground forces to rapidly emplace short-term minefields. It is activated like a hand grenade and is configured and functions similar to the ADAM mine.

5.1.8. 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 458 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 most of the workday.

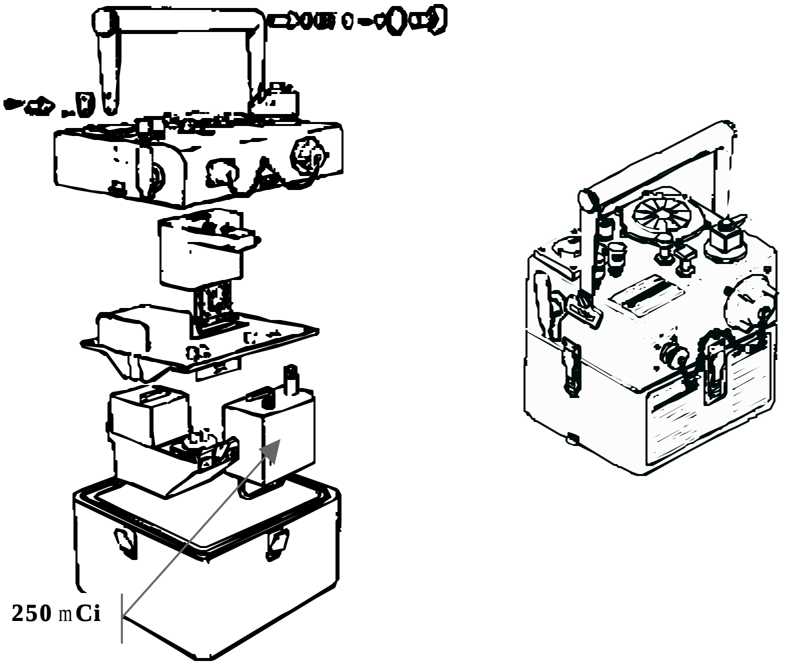
The high-energy alpha emission can present an internal radiation hazard if it is ingested. Americium-241 is chemically analogous to calcium and can replace calcium in the body, especially in bone material. For this reason it is often referred to as a “bone seeker”. Once incorporated in the bone, the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

5.1.8.1. The M43A1 Chemical Agent Detector

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. Figure 5.41 illustrates the M43A1 Chemical Agent Detector.

Figure 5.41. The M43A1 Chemical Agent Detector

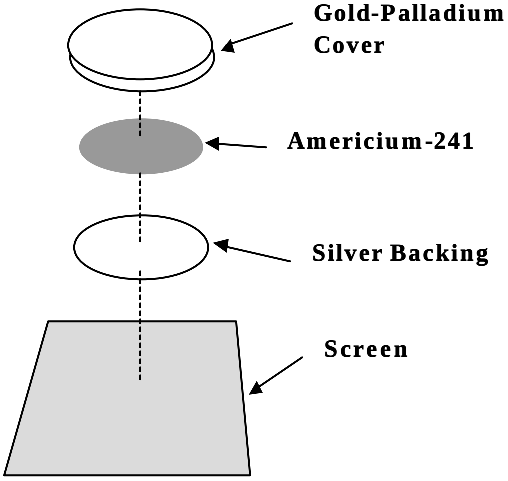


The M43A1 Detector operates on the principle of molecular ion clustering. An air sample is drawn over the radiation source that causes clustering of molecules with water and air. The air sample is drawn through a sensor cell that is geometrically configured to allow passage only to clusters below a certain mass. The nerve agents cluster very rapidly, whereas atmospheric agents do not. The molecules are impacted on a collector and an electrical signal is obtained when nerve agents are present.

Figure 5.42 illustrates the components of the ^{241}Am source, which is located in the cell module of the detector. It consists of a foil disc made of 250 μCi of ^{241}Am oxide in a gold matrix contained between a gold-palladium alloy face and a silver backing. The disc is affixed onto a metal screen that is secured by a retaining ring within the sensing housing. This source is considered a "special form"[24] source.

The ^{241}Am source has passed rigorous environmental and accident situations without damage or leakage and is expected to remain intact throughout its life cycle. Small amounts of radioactive contamination have been detected in some M43A1 Chemical Agent Detectors. Constant bombardment from the alpha particles emitted by the ^{241}Am has caused the gold-palladium cover in some of the detector modules to deteriorate. This deterioration is in the form of small cracks similar to "heat checking". In the most severe cases these cracks may penetrate the cover allowing moisture from the air to contact the americium oxide causing it to plate out onto the outer surface of the cover. Continued use of the device will cause this contamination to migrate through the air path. The contamination is in the form of a powder found in the plastic tubing between the pump module and the cell module.

Figure 5.42. Americium-241 source in the M43A1 Chemical Agent Detector



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[24] Special form is a term used in the packaging and transportation of radioactive materials for limiting activity. For example, a type A package (package that must be designed and tested to resist normal transport conditions without leakage) has a value A_1 associated with it that represents the maximum amount of special form (encapsulated or massive solid metal) material allowed in this type of package.

5.1.8.2. The Density and Moisture Tester MC-1

Figure 5.43 includes a picture of a density and moisture tester MC-1. This tester contains a 50mCi ^{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.

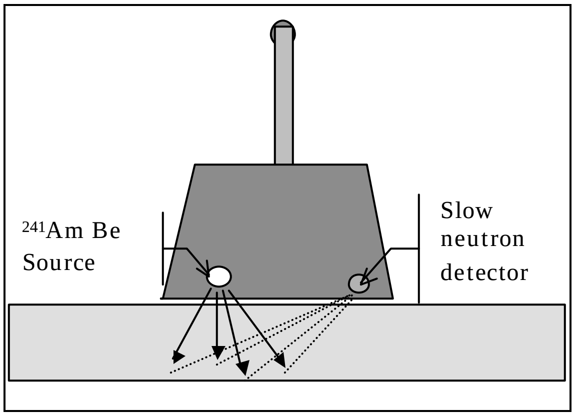
Figure 5.43. The density and moisture tester (Campbell Pacific Model MC-1)

Typical neutron detectors "see" (detect) only slow or "thermal" (of lower energies) neutrons. Therefore, the fast neutrons (of higher energies) must slow down or are ignored by the detector. Neutrons slow down by colliding with other atomic particles. Collision of fast neutrons with the nuclei of large atoms results in rebounding of the neutrons with little loss of energy. Collision with the orbiting electrons (approximately $^{1}/_{1840}$th the weight of a neutron) produces little loss of energy.

A simple analogy would be that of a billiard ball colliding with a bowling ball. The billiard ball would bounce off with little change in energy; however, the direction of the billiard ball would probably change drastically. When a billiard ball goes crashing through a bunch of BBs, the BBs will fly off in all directions but the billiard ball would continue in much the same direction with nearly all of its original energy.

The only atom which can markedly slow down a fast neutron, and which would likely be found in soil, is hydrogen. The hydrogen atom consists of one proton (about the same mass as a neutron) and one electron. When the fast neutron collides with a hydrogen atom it is much the same as when a billiard ball hits another billiard ball. One slows down a lot, the other starts moving (or speeds up), and they both change direction. The only form of hydrogen normally found in a typical construction site is water (H_2O). So if one "pumps in" fast neutrons and "reads" the amount of slow ones that result, the amount of moisture in the soil can be determined. This is illustrated in Figure 5.44.

Figure 5.44. Illustration of the functioning of the density and moisture tester MC-1



5.2. Radiation Safety Information Pertaining to Commodities

Table 5.7 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.

Generally, military radioactive commodities are of several different types. The most predominant use of radioactive isotopes in the military is to provide illumination in low light situations for weapons sights, dial faces and switch locations. This material is typically ^{3}H, ^{226}Ra, or ^{147}Pm. Another common use is in thermal optics (^{232}Th). Furthermore, personnel will be familiar with the sources found in the M-8 Chemical Alarm (^{241}Am) and the Chemical Agent Monitor-CAM (^{63}Ni).

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 back light the instrument. Promethium-147 and ^{226}Ra are used in luminous paints and applied directly to the surfaces of the dials, switches and indicators. The primary hazard from these isotopes is created by a damaged gauge, 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. For example, 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 will only be found as calibration or check sources such as ^{14}C, ^{131}I, ^{133}Ba, ^{210}Bi, ^{234}Pa, ^{238}U, ^{239}Pu, and the Am/Be sources. 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 threat, 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 bremsstrahlung, or ”braking” radiation, given off as a result 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 will 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 equivalent to the VDR-2. The neutron source is unique, in that it requires special instrumentation (Bonner sphere) to measure dose rate accurately, but can usually be detected using the beta/gamma probe on one of the aforementioned instruments.

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).

Some industrial and medical sources may be in the form of an irradiator, and will only be used with many safeguards to attempt to eliminate the possibility of accidental exposure. The sources are typically very dangerous, and can cause serious bodily injury or death in a matter of minutes if exposure occurs. If these sources are activated or unshielded, detection will be immediate, due to the strength of the sources. In the United States there are strict requirements for posting visible signs and indicators, as well as numerous other safety precautions, in areas that these instruments are used. These requirements may be different, or totally absent in other countries. The guiding principles should be caution and thoroughness to clear and/or identify any suspected sources of radiation.

Table 5.7. Radiation safety information pertaining to commodities [1, 2, 5-7]

Isotope	Max. Activity -Bq (Ci)[1]	Exposure Hazard (critical organ)[2]	Methods of Detection (external)[3]
^{3}H (T)	1.5E13 (400)	ext. (skin), int. (w. body)	S (LS), BG (SP)
^{14}C	3.7E4 (50.3E-6)	external (skin)	S (LS), BG (SP)
^{60}Co	4.0E13 (1081)	ext., int. (w. body)	BG, S
^{63}Ni	7.4E8 (20E-3)	internal (bone)	BG (SP)
^{85}Kr	1.85E8 (5E-3)	ext. (w. body) int (lung)	BG
^{90}Sr	6.66E9 (0.18)	ext. (skin), int. (bone)	BG, S
^{90}Y	9.25E5 (25E-6)	ext. (skin), int. (bone)	BG, S
^{131}I	3.7E4 (1.0E-6)	external (skin, w. body)	BG, S
^{137}Cs	4.81E12 (130)	ext., int. (w. body)	BG, S
^{133}Ba	3.7E4 (1.0E-6)	external (whole body)	BG, S
^{147}Pm	1.79E8 (4.8E-3)	int. (bone)	BG, S
^{204}Tl	5.92E7 (0.16)	internal	BG
^{210}Pb	2.22E4 (0.6E-6)	internal (kidney)	BG, S
^{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)	int. (kidney)	A, BG
DU(5)	6.66E11 (18)	int. (kidney)	A, BG
^{239}Pu	1.9E6 (50.3E-6)	internal (bone)	A, BG (SP)
^{241}Am	1.85E9 (0.05)	ext. (w. body), int. (bone)	A, BG (SP), S
Am/Be	1.5E11 (4.0)	external (whole body)	Bonner sphere[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 Bonner sphere is not the only method of detecting neutrons, but is one of the most common.

5.3. Radioactive Sources in Foreign Materiel

Radioactive sources in foreign materiel have been identified in AST-1500Z-100-93 [2] and summarized in Table 5.8. Like in U.S. Army commodities, some foreign materiel contains radioactive sources. 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.

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.

Table 5.8. Sources in foreign materiel [2]

Materiel	Origin	Radioactive Item	Source	Type of Radiation	Maximum Activity
NSB-3 Mortar Sight Kit	Yugoslavia	NT-M70 Sighting Point	^{3}H	β^{-}	74 GBq (2 Ci)
		NSB-3 Sighting Device			*
PAB-2 Sight, Sighting Point and Case	Former Soviet Union	PAB-2 Sight, Sighting Point	^{226}Ra	" and (	* (small)
PRKHR Chemical Agent Detector	Former Soviet Union Czechoslovakia Hungary	Upper portion of detector	^{239}Pu	" and (	0.4 – 0.6 MBq (11.5-16.1 :Ci)†
RWA 72K Radiation Warning and Detection Kit	Former Soviet Union	Case holding RWA 72M has a source in one of the straps	^{137}Cs	β and γ	0.2 MBq (5.9 μCi)
GVJ-1 Chemical Agent Detector	Hungary	Detector sources (2)	^{241}Am	" and (	4.51 MBq (122 :Ci) ‡
RAM 63 Radiation Detection Instrument	Democratic Republic of Germany	Check sources in RAM 63/2 Probe, and RAM 63/3 Probe	^{239}Pu	" and (	0.037 MBq (1 :Ci)
			^{60}Co	β and γ	0.2 MBq (5 :Ci)
			^{137}Cs	β and γ	0.2 MBq (5 :Ci)
NSB-4B Mortar Sight System	Yugoslavia	2 lighted vials (sources) in the NSB-4B Sight Device, plus 2 replacement vials	^{3}H	β^{-}	31.5 GBq (850 mCi)
		Light source from TS-3 sight points (2 set each)			92.5 GBq (2.5 Ci)
		TS-2 tritium light			
RIO-3 Ice Detection System	Former Soviet Union	Source in ice detector probe	^{90}Sr / ^{90}Y	β^{-}	0.9 MBq (25 μCi)
Dials and Switches	Former Soviet Union	Various, e.g., Compass inside T55 tank, switch box and instrument panel on YW531 Armored Personnel Carrier	^{3}H ^{226}Ra ^{147}Pm	β^{-} " and (β and γ	Varies (~ small)
Dials and Switches	China	Various, e.g., Dial from S60 Antiaircraft gun in Chinese T-57 Tips of switch bank from Chinese T69II tank	^{3}H ^{226}Ra ^{147}Pm	β^{-} " and (β and γ	Varies (~ small)

* Actual amount or source strength is unknown.

† This activity corresponds to about 185 to 260 μg of ^{239}Pu

‡ Source activity in 1985

5.4. Summary of Identified Sources in Army Commodities and Foreign Materiel

The following table summarizes the radiation sources from Army commodities and from foreign materiel that have been identified in Chapter 5.

Table 5.9. Summary of radiation sources in Army commodities and foreign materiel

Isotope	Radiations	Half-life	Precaution level(s)
^{3}H	$\$^{-}$	12.3 y	E-T
^{14}C	$\$^{-}$	5730 y	E-I
^{60}Co	$\$^{-}$; (	5.258 y	X
^{63}Ni	$\$^{-}$	92 y	E-I
^{85}Kr	$\$^{-}$; (	10.76 y	X-E-I
^{90}Sr	$\$^{-}$ (^{90}Y radiation)	28 y	X-E-I
^{90}Y	$\$^{-}$; (	64.0 h	X-E-I
^{131}I	$\$^{-}$; (	8.065 d	X-E-I
^{137}Cs	$\$^{-}$; (	30.2 y	X
^{133}Ba	(	10.7 y	X
^{147}Pm	$\$^{-}$ (^{147}Sm radiation)	2.62 y	E-I
^{204}Tl	$\$^{-}$; ((^{204}Pb radiation)	3.81 y	X-E-I
^{210}Pb	"; $\$^{-}$; (	22 y	X-E-I
^{210}Bi	"; $\$^{-}$; (	5.01 d	X-E-I
^{226}Ra	"; (	1602 y	X-I
^{232}Th	"; (Ra L x-rays)	1.4E10 y	X-I
^{234}Pa	$\$^{-}$; ((^{234}U radiation)	6.75 h	X-E
^{235}U	"; (	7.1E8 y	X-I-U
^{238}U	"; (Th L x-rays)	4.5E9 y	X-I-U
DU	"; (	6.5E15 y	I-U
^{239}Pu	"; $\$$; (	2.4E4 y	X-E-I
^{241}Am	"; (	458 y	X-E-I

References:

1. DA: Identification of Radioactive Items in the Army. Washington, DC: Department of the Army, 1993.

2. DA: Identification Guide for Radioactive Sources in Foreign Materiel. Washington, DC: Department of the Army, 1993.

3. DA: Instructions for safe handling, maintenance, storage and disposal of radioactive items licensed by U.S. Army armament and chemical acquisition and logistics activity. Washington, DC: AMSTA-AC-NML, 1997.

4. DA: Radioactive Material Handling Safety. Washington, DC: ACALA, 1998.

5. DA: Health and Environmental Consequences of Depleted Uranium Use in the U.S. Army. Washington, DC: Department of the Army, 1995.

6. Shleien, B., Slaback, J.L.A. and Birky, B.K.: The Health Physics and Radiological Health Handbook, 3rd ed. Baltimore, Maryland: Williams & Wilkins, 1998. (Shleien, B., ed.)

7. NCRP: Management of Persons Accidentally Contaminated with Radionuclides. Bethesda, Maryland: National Council on Radiation Protection and Measurements, 1979.

Chapter 6. Sources from Industrial Practices and Transportation of Radioactive Material

Deployed soldiers can be exposed to radiation from industrial processes and from the transportation of radioactive sources. These types of radioactive materials can be found in agricultural, scientific research, manufacturing, and educational facilities. Exposure from these sources may not be common but accidental exposures involving these sources can result in serious consequences.

6.1. Man-made Radiation Sources from Industrial Practices

In general, the public is exposed to low levels of radiation from routine industrial practices and the transportation of radioactive materials. Industry and science comprise a very broad range of activities, from high technology activities to heavy manufacturing. The use of radiation (RAD) and radioactive materials (RAM) can be found in many sectors of industry and science. The specific radionuclides and radiation sources found in industry and scientific endeavors are almost boundless. For example, one should be aware that radiation sources include x-ray machines and particle accelerators. X-ray machines produce no radiation when they are turned off; however, particle accelerators can still present hazards even when not powered.

Because of the physics of accelerators, there may still be current flow when the machine is not energized (dark current), there may be a reverse flow of charged particles (back streaming) that can produce x-rays, and there may be activation of surrounding materials from neutron production. Most accelerators have safety systems that address these exposure potentials. Just because an accelerator is not operating, does not mean that there is no potential for radiation exposure. Appendix E summarizes common types of accelerators that have been identified as potential sources of radiation exposure.

Any manufacturing process produces waste and byproducts, and those processes using radioactive materials are no exception. Radioactive wastes are disposed of in different ways, depending on their classification. Waste and byproducts include spent fuel from nuclear reactors to slightly contaminated gloves from routine operations. Appendix C includes a list of the categories of radioactive wastes and byproducts. These categories not only apply to the fuel cycle but to the manufacturing process that uses radionuclides in industrial practices.

Personnel must always be aware of their surroundings and be alert to the possibility of danger from the exposure to identified radioactive sources. Under normal operating conditions, most industrial and scientific sources of radiation present minimal exposure potentials when used safely. Examples of industrial radiation sources can be found in the pictures that are included in Figures 6.1 to 6.4. Regarding the production of x-rays, this type of equipment does not represent an immediate hazard. However, associated activation products and defective equipment are of concern. Devices like x-ray diffraction machines are also of concern because they emit intense beams of radiation.

Figure 6.1. Low energy Electron microscope

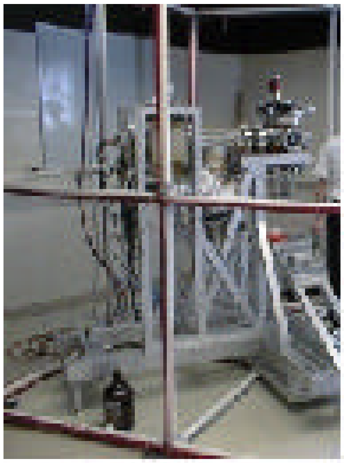


Figure 6.2. Auger Electron Spectroscopy equipment

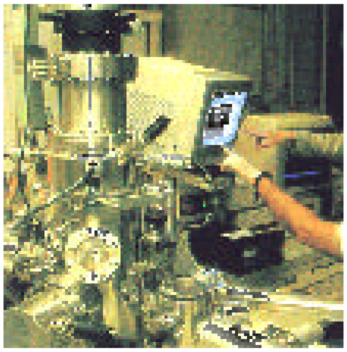
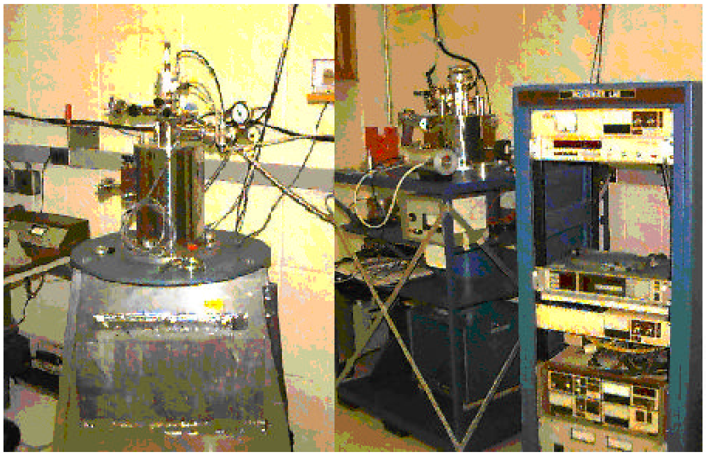


Figure 6.3. X-ray diffractometer equipment (bottom portion is a close-up look)

Figure 6.4. Ranger Scientific M ` ssbauer Spectrometer[25]



6.2. The Use of Radioisotopes in Industry

Modern industry uses radioisotopes in a variety of ways to improve productivity and, in some cases to gain information that cannot be obtained in any other way. 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 increasingly for food preservation and sterilization.

Table 6.1 encompasses the most common radioisotopes used in industry that can be identified as possible sources of exposure or contamination, the corresponding half-lives, type of radiation, usage and specific precaution levels. The following sections discuss examples of the usage of radioisotopes in industry

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[25] The M ` ssbauer spectrometer uses a radioactive ^{57}Co source to generate gamma rays that are absorbed by ^{57}Fe (a stable isotope of iron) in a sample [1].

Table 6.1. Most commonly used radioisotopes in industry

Radionuclide	Half-life	Radiation	Usage {Specific precaution level(s)}
Naturally occurring radioisotopes			
^{3}H	12.3 y	$\$^{-}$	Measurement of "young" groundwater (up to 30 years) Triated water is used as a tracer to study sewage and liquid wastes. {E-T}
^{14}C	5730 y	$\$^{-}$	Measurement of the age of water (up to 50,000 years). {E-I}
^{36}Cl	3.1 E5 y	$\$^{-}$, (	Measurement of sources of chloride and the age of water (up to 2 million years). {X-E-I}
^{210}Pb	22.3 y	", $\$^{-}$, (	Dating layers of sand and soil up to 80 years. {X-E-I}
Artificially produced radioisotopes			
^{46}Sc	83.9 d	$\$^{-}$, (	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. {X-E-I}
^{51}Cr	27.8 d	(	Together with ^{198}Au and ^{192}Ir is used to label sand to study coastal erosion. {X}
^{54}Mn	312.5 d	(	Together with ^{65}Zn is used to predict the behavior of heavy metal components in effluents for mining waste water. {X}
^{57}Co	270 d	(	Together with ^{57}Fe (stable isotope) is used in M`ssbauer analysis. {X}
^{60}Co	5.3 y	$\$^{-}$, (	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. {X}
^{65}Zn	243.9 d	$\$^{+}$, (	Together with ^{54}Mn is used to predict the behavior of heavy metal components in effluents for mining waste water. {X)
^{82}Br	35.34 h	$\$^{-}$, (	Hydrological tracing. {X-E-I}
^{85}Kr	10.76 y	$\$^{-}$, (	Reservoir engineering. {X-E-I}
^{90}Sr	28 y	$\$^{-}$, (	Radiation gauges, automatic weighing equipment. {X-E-I}
^{99m}Tc	6.0 hr	(	Together with ^{198}Au is used to sewage and liquid waste movements. {X}
^{110m}Ag	253 d	$\$^{-}$, (	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. {X-E-I}

Radionuclide	Half-life	Radiation	Usage {Specific precaution level(s)}
^{137}Cs	30 y	$\$^{-}$, (	Industrial radiography, radiation gauges, automatic weighing equipment, food irradiators and for radiotracing techniques in identifying sources of soil erosion and deposition. {X}
^{140}La	40.22 hr	$\$^{-}$, (	Together with ^{60}Co and ^{198}Au in blast furnaces to determine resident time and to quantify yields to measure the furnace performance. {X-E-I}
^{144}Ce	284 d	$\$^{-}$, (	Radiation gauges, automatic weighing equipment. {X-E-I}
^{147}Pm	2.62 y	$\$^{-}$, (	Radiation gauges, automatic weighing equipment. {E-I}
^{169}Yb	31.8 d	(	Industrial radiography. {X-I}
^{170}Tm	134 d	$\$^{-}$, (	Industrial radiography. {X-I}
^{192}Ir	74.2 d	$\$^{-}$, (	Industrial radiography and together with ^{51}Cr and ^{198}Au to label sand to study coastal erosion. {X-I}
^{198}Au	2.7 d	$\$^{-}$, (	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. {X-I}
^{239}Pu	2.4E4 y	", $, (, n	Borehold logging. ^{241}Am is also used in smoke detectors. {X-E-I}
^{241}Am	458 y	", $, (, n	
^{252}Cf	2.65 y	", (, n	

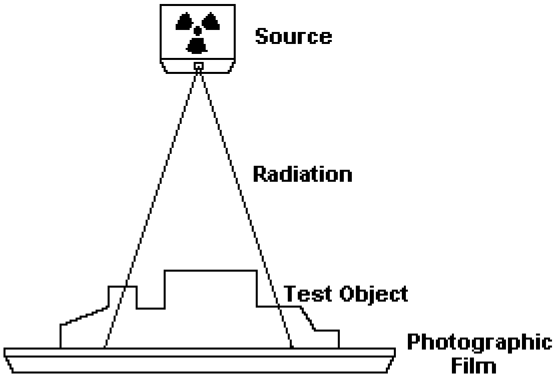
6.2.1. Gamma Radiography [2]

Gamma radiography works in much the same way as the x-ray machines at airports. Instead of the bulky machine needed to produce x-rays, all that is needed to produce effective gamma rays is a small pellet of radioactive material in a sealed titanium capsule. 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, like x-rays, pass through the object and create an image on the film. Just as x-rays show a break in a bone, gamma rays show flaws in metal castings or welded joints. The technique allows critical components to be inspected for internal defects without damage.

Because isotopes can be transported easily, gamma radiography is particularly useful in remote areas where, for example, it can be used to check welds in pipelines that carry natural gas or oil. Where a weld has been made, special film is taped over the weld around the outside of the pipe. A machine called a "pipe crawler" carries a shielded radioactive source down the inside of the pipe to the position of the weld. There, the radioactive source is remotely exposed and a radiographic image of the weld is produced on the film. This film is later developed and examined for signs of flaws in the weld.

X-ray sets can be used when electric power is available and the object to be x-rayed can be taken to the x-ray source and radiographed. Radioisotopes have the supreme advantage in that they can be taken to the site when an examination is required and no power is needed. The radiographer produces a radiograph that is a permanent photographic record of the non-destructive test (NDT). Figure 6.5 illustrates how radiographic sources are arranged.

Figure 6.5. Arrangement of a radiographic source



6.2.1.1 Radiation Used for Radiography

Radiation used for radiography uses gamma radiation. The necessary equipment is easily portable and ideally suited for remote and often difficult working conditions. Table 6.2 includes examples of radiographic sources from the industry. The radiation must have enough energy to penetrate through the object but with sufficiently reduced attenuation (increase of transmission) when passing through a flaw. The increased transmission through a flaw must produce a darker image on the developed film. The activity of the source determines how much radiation is available. Too much radiation adds fog to the film, darkening it overall and reducing the likelihood of identifying the flaw and requires safety precautions over a wider area. A low activity source requires longer exposure times to allow sufficient radiation to reach the film and create the images. The longer exposures extend the duration of the work and require the safety precautions to be enforced for longer times.

Table 6.2. Example 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

6.2.1.2. Equipment Used for Radiography

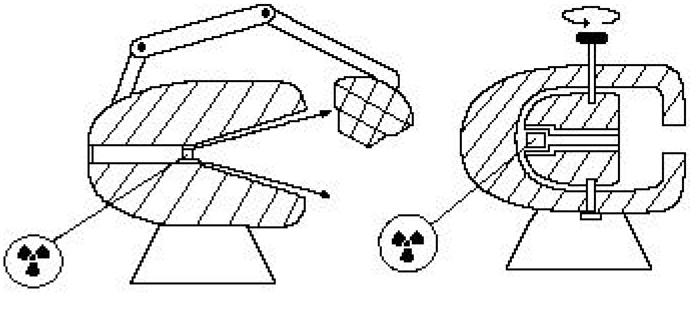
Radiographic sealed sources are special form, stainless steel capsules containing a high activity. Their gamma emissions are continuous and during transportation, the sources need to be housed in special portable containers. These exposure containers (in some countries also called cameras) totally surround the source with shielding such as lead or, more effectively, uranium (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, or
3. The source is fully removed from the container.

The first two types are often called shutter or beam containers. They collimate the radiation that is released, shaping and limiting the size of the beams that emerge. The shutter mechanisms are sometimes automatic and sometimes manual. Figure 6.6 is an illustration of the shutter type exposure container.

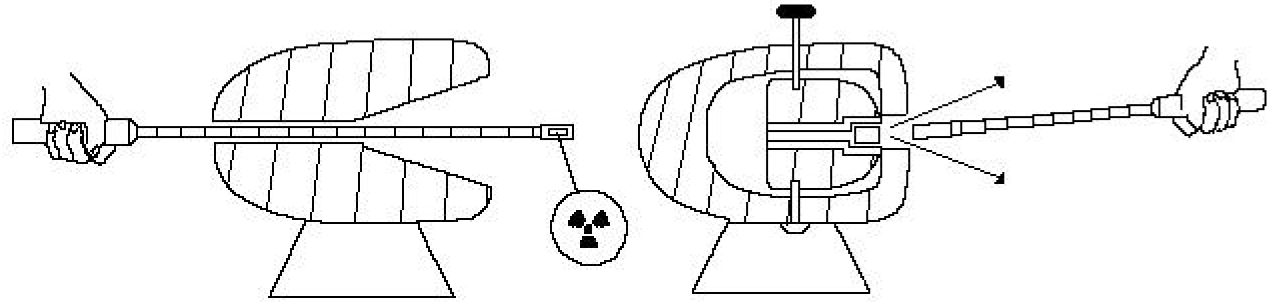
Figure 6.6. Shutter type exposure containers: removable shutter exposure container (top) and rotating shutter exposure container (bottom)



Situations occur where beam radiography using shutter containers is not possible. This may be because the container will not fit into the available space or a film area to be exposed exceeds the beam size. The manufacturers provide special long handling tools designed to remove the source from the container. The source can then be installed in a suitable collimator or used to carry out panoramic radiography. For the latter, there are no restrictions on beam direction. The radiographer usually gets higher doses from this kind of work and therefore, stringent procedures are needed to ensure that the length of the handling tool (of about 1m) is maintained between the radiographer and the source. This is illustrated in Figure 6.7. Contact with a highly active source for a few seconds could cause a tissue injury that would not become apparent for several weeks.

The most widely used equipment is now of the third type and it is called the projection container or crank-out camera. This design ensures that exposing the source from a distance can nearly always protect the radiographer.

Figure 6.7. Special rod mechanism used in panoramic radiography



6.2.1.2.1 Projection Containers

The source for the projection container is mounted on the end of a flexible wire called the pigtail. The non-active end of the pigtail protrudes from the container and is secured by a locking ring holding the source in the center of the shield. As shown in Figure 6.8, the s-shaped tube through the shield does not allow the radiation a direct path to the outside. A transit plug closes the exit port and prevents grit from fouling the S-tube. Ancillary components of the projection container include the control cable and crank, the guide tube and the extension guide tube (which is not always needed). A variety of collimators fit the end of the guide tube - the snout. To operate the projection container the snout is positioned close to the object, the cable is connected to the pigtail and the cable housing and guide tube are connected to the container.

Securing the cable housing to the container involves rotating the locking ring, which releases the pigtail. Turning the crank then drives the cable, pushing the pigtail out of the container and along the guide tube until the source reaches the snout.

The guide tube and collimator must be firmly secured by tape or held by a stable support to prevent movement as the source enters the snout. Reversing the crank control retracts the source.

Figure 6.8. Projection exposure container that shows s-tube and auxiliary components

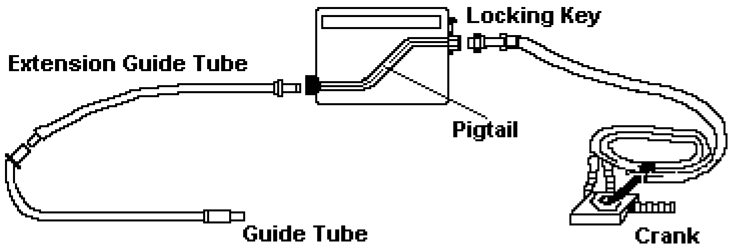
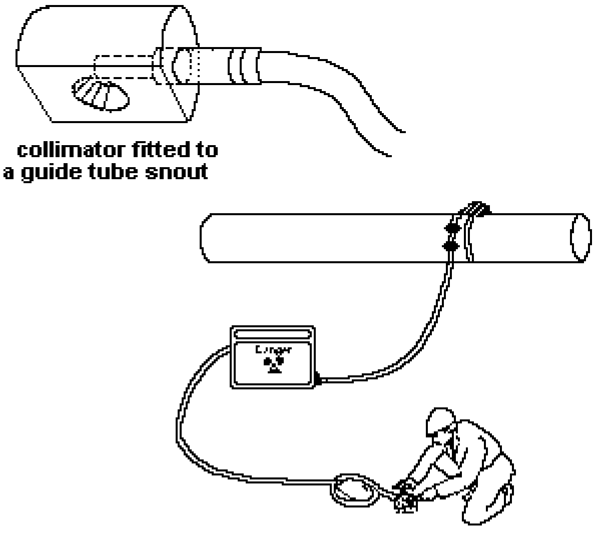


Figure 6.9. Representation of an assembled projection container arrangement in use



6.2.1.2.2. Possible Problems with Containers

Mechanical and automatically operated components are most vulnerable and become critical if their failure is likely to result in the source remaining exposed. The technical operator's handbooks supplied with the equipment should make it possible to identify possible malfunctions and their remedies. For example, although projection containers have proved very reliable, there are a number of potential problems:

1.) The end of the cable may run through the crank because of a cable fault or a failure to secure the guide tube or snout.
2.) The crank may become difficult or impossible to turn after it has been fouled by grit from the cable or container.
3.) If the cable or pigtail is kicked, it might weaken and break.
4.) The cable-pigtail connection may uncouple because of damage, wear or grit fouling.
5.) The cable housing may disconnect from the container because of a fault or rough handling.

6.) The cable housing may be crushed, trapping the cable.
7.) The guide tube may be crushed or guide tube connectors become burred, trapping the source or pigtail.

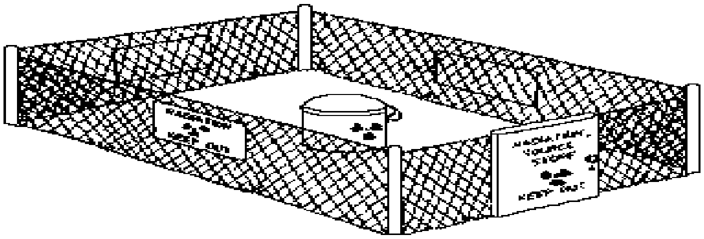
6.2.1.2.3. Storage of Equipment

Exposure containers only have sufficient shielding to enable them to be carried for short time periods and to be transported. No one should stay close to them for longer than is necessary. When a source is used regularly on a site, a special store is normally reserved for keeping the exposure container while it is not in use. The site operator's cooperation is needed so that the store can be isolated and in particular positioned well away from other hazardous materials such as explosives and corrosive substances.

The storage normally would and should display clear warning notices and be dry inside. The dose rates accessible outside the store should be as low as reasonably practicable, less than 7.5 µSv/hr or, preferably, less than 2.5 µSv/hr [2].

A lock should normally be kept on the door to prevent unauthorized people entering the area of higher dose rates or tampering with the container and the key should be kept in a safe place. A record showing where each source has been at all times may be available. Figure 6.10 illustrates a typical storage area.

Figure 6.10. Typical storage for exposure containers



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. Sometimes, on a construction site, the Controlled Area extends above and below the level on which the radiographic equipment is situated.

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

6.2.2. Gauging

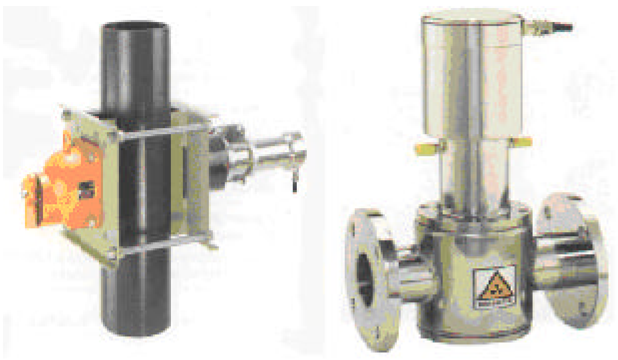
Practical examples of gauges are the measurement of concentration in the chemical industry for acids, alkalis and saline solutions; in the food industry for sugar solutions, evaporated milk, chocolate, and soup seasoning. Density gauges can be used in monitoring chemical conversions which result in density changes, for example sludge content in pipelines (extraction of ores or minerals), bauxite content for aluminum production, monitoring the precipitation of coal sludge in coal washing and sewage sludge in sewage plants. Gauges are also used in military commodities as identified in Chapter 5.

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 the absence, or even to measure the quantity, of material between a source and a detector. The advantage in using this form of gauging or measurement is that there is no contact with the material being gauged.

Another principle lies in the use of backscatter radiation. Some radiation is scattered back towards the source when matter is reducing the intensity of a radioisotope. The amount of “backscattered” radiation is related to the amount of material in the beam, and this can be used to measure characteristics of the material. This principle is used to measure different types of coating thickness.

Figure 6.11 is an example of a density gauge. The absorption of radiation as it passes through the matter between the source and the detector is an exponential function of measuring distance and density. If therefore, the measuring path is constant, the attenuation of radiation is an indication of the product density. A sensitive detector measures the residual radiation and supplies a digital signal dependent on radiation intensity. In most cases a ^{137}Cs source is used. 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 [3].

Figure 6.11. Picture of a density gauge from Berthold Industrial Systems [3]



6.2.3. Gamma Sterilization

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

Food preservation is an increasingly important application, and has been used since the 1960s. In 1997 the irradiation of red meat was approved in the U.S. Some 40 countries, excluding Australia, have approved irradiation of more than 50 different foods, to extend shelf life and to reduce the risk of food-borne diseases.

Sources of radiation can be identified in the process of food irradiation. Food irradiators can also be made with electron beams and not with radioactive material. However, the most common irradiators use ^{60}Co or ^{137}Cs. A food irradiation facility resembles any other warehouse. Workers would typically load untreated food into containers attached to a conveyor system. The containers would then move into the irradiation chamber, which is commonly enclosed by thick concrete walls (for example, 6-foot-thick concrete walls). Inside the irradiator, one can find racks of pencil-shaped rods that contain the 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.

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. Figure 6.12 is a picture of the source rack and protection grid found in the inside of a typical food irradiator.

Figure 6.12. Inside a ^{60}Co food irradiator [4]

6.3. Other Scientific Uses of Radioisotopes

Radioisotopes are used as tracers in many research areas. Most physical, chemical and biological systems treat radioactive and non-radioactive forms of an element in exactly the same way, so a system can be investigated with the assurance that the method used for investigation does not itself affect the system. An extensive range of organic chemicals can be produced with a particular atom or atoms in their structure replaced with an appropriate radioactive equivalent. Using tracing techniques, research is conducted with various radioisotopes, which occur broadly in the environment, to examine the impact of human activities. The age of water obtained from underground bores can be estimated from the level of naturally occurring radioisotopes in the water. This information can indicate if groundwater is being used faster than the rate of replenishment. Tracer radioactive fallout from nuclear weapons' testing in the 1950s and 60s is now being used to measure soil movement and degradation. This is assuming greater importance in environmental studies of the impact of agriculture.

6.3.1. Tracing/mixing Uses of Radioisotopes

Even very small quantities of radioactive material can be detected easily. This property can be used to trace the progress of some radioactive material through a complex path, or through events that greatly dilute the original material. In all these tracing investigations, the half-life of the tracer radioisotope is chosen to be just long enough to obtain the information required. No long-term residual radioactivity remains after the process.

Sewage from ocean outfalls can be traced in order to study its dispersion. Small leaks can be detected in complex systems such as power station heat exchangers. Flow rates of liquids and gases in pipelines can be measured accurately, as can the flow rates of large rivers. Mixing efficiency of industrial blenders can be measured and the internal flow of materials in a blast furnace examined. Feeding the insects with radioactive wood substitute and then measuring the extent of the radioactivity spread by these insects can be used to find the extent of termite infestation in a structure. This measurement can be made without damaging any structure as the radiation is easily detected through building materials.

6.3.2. Mineral Analysis

X-rays from a radioactive element can induce fluorescent x-rays from other non-radioactive materials. The energies of the fluorescent x-rays emitted can identify the elements present in the material, and their intensity can indicate the quantity of each element present. This technique is used to determine element concentrations in process streams of mineral concentrators. Probes containing radioisotopes and a detector are immersed directly into slurry streams. Signals from the probe are processed to give the concentration of the elements being monitored, and can give a measure of the slurry density. Elements detected this way include iron, nickel, copper, zinc, tin and lead.

Gamma ray transmission or scattering can be used to determine the ash content of coal on-line on a conveyor belt. The gamma ray interactions are atomic-number-dependent, and the ash is higher in atomic number than the coal combustible matter. On-line ash gauges are most common in Australia, having many of this type system installed worldwide.

Neutrons can react with elements in a sample causing the emission of gamma rays which, when analyzed for characteristic energies and intensity will identify the types and quantities of elements present. Additionally, neutrons can be deflected back to their source by surrounding material. For instance, a probe containing a neutron source can be lowered into a bore-hole where the radiation is scattered by collisions with surrounding soil. Since hydrogen (the major component of water) is by far the best scattering atom, the number of neutrons returning to a detector in the probe is a function of the density of the water in the soil.

6.4. Sources from the Transportation of Radioactive Materials

About 100 million packages of hazardous materials are shipped every year in the United States; 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 is 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. [5]. 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 6.3 in order to ease the identification of these sources. These concepts are commonly linked with packages containing radioactive material that are to be transported or stored.

Table 6.3. Basic concepts for the storage and transportation of radioactive materials [6-8]

Concept	Definition
Contamination Wipe Survey	A survey for non-fixed (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[26].
Limited Quantity of Class 7 (Radioactive) Material	A quantity of radioactive material not exceeding the package limits specified in 49 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.

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[26] Analysis of the wipes can be obtained from the U.S. Army Communications-Electronics Command, the U.S. Army Ionizing Radiation Dosimetry Center or a processing facility with a proportional counter, liquid scintillation counter or other detector (not survey instrument) capable of detecting the contamination levels in 49 CFR 173.443.

Concept	Definition
Non-Fixed 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 non-dispersible 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 (:Ci/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 (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 meter, as measured from the surfaces of the shipping container rounded up to the nearest tenth (i.e., 0.13 mrem/hr at 1 meter 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.

Concept	Definition
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. 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.

The following figures include examples of the packaging and transportation of radioactive materials that can be used to identify possible sources of exposure or contamination. Figures 6.13 and 6.14 include typical type A and type B packages used for the transportation of radioactive materials. Figure 6.15 is a picture of a container used for the transportation of enriched uranium, but not for weapon-grade enriched uranium. Figures 6.16, 6.17, 6.18 and 6.19 are representative of the most common ways radioactive materials from the nuclear fuel cycle are transported, including ground, ship and rail transportation.

Figure 6.13. Typical Type A packaging of radioactive materials (DOT specification 7A) [9]

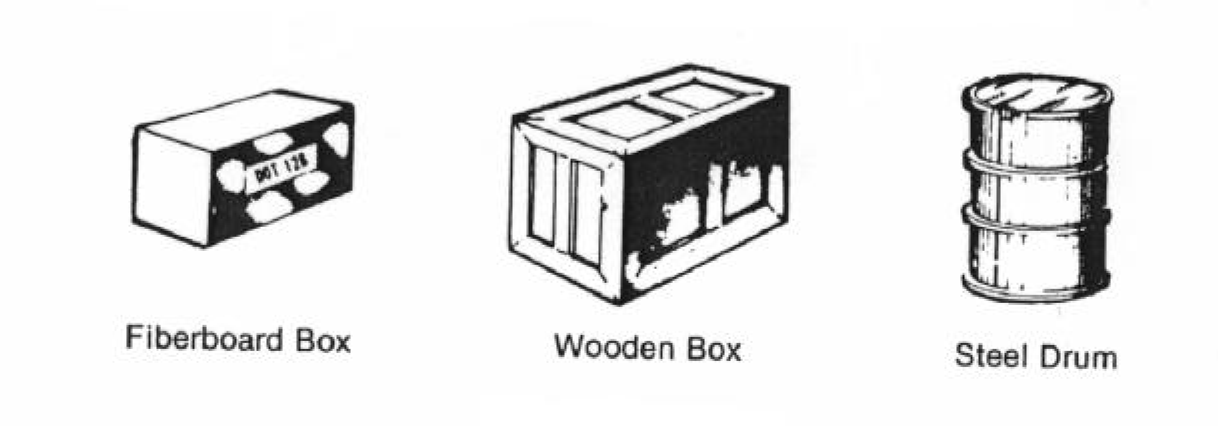

Figure 6.14. Typical type B packaging schemes [9]

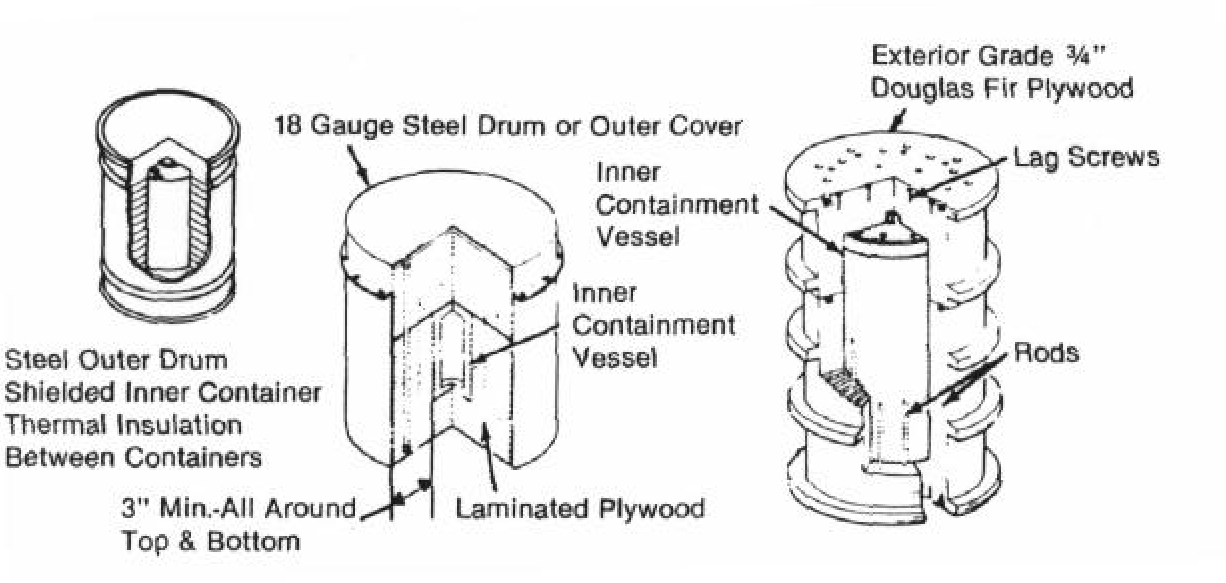

Figure 6.15. Container of enriched uranium (Eurodif's Georges Besse plant, Tricastin site, France)

Figure 6.16. Shipment of spent fuel by road

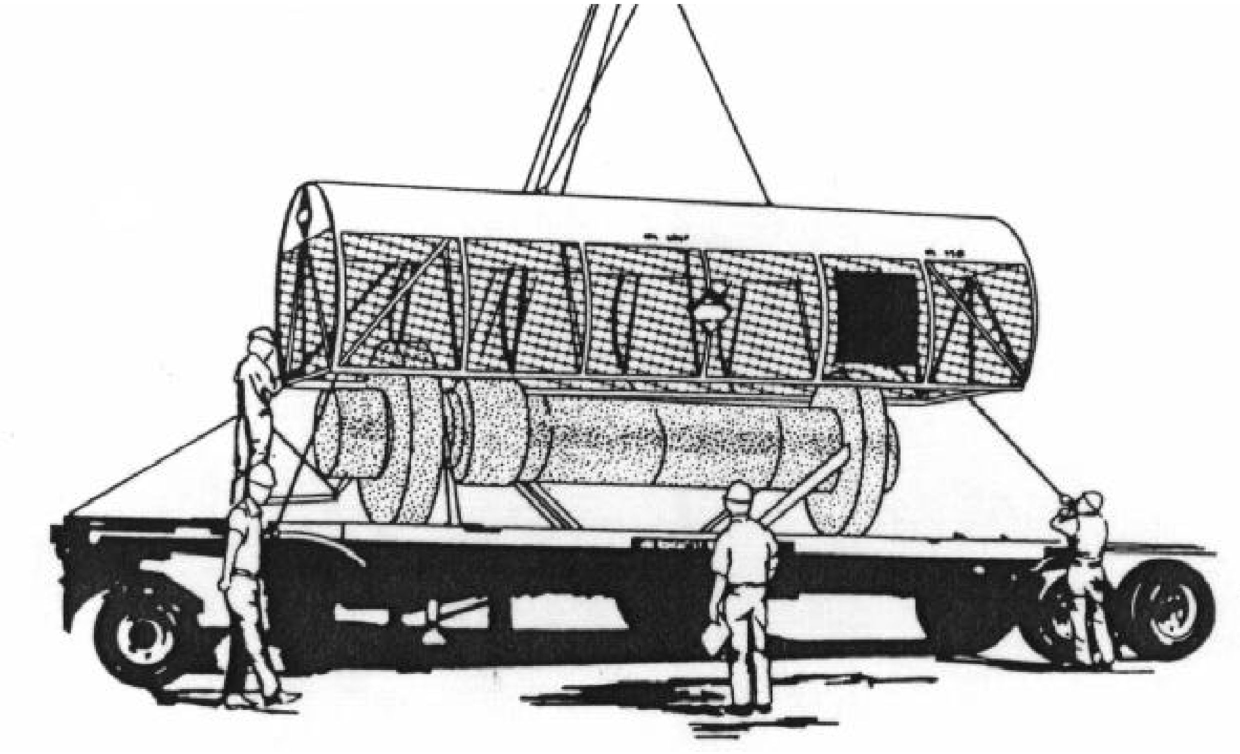

Figure 6.17. Transport by road of spent fuel cask (picture in front of the Chinon Power Plant, France)

Figure 6.18. Picture of ship loading and transporting nuclear material (transport ship, TRANSNUCLEAIRE, France)

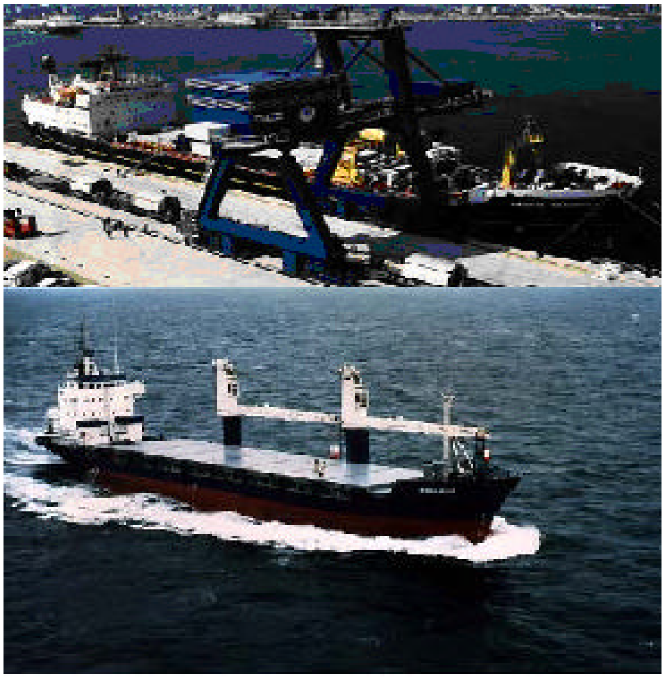

Figure 6.19. Transportation of nuclear material via railways (Valognes railway terminal, Cherbourg, France)

6.5. Summary of Sources from Industrial Practices and the Transportation of Materials

Table 6.4 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 6.4. Summary of radiation sources from industry and transportation of radioactive materials

Identified source	Radiations	Longest Half-life	Examples	Precaution level(s)
X-ray machines	γ and X-rays	n/a	Electron microscopes Spectroscopy equipment Diffractometer equipment	X
Industrial accelerators	γ, x-rays, and neutrons (n)	n/a	See Appendix E for examples	X
Radioactive waste	α, β, γ, and n	n/a	See Appendix C and waste from industrial and biomedical practices	X-E-I
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 as those identified in Appendix B	X-E-I-U
Naturally occurring radioisotopes				
^{3}H	\$$^{-}$	12.3 y	Age water measurements	E-T
^{14}C	\$$^{-}$	5730 y	Carbon dating	E-I
^{36}Cl	\$$^{-}$, (	3.1 E5 y	Age water measurements	X-E-I
^{210}Pb	", \$$^{-}$, (	22.3 y	Sand and soil dating	X-E-I
Artificially produced radioisotopes				
^{46}Sc, ^{60}Co, ^{82}Br, ^{85}Kr, ^{90}Sr, ^{110m}Ag, ^{137}Cs, ^{140}La, ^{144}Ce, ^{147}Pm	\$$^{-}$, (	30 y	Resident time determination, gamma sterilization, industrial radiography, hydrological tracing, gauges, food irradiators.	X-E-I
^{51}Cr, ^{54}Mn, ^{57}Co, ^{65}Zn, ^{99m}Tc, ^{169}Yb	(	312.5 d	Labeling, spectrometry, industrial radiography	X
^{170}Tm, ^{192}Ir, ^{198}Au	\$$^{-}$, (	5.3 y	Industrial radiography, labeling	X-I
^{239}Pu, ^{241}Am	", \$, (, n	2.4E4 y	Borehold logging, smoke detectors	X-E-I
^{252}Cf	", (, n	2.65 y	Borehold logging	X-E-I

References:

1. Hunt, C.: Mossbauer: Marvelous Measurements of Magnetic Minerals. *The Institute for Rock Magnetism (IRM) Quarterly* 1992; 2(No.3): 2388.

2. Web: http://www.iaea.org/ns/rasanet/training/index.html. Vienna: International Atomic Energy Agency, 1999.

3. Web: http://berthold.com.au/industial_pages/. Australia: Berthold Industrial Systems, 1999.

4. IAEA: The Radiological Accident at the Irradiation Facility in Nesvizh. Vienna: VIC Library, 1996.

5. UNSCEAR: Sources, Effects, and Risks of Ionizing Radiation, United Nations. New York: United Nations Scientific Committee on the Effects of Atomic Radiation, 1988.

6. DOT: Shippers - General Requirements for Shipments and Packgages. Washington, DC: Department of Transportation, 1988.

7. DA: Transportation information for CECOM radioactive commodities. Washington, DC: Department of the Army, 1997.

8. NRC: Packaging and Transportation of Radioactive Materials. Washington, DC: Nuclear Regulatory Commission, 1991.

9. DOT: Hazardous Materials Regulations. Washington, DC: Department of Transportation, Government Printing Office.

Chapter 7. Radiation Exposure and Contamination Caused by the Production and Use of Nuclear Weapons

This section presents potential sources of exposures and contamination from the production and use of nuclear weapons. There are several countries that have nuclear weapons or have the technical ability to produce nuclear weapons. Nations that have declared possessing nuclear weapons are: the United States, Russia, Britain, France, China, Ukraine, Kazakhstan, Belarus, India and Pakistan. Nations that are suspected to possess nuclear weapons are: Iran, Israel, Libya and North Korea. Countries that have possessed or have pursued nuclear weapons are: Argentina, Brazil, Iraq, South Africa, Sweden, Switzerland, and Taiwan. A selected set of countries that could undertake and build nuclear weapons in a few years is: Australia, Canada, Germany, Japan, and [1]. Almost any industrial nation can produce nuclear weapons within several years if they decide to put forth the effort. Thus, it is possible to encounter a weapons plant on foreign soil or, under some circumstances, discover a previously unknown weapons production plant. The primary focus of this section is on radiological hazards presented by production plants, the presence of weapon feed materials and wastes, and the accidental or intentional dispersion of radioactive materials. Much information about the principles and design of nuclear weapons can be found in unclassified literature. The brief outlines of the physics and designs of nuclear weapons are based on some of these sources. Nuclear war and nuclear explosion are discussed at length in many military documents and will be incorporated by reference.

7.1. Summary of Basic Physics of Significance in the Production of Nuclear Weapons

Subsequent to identifying potential sources that come from the production of nuclear weapons, it is important to cover some basic physics principles. Basic understanding of these principles will help comprehension of this section and easy identification of potential sources.

There is tremendous energy stored within the nucleus of an atom; nuclear weapons are designed to release a small portion of this energy in a devastating explosion. The two processes by which this nuclear energy can be released are fission and fusion.

7.1.1. Fission

The fission concept was introduced in this tech guide in the section that identified sources from the nuclear fuel cycle and it is emphasized here. In a fission reaction, a nucleus absorbs a neutron and a very unstable compound nucleus is formed that quickly splits with burst of energy. A sample fission reaction is presented below:

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow {}^{137}_{55}\mathrm{Cs} + {}^{97}_{37}\mathrm{Rb} + 2\,{}^{1}_{0}\mathrm{n} + \mathrm{Q}$$

The ^{236}U is a compound nucleus that can undergo spontaneous fission; Q is the energy released and is equal to about 200 MeV. This reaction is not the only one possible. The actual reaction that occurs is a matter of chance but the probability distribution of the reactions is known. Each reaction produces different fission products and because of the probabilistic nature over 400 fission products are produced in a nuclear reaction.

A fission of any fissionable nuclide releases about 200 MeV of energy. The table below shows the average energy distribution from a fission of ^{235}U.

Table 7.1. Average energy distribution of the fission product from the thermal fission of ^{235}U

Fission Product	Energy (MeV)	Percentage
Fission fragments - kinetic energy	~168	81.2
Fission product decay ($, (, and 0)	~27	13.0
Prompt (-rays	~7	3.4
Fission (prompt) neutrons	~5	2.4

On average there are just over two neutrons produced per fission; these neutrons are available to induce additional fission reactions. If there are enough ^{235}U nuclei available then a continuing series of induced reactions, called a chain reaction, may occur. The minimum mass of ^{235}U required to maintain the chain reaction is called the critical mass. If less than a critical mass is present, the mass is subcritical; if more is present the mass is supercritical.

The value of the critical mass for a nuclide depends on density of the material, the purity of the material, geometry of the material, and the presence of neutron reflectors. Because of the large number of nuclei in gram quantities of fissile materials, the limiting factor for criticality is usually the number of neutrons available to induce fissions. The density of the material is important because the denser the material is the shorter the distance a neutron will travel before it is absorbed; hence, it is less likely to escape the mass. Impurities in the material may absorb neutrons without inducing a fission, lowering the number of neutrons available for fission. The escape of neutrons also depends on the amount of surface area as opposed to the volume or mass of the material. A larger area means more opportunity for escape. Spheres have the lowest surface area to volume ratio, and so, are the most efficient for maintaining criticality for a given mass of material. Neutron reflectors are those materials that would surround a critical mass and scatter escaping neutrons back toward the material.

7.1.2. Fusion

Fusion reactions are those that combine two light elements into a heavier element with a subsequent release of energy. However, it is required that the coulomb forces be overcome so the nuclei come into contact and remain in contact long enough for fusion to occur. To do this, elements to be fused are often heated to very high temperatures and compressed to very high density.

The most familiar example of fusion is the sun. In the sun, hydrogen atoms are fused to produce helium both by direct fusion of two hydrogen atoms or by a reaction in which carbon acts as a catalyst. This is a relatively slow reaction that is started by heat produced by the enormous pressures in the interior of the sun. Some fusion reactions are:

$$
\begin{aligned}
&{}^{2}_{1}\mathrm{H}+{}^{3}_{1}\mathrm{H}\rightarrow{}^{4}_{2}\mathrm{He}+{}^{1}_{0}\mathrm{n} + 17.588\ \mathrm{MeV}\\
&{}^{2}_{1}\mathrm{H}+{}^{2}_{1}\mathrm{H}\rightarrow{}^{3}_{2}\mathrm{He}+{}^{1}_{0}\mathrm{n} + 3.268\ \mathrm{MeV}\\
&{}^{2}_{1}\mathrm{H}+{}^{2}_{1}\mathrm{H}\rightarrow{}^{3}_{1}\mathrm{H}+{}^{1}_{1}\mathrm{H} + 4.03\ \mathrm{MeV}\\
&{}^{3}_{2}\mathrm{He}+{}^{2}_{1}\mathrm{H}\rightarrow{}^{4}_{2}\mathrm{He}+{}^{1}_{1}\mathrm{H} + 8.34\ \mathrm{MeV}\\
&{}^{6}_{3}\mathrm{Li}+{}^{1}_{0}\mathrm{n}\rightarrow{}^{3}_{1}\mathrm{H}+{}^{4}_{2}\mathrm{He} + 4.78\ \mathrm{MeV}\\
&{}^{7}_{3}\mathrm{Li}+{}^{1}_{0}\mathrm{n}\rightarrow{}^{3}_{1}\mathrm{H}+{}^{4}_{2}\mathrm{He}+{}^{1}_{0}\mathrm{n} - 2.47\ \mathrm{MeV}
\end{aligned}
$$

The last two reactions above are not technically fusion reactions but are included here because of their importance in weapon design. These reactions are called neutronic reactions or neutron absorption reactions.

In weapons, fusion reactions are used both for their own explosive energy release and in some cases, as neutron sources for additional fission reactions. All of the above reactions are candidates for use in nuclear weapons.

7.2. Designs and Types of Weapons

The basic types of weapons are fission only and combined fission-fusion weapons. There are subgroups of these types. Fission-fusion weapons can be made in stages to achieve very high yields (tens of megatons), or they can be designed to enhance neutron output to make neutron bombs. Any of the weapon types can be salted with elements to enhance residual radiation through contamination.

7.2.1. Fission Only Weapons

These weapons use only the energy released by fissionable elements. The main radionuclides used are highly enriched uranium (HEU) and ^{239}Pu. Enriched uranium is uranium whose ^{235}U content is greatly increased over natural uranium. In many weapons, the HEU can be up to 93.5% ^{235}U. For plutonium, the mixture of isotopes can vary but on average the mix is 93.4% ^{239}Pu, 6.0% ^{240}Pu, and 0.6% ^{241}Pu [1]. In addition to the fissile material, fissionable material such as ^{238}U can be used to enhance the fission yield. When wrapped by a layer of ^{238}U, the weapon can take advantage of the high energy neutrons produced by the fission reactions in the fissile center. In effect, neutrons escaping from the first fission explosion induce additional fissions in the outer shell causing a second explosion.

Because of the limitations on size (larger yields require more material), the maximum yield for a fission only weapon may be about 500 kt [1]. To achieve higher yields, fission and fusion reactions are combined.

7.2.2. Combined Fission Fusion Weapons

Combined fission and fusion reactions can produce weapons of vastly greater yields than by fission alone. Essentially, in combined weapons, a fission explosion ignites a fusion reaction. This combination can be manipulated with a multitude of designs to achieve different goals.

Fusion can be used to boost the yield of a given fission only weapon - a fusion boosted weapon. Because many fission weapons are inefficient (only about 20% of the fissile material undergoes fission), the addition of more neutrons from a concurrent or slightly delayed fusion reaction can greatly increase the efficiency. It is possible to increase the efficiency to about 50% with fusion boosting. The fusion reactions add only about 1% to the yield of the weapon.

Staged weapons combine a series of fission-fusion-fission steps to greatly increase yields. In these weapons, the fusion reactions use both the energy released in the reaction and the high energy neutrons to induce fissions in fissionable materials. These weapons give the highest yields per unit weight.

Nuclear weapons designed to maximize neutron output, which are not to be used in an explosion but to enhance external radiation effects, are called neutron bombs. These weapons are low yield combined fission-fusion weapons.

If instead of a fissionable outer layer, a layer of a material chosen to enhance residual radioactive contamination is used, the weapon is said to be salted. An example is a combined fission-fusion weapon with an outer jacket of ^{59}Co to enhance the production of radioactive ^{60}Co. The choice of the salting element depends on the contamination wanted. No salted weapons have ever been used in an atmospheric test, and it seems unlikely that one will be built given the availability of combined fission-fusion-fission weapons [2].

7.3. Weapons Production

In general radiological terms, making nuclear weapons entails the same materials and processes used in the nuclear fuel cycle. A brief schematic of this once through cycle is shown in Table 7.2.

The major distinctions between weapons production and fuel fabrication are that the weapons production requires HEU, ^{239}Pu, and tritium. Typical reactor fuels are 3.5% by weight ^{235}U whereas for weapons enrichments of ^{235}U of up to 93.5% are common. Radionuclides necessary for weapons production are: ^{3}H (tritium), ^{235}U, ^{239}Pu, and DU (depleted uranium). Also ^{232}Th, ^{233}U, and small amounts of ^{210}Po (alpha emitter combined with beryllium and used as a neutron source in bombs) and small amounts of transuranic wastes can be present.

Table 7.2. Major processes in the production of nuclear weapons [3]

Step	Process	Description
1	Uranium Mining, Milling and Refining	Mining and milling are the processes involved with removing uranium ore from the Earth and processing it chemically to make uranium oxide (U_3O_8), called yellowcake. Refining is the process of converting the uranium oxide into purified forms for the next step of weapon production.
2	Isotope Separation	Isotope separation (enrichment) is the process of separating the natural isotopes of the elements of interest.
3	Fuel Fabrication	Fabrication involves the mechanical processes used to make the weapon fuel.
4	Reactor Operations	Nuclear reactors are used to produce ^{239}Pu, ^{3}H, and to make smaller amounts of other radionuclides for weapons.
5	Chemical Separations	In this step, the fuel from the reactors on Step 4 is chemically dissolved and the uranium, plutonium, and other radionuclides are separated and concentrated. This step also includes reprocessing operations.
6	Component Fabrication	This step is the manufacturing, assembly, inspection, bench testing, and verification of the parts of the weapons. Also included are the recovery and recycling of radionuclides and other weapon components from retired warheads and waste materials.
7	Weapons Operations	This is the final assembly, maintenance, and decommissioning of the weapons.
8	Research, Development, and Testing	This step proceeds concurrently with the other seven and involves all the scientific, engineering, and technical research and development of the weapons.

7.4. Safeguards

Nuclear weapons are extremely destructive, so great precautions are taken to ensure the safety and security of the weapons [1]. In addition to preventing accidental detonations, precautions are made to ensure the containment of radioactive materials. Multiple safety measures of different complexity have been built into weapons.

First, the detonation system (the warhead) is isolated from electrical energy. The link to warhead is physically isolated and must be closed by the arming system. However, it is remotely possible for an accident to close this link, and so several fail safe or weak links are built into the arming system. These links fail if exposed to abnormal conditions; the failure of these weak links does not compromise the integrity of the weapon. In effect, any incident that bridges the link to the warhead will cause one or more of the weak links to fail and thus disable the weapon.

There are also precautions against unauthorized detonations of nuclear weapons. The first defense is a lock on the weapon also called a *permissive action link* (PAL) [1]. This is essentially an electronic combination lock on the weapon. The weapon cannot be armed unless the two proper combinations are entered simultaneously or in very close sequence. One person does not know both codes; a single individual cannot arm a weapon. The codes are also changed regularly.

Once the PAL has been activated, the weapon can be armed and fired. The arming system has very robust signal discriminating features so false signals (random noise or unauthorized attempts) cannot arm the weapon. The weapons also contain *environmental sensing devices* (ESD) to prevent detonation of the weapon unless proper external conditions exist [1]. For example, the ESD detect length of free fall, acceleration forces, temperatures, barometric pressures, and so on and compare these values to expected values. If the external conditions do not fall within expected values, the weapon will not detonate.

Other safety measures include fire resistant construction and robust high explosives, limited retry on code entries, and automatic self-damaging components. Some or all of these features are present on weapons. Fire resistance helps to minimize the chances of an accidental detonation or dispersal of the fissile material. Limited retry codes require that authorized persons reset the codes after a set number of incorrect entries. Self-damaging components will break in a safe mode and require factory service to be fixed. Also, it is possible to activate the self-damaging systems remotely.

7.5. Transportation, Storage and Deployment, and Decommissioning

This section encompasses a brief summary of the transportation of radioactive materials to be used for the production of nuclear weapons and the transportation of weapons themselves. The storage and deployment of these weapons and their decommissioning are also included in this section because these activities lead to scenarios of a radiological threat.

7.5.1. Transportation

The Department of Energy’s Transportation Safeguards Division (TSD) controls the transportation of nuclear weapons, weapons components, and special nuclear materials (SNM) in the United States. The transportation of weapons materials is currently under complete Federal control [4].

Safety and security are entwined in planning the transportation of weapons material. The TSD has the ability to maintain constant contact with each convoy. The actual materials are carried on a Safe Secure Trailer (SST). An SST is an 18-wheeled rig that has been modified for secure and safe transport of cargo. These rigs are armored and have special mountings for the weapons components, crumple zones, and other precautions. Furthermore, each rig and accompanying vehicle has a full complement of radiological, communications, electronic, and other equipment.

Specially trained couriers are employed by the TSD to drive and escort the shipments. The couriers undergo a 12-week training course that includes tractor-trailer driving, firearms, and communications. Furthermore, there are a series of tests and a one-year on the job training program. At the end of the first year, the courier will be evaluated to continue employment.

In the United States, fully assembled weapons are not transported and armed weapons are never transported. Therefore, the chance of an accidental detonation from an accident involving nuclear weapons is extremely remote. However, the situation for already assembled weapons is different. Assembled warheads and bombs are transported to appropriate DOE plants for disassembly - again no armed weapons are ever transported.

7.5.2. Storage and Deployment

Weapons are stored unarmed with all the safeguards activated, so the chance of accidental detonation is extremely remote. In some cases, the final assembly of the weapons takes place at the deployment location, and even then the weapons are not fully assembled until specific wartime conditions exist. Also, stockpiles of inactive weapons are maintained in the United States arsenal. In these stockpiles, the operational warheads are stored separately from the delivery systems.

7.5.3. Decommissioning

The decommissioning of weapons includes the removal of all weapons components, storage of the fissile material, and final disposition of the fissile materials. Currently, in the United States, weapons grade uranium (~93.5% ^{235}U) is processed into reactor grade uranium (~3.5% ^{235}U) for power reactor use. Plutonium is presently being stored with no plans for use in U.S. power plants. However, other countries such as France and Japan can and do use plutonium in power reactors.

7.6. The Use of Nuclear Weapons

Nuclear weapons have evolved since the era of the Manhattan Project. Several documents have addressed this issue and are summarized in this section. Another type of weapon, called nuclear dispersal weapons, are also referred to, as they possess a radiological threat in the nuclear warfare arena.

Appendix H describes three scenarios involving weapons grade uranium, ^{238}U, and weapons grade plutonium. The examples include sections on how to estimate the specific activity of radionuclides present, the computation of the inhaled activity, the committed effective dose equivalent, and the evaluation of internal and external exposure. These computations are performed using the tabulated parameters from the following sections in order to obtain preliminary estimates of doses to exposed personnel.

7.6.1. Nuclear explosions

Operations in areas in which nuclear weapons have been used are covered extensively in other military documents and are summarized in the Medical NBC Battlebook. Below is a table of selected references for operations in an area where nuclear weapons have been used.

Table 7.3. Selected military references for operations in a nuclear war

Manual Number	Manual Title
FM 3-7	NBC Field Handbook
FM 3-3-1	Nuclear Contamination Avoidance
FM 3-4	NBC Protection
FM 3-19	NBC Reconnaissance
FM 100-30	Nuclear Operations
FM 8-10-7	Health Service Support in a Nuclear, Biological, and Chemical Environment
FM 8-9, Part 1	NATO Handbook on the Medical Aspects of NBC Defensive Operations

7.6.2. Radiation Dispersal Weapons

Radiation dispersal weapons are simply conventional weapons used to disperse radioactive material into the environment. These weapons span diverse categories limited only by human ingenuity; for example, a dispersal weapon can be a nuclear weapon exploded to disperse fissile and fissionable material. Other examples are the use of a weapon at a ^{137}Cs irradiator in order to spread radioactive cesium contamination, or an explosion involving any other radioactive materials. The radiological consequences from radiation dispersal weapons are very similar to conventional contamination incidents.

7.6.2.1. Accidents and Incidents

Accidents and incidents discussed here are events not involving nuclear explosions but may involve significant contamination and potential for exposures. The DOD has a comprehensive document on the response to a nuclear weapons accident, *Nuclear Weapon Accident Response Procedures (NARP),* DoD 5100.52.M, September 1990 [5]. The NARP document addresses all the issues dealing with the response to a nuclear weapons accident including non-radiological hazards and logistics.

Thirty-two serious weapons accidents occurring between 1950 and 1980 have been reported by the DOD [4]. In only two of the accidents was plutonium dispersed [6]. However, it is possible for depleted uranium and other radioactive materials in the bomb casings to be released whenever the casings are damaged.

7.6.2.1.1. Palomares, Spain - 1966

During a refueling exercise, two U.S. Air Force planes crashed over Palomares, Spain. Four thermonuclear weapons were involved with the crash: one landed in the Mediterranean sea and was recovered after a t3 month search, one fell by parachute on to a nearby field and was recovered intact, and two were destroyed when the chemical explosives detonated on impact. No nuclear detonations occurred. However, the plutonium metal burned and was distributed as plutonium oxide over about 2.26 km^2 (0.87 square miles) of farmland.
The response to the accident was intense and included removal of soil with concentrations of Pu greater than 1.2 MBq m^{-2} (32 :Ci m^{-2}) by plowing and mixing of farmland with lower Pu concentrations. Where plowing was not feasible, soil and rocks with contamination greater than 120kBq m^{-2} (3.2 :Ci m^{-2}) were removed by hand. Measurements of residual contamination and on humans continued until at least 1988. There have been no significant medical effects reported among the villagers.

7.7. Potential Exposures from the Production of Nuclear Weapons

The potential for radiation exposures from uranium mines and mills for use in the production of nuclear weapons is very similar to that for reactor fuel production. Regardless of the enrichment method used, all enrichment processes consist of a feed of natural-to-low enrichment uranium and an output of HEU and DU. Generally, HEU is uranium whose ^{235}U specific activity has been increased over its natural abundance. Weapons grade enriched uranium contains by mass about 93.5% ^{235}U, 1.5 to 2.0% ^{234}U, and the remainder ^{238}U. Depleted uranium is the remainder of the enrichment process and had less than the natural abundance of ^{235}U. The Department of Defense defines DU as about 98.8% ^{238}U, 0.2% ^{235}U, and 0.001% ^{234}U. The major radionuclides of concern in processing and enrichment are natural uranium, thorium, and progeny in the feed materials, and HEU, DU, and progeny wastes at the output.

Plutonium is produced by neutron activation of ^{238}U. For weapons production, reactors designed to enhance ^{239}Pu production and recovery were used. In these plants, there would be fission products common to any irradiated nuclear fuel. The exposure potential at a plutonium production site would be very similar for a nuclear fuel-reprocessing site with high levels of fission products and chemically toxic materials. Although reprocessing of fuel does not currently happen in the United States, several European countries do reprocess their fuel. For a more detailed discussion of the exposure potentials associated with reactors and the nuclear fuel cycle see Chapter 3.

Tritium is produced through a neutron absorption reaction with ^{6}Li in specially designed reactors and in heavy water moderated reactors. Tritium is present in many assembled nuclear warheads.

Assembled fission weapons contain tens of kilograms of fissile materials and may contain up to about a 1000 kg of fissionable tamper material (most likely ^{238}U). Fission-fusion combination weapons may contain tritium in quantities on the order of a few grams [1].

The following table shows the major processes in the production of nuclear weapons and the radionuclides that may be present. These nuclides may be present as bulk materials, low level waste, or as low level contamination of equipment and surfaces.

Table 7.4. Radioactive materials associated with the production of nuclear weapons (This table is based on the 8 processes shown in Table 7.2)

Step	Process	Radioactive Materials
1	Uranium Mining, Milling and Refining	Large volumes of mill tailings containing Th, Ra, Rn, at low concentrations; natural uranium.
2	Isotope Separation	Enriched U at various stages of enrichment, depleted U, natural uranium.
3	Fuel Fabrication	Enriched uranium, depleted uranium, and natural uranium.
4	Reactor Operations	Enriched uranium, depleted uranium, natural uranium, fission products, activation products, transuranic nuclides, spent nuclear fuel, Pu.
5	Chemical Separations	Enriched uranium, depleted uranium, natural uranium, fission products, activation products, transuranic nuclides, and tritium.
6	Component Fabrication	Tritium, plutonium, transuranic nuclides, enriched uranium, depleted uranium.
7	Weapons Operations	Tritium, plutonium, enriched uranium, depleted uranium
8	Research, Development, and Testing	Fallout, plutonium, depleted and enriched uranium, fission products, and activation products.

7.8. Radiological Properties of Weapons Related Radionuclides

Only uranium, plutonium, and tritium are covered here. Information on other radionuclides can be found in the references cited in this section.

7.8.1. Uranium

Uranium was identified as a naturally occurring radioactive material in Chapter 2 and as part of the nuclear fuel cycle in Chapter 3. This section identifies uranium as a source related with nuclear weapons; it expands on its physical and radiological properties, as well as its radiotoxicity.

First isolated in 1841, uranium and its compounds have been used for at least 2,000 years; yellow glass containing uranium oxide dating from 79 A.D. was found near Naples, Italy. Uranium occurs naturally and is the 50th most abundant element in the earth's crust, making it about as abundant as arsenic and molybdenum. Uranium is widely distributed in the lithosphere and the oceans. Uranium is a primordial radionuclide, meaning that it was present at the formation of earth.

7.8.1.1. Physical and Radiological Properties

Uranium is a silvery-white metal that is pyrophoric (burns readily) when in small pieces (e.g., machining shavings and dusts). If exposed to air, it forms a layer of a powdery mossy green/yellow oxide. Its melting point is 1135 °C and its boiling point is 4131 °C. It has a density of about 18.9 g cm^{-3}. There are eighteen isotopes of uranium and all are radioactive. The half-lives of these isotopes range from about 1 μs for ^{222}U to about 4.5 billion years for ^{238}U.

In nature, there are three isotopes of uranium distributed by mass as follows: ^{238}U ($T_{1/2}$ = 4.5 billion years) 99.2830%, ^{235}U ($T_{1/2}$ = 704 million years) 0.7110%, and ^{234}U ($T_{1/2}$ = 246,000 years) 0.0054%. Because of the long half-lives ^{238}U and ^{235}U are sources of long chains of decay products in nature. If completely isolated from chemical alteration in nature and present in the abundance above, then about 49% of the radioactivity is caused by ^{238}U, another 49% by ^{234}U, and remaining 2% by ^{235}U. Table 7.5 below shows the decay schemes for the three major uranium isotopes and Table 7.6 shows the specific activities of the three major uranium isotopes.

Table 7.5. Decay data for the three major uranium isotopes and progeny [7]

		Major Radiation Emitted					
		"		$		(	
Isotope	Half life	MeV	%	MeV	%	MeV	%
^{235}U	7.04 x 10^{8} y	4.25	10.3			0.144	10.5
		4.37	17.6			0.163	4.7
		4.40	56			0.186	54
		4.55	11.3			0.205	4.7
^{231}Th	25.5 h			0.205	15	0.0256	14.8
				0.287	49	0.0842	6.5
				0.304	35		
^{238}U	4.5 x 10^{9} y	4.15	22.9			0.05	0.07
		4.20	76.8				
^{234}Th	24.1 d			0.076	2.7	0.0633	3.8
				0.095	6.2	0.0924	2.7
				0.096	18.6	0.0928	2.7
				0.189	72.5	0.1128	0.24
^{234}Pa^{m}	1.17 m			2.28	98.6	0.766	0.21
						1.001	0.59
^{234}U	2.44 x 10^{5} y	4.72	27.4			0.053	0.12
		4.77	72.3			0.121	0.04

Table 7.6. Specific activities of the three major uranium isotopes

Uranium Isotope	Specific Activity (TBq g^{-1})	Specific Activity (mCi g^{-1})
^{234}U	2.31 x 10^{-4}	6.25
^{235}U	8.00 x 10^{-8}	2.17 x 10^{-3}
^{238}U	1.24 x 10^{-8}	3.6 x 10^{-4}

From these numbers, the values in Table 7.7 can be derived:

Table 7.7. Specific activities of uranium mixtures in weapons production

Uranium Isotope Mixture	Specific Activity (TBq g^{-1})	Specific Activity (mCi g^{-1})
Typical DOD DU[27]	1.59×10^{-8}	4.30×10^{-4}
Average Weapons Grade U (93.5% ^{235}U, 4.75% ^{238}U, and 1.75% ^{234}U)	4.12×10^{-6}	1.11×10^{-1}
Natural Uranium (excluding progeny)	2.54×10^{-8}	6.85×10^{-4}

In weapons grade uranium, most of the radioactivity is caused by the presence of ^{234}U, which has much higher specific activity than ^{235}U or ^{238}U and is enriched to a greater degree. In this example of highly enriched uranium, about 98% of the activity is ^{234}U.

7.8.1.2. Radiobiological and Toxicity Concerns

In situations involving nuclear weapons natural uranium is not likely to be encountered. Most likely, personnel will find enriched and depleted uranium. Weapons grade enriched uranium contains by mass about 93.5% ^{235}U, 1.5 to 2.0% ^{234}U, and the remainder ^{238}U. Depleted uranium as used by the DOD is typically about 99.8% ^{238}U, 0.2% ^{235}U, and 0.001% ^{234}U. Because during the enrichment process uranium is chemically separated from its radioactive progeny, the external radiation hazard is somewhat reduced compared to an equal activity of natural uranium. Uranium remains an internal hazard regardless of the isotope considered, because depending on the amount of enrichment the chemical toxicity of uranium can be as important as or more important than the radiological toxicity. The chemical toxicity is believed to be greater than the radiological toxicity when the enrichment is less than about 7 to 20 percent [8].

7.8.1.2.1. Chemical Toxicity

Acute toxicity of uranium intake is caused by chemical effects on the kidneys. Uranium that makes it into the bloodstream (soluble) damages the very small tubules in the kidney. However, even after exposures to high levels of uranium the kidneys recover. In addition, there is evidence that repeated exposures cause less damage after the first exposure [9]. The estimated threshold concentration of uranium for kidney damage ranges from less than 1 :g g^{-1} to 3 :g g^{-1} of kidney mass. For an acute ingestion intake of soluble uranium, the LD_{50} from kidney damage in man is estimated to be greater than about 1 to 3 mg kg^{-1} of body mass [10]. This estimate is very rough because information on humans is scarce.

7.8.1.2.2. External Radiological Hazards

Below is a table of gamma dose equivalent rates from the 3 isotopes of uranium that may be encountered in nuclear weapon production. These constants give the gamma dose equivalent rates of the uranium isotopes and their short-lived progeny at 1 meter from a point source of the

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[27] Reported values for the specific activity of depleted uranium vary depending primarily on the weight percentages of ^{234}U and ^{235}U (10CFR20). While the exact ratio will vary, the radioactivity of depleted uranium will always be less than that of naturally occurring uranium.

isotope listed. Furthermore, radiation emitted from radioactive progeny are not included in the specific gamma ray constants. The gamma ray constants for the immediate short-lived progeny are listed as well.

Table 7.8. External gamma dose rate constants for uranium isotopes and selected progeny [7]

Uranium Isotope	Specific Gamma Ray Dose Equivalent Constants for a Point Source	
	mSv h^{-1} MBq^{-1} at 1 Meter	Mrem h^{-1} mCi^{-1} at 1 Meter
^{235}U	9.159×10^{-5}	3.389×10^{-1}
^{231}Th	1.473×10^{-4}	5.450×10^{-1}
Total	2.389×10^{-4}	8.839×10^{-1}
^{238}U	1.763×10^{-5}	6.523×10^{-2}
^{234}Th	2.380×10^{-5}	8.806×10^{-2}
^{234m}Pa	2.381×10^{-6}	8.810×10^{-2}
^{234}U	2.097×10^{-5}	7.759×10^{-2}
Total	6.518×10^{-5}	2.412×10^{-1}

The beta dose rates at selected distances in air from a source of ^{234}Th-^{234m}Pa beta particles is given in the table below.

Table 7.9. Beta dose rates in air from ^{234}Th-^{234m}Pa, the short-lived progeny of ^{238}U [7]

Distance (cm)	Point Source (1 MBq) mGy h^{-1}	Infinite Plane (1 MBq cm^{-2}) mGy h^{-1*}
0	562.4	See Table (Skin Exposure)
16	0.4129	828
32	8.770×10^{-2}	622
80	1.364×10^{-2}	375
200	1.755×10^{-3}	144

Multiply the above values by 3.7 to get rads h^{-1} for a 1 mCi point source or an infinite plane of 1 mCi cm^{-2}.
*These values have been divided by 2 to account for the shielding effect of the body.

Uranium-235 decays by alpha emission to ^{231}Th (T_{2} = 25.5 h). Thorium-231 decays by beta emission and will reach equilibrium with ^{235}U within 2 weeks. Thus, highly enriched uranium can be a source of skin exposures but the beta particles emitted from ^{231}Th are of much lower energy and therefore present a smaller hazard. For example, the beta dose to the skin for an infinite plane source of ^{231}Th is negligible. However, neither the submersion nor the gamma dose is negligible. The metastable radionuclide ^{234m}Pa emits a 2.28 MeV beta particle and reaches secular equilibrium with ^{238}U through the decay of ^{234}Th in less than a year. Thus, depleted uranium can present a potential for significant beta exposures.

Table 7.10. Beta dose rate factors to the skin at a depth of 70 μm for ^{231}Th for various exposure geometries [11]

At	Beta Dose Rate Factor	
Immersion in contaminated water	4.9 x 10^{-5} Sv y^{-1} Bq^{-1} cm^{3}	21 mrem h^{-1} μCi^{-1} cm^{3}
Immersion in contaminated air	4.6 x 10^{-2} Sv y^{-1} Bq^{-1} cm^{3}	19,000 mrem h^{-1} μCi^{-1} cm^{3}
One meter above an infinite plane	0.0 Sv y^{-1} Bq^{-1} cm^{2}	0 mrem h^{-1} μCi^{-1} cm^{2}

Table 7.11. Beta dose rates to the skin at a depth of 7 mg cm^{-2} for selected nuclides uniformly deposited on the body surface [12]

Radionuclide	Dose Rate Factor Sv y^{-1} Bq^{-1} cm^{2}	Dose Rate Factor rem h^{-1} mCi^{-1} cm^{2}
^{231}Th	8.2 x 10^{-3}	3.5 x 10^{3}
^{235}U	1.1 x 10^{-3}	4.6 x 10^{2}
Total (^{235}U Series)	9.3 x 10^{-3}	4.0 x 10^{3}
^{234m}Pa	2.1 x 10^{-2}	8.9 x 10^{3}
^{234}Th	3.1 x 10^{-3}	1.3 x 10^{3}
^{234}U	2.1 x 10^{-5}	8.9
^{238}U	1.6 x 10^{-5}	6.8
Total (^{238}U Series)	2.4 x 10^{-2}	1 x 10^{4}

Tables 7.12 to 7.16 show external dose rate factors for various exposure scenarios. Notes on using the tables follow on section 7.8.

Table 7.12. Dose equivalent (ICRP-30) rate factors for external exposure (β+γ) for various geometries, for ^{234}U (Sv s^{-1} Bq^{-1} m^{3} except where noted) [13]

Geometry	Skin	Effective
Air Submersion	4.25 x 10^{-17}	7.63 x 10^{-18}
Water Submersion	9.55 x 10^{-20}	1.75 x 10^{-20}
Infinite Plane (Sv s^{-1} Bq^{-1} m^{2})	9.09 x 10^{-18}	7.48 x 10^{-19}
Soil Contaminated to 1 cm	4.66 x 10^{-21}	1.01 x 10^{-21}
Soil Contaminated to 5 cm	5.61 x 10^{-21}	1.82 x 10^{-21}
Soil Contaminated to 15 cm	5.98 x 10^{-21}	2.14 x 10^{-21}
Soil Contaminated to an Infinite Depth	5.99 x 10^{-21}	2.15 x 10^{-21}

Table 7.13. Effective dose equivalent (ICRP-30) rate factors for external exposure (\$+() for various geometries, for ^{235}U - ^{231}Th (Sv s^{-1} Bq^{-1} m^{3} except where noted) [13]

Geometry	^{235}U	^{231}Th	Total
Air Submersion	7.20×10^{-15}	5.22×10^{-16}	7.72×10^{-15}
Water Submersion	1.59×10^{-17}	1.18×10^{-18}	1.71×10^{-17}
Infinite Plane (Sv s^{-1} Bq^{-1} m^{2})	1.48×10^{-16}	1.85×10^{-17}	1.67×10^{-16}
Soil Contaminated to 1 cm	9.49×10^{-19}	7.04×10^{-20}	1.02×10^{-18}
Soil Contaminated to 5 cm	2.65×10^{-18}	1.59×10^{-19}	2.81×10^{-18}
Soil Contaminated to 15 cm	3.75×10^{-18}	1.94×10^{-19}	3.94×10^{-18}
Soil Contaminated to an Infinite Depth	3.86×10^{-18}	1.95×10^{-19}	4.06×10^{-18}

Table 7.14. Dose equivalent (ICRP-30) rate factors for external exposure (\$+() to the skin for various geometries, for ^{235}U - ^{231}Th (Sv s^{-1} Bq^{-1} m^{3} except where noted) [13]

Geometry	^{235}U	^{231}Th	Total
Air Submersion	8.64×10^{-15}	2.52×10^{-15}	1.12×10^{-14}
Water Submersion	1.89×10^{-17}	3.97×10^{-18}	2.29×10^{-17}
Infinite Plane (Sv s^{-1} Bq^{-1} m^{2})	1.94×10^{-16}	8.58×10^{-17}	2.80×10^{-16}
Soil Contaminated to 1 cm	1.08×10^{-18}	1.14×10^{-19}	1.19×10^{-18}
Soil Contaminated to 5 cm	3.01×10^{-18}	2.15×10^{-19}	3.29×10^{-18}
Soil Contaminated to 15 cm	4.28×10^{-18}	2.56×10^{-19}	4.54×10^{-18}
Soil Contaminated to an Infinite Depth	4.40×10^{-18}	2.56×10^{-19}	4.66×10^{-18}

Table 7.15. Effective dose equivalent (ICRP-30) rate factors for external exposure (\$+() for various geometries, for ^{238}U and short-lived progeny (Sv s^{-1} Bq^{-1} m^{3} except where noted) [13]

Geometry	^{238}U	^{234}Th + ^{234m}Pa	Total
Air Submersion	3.41×10^{-18}	1.05×10^{-15}	1.05×10^{-15}
Water Submersion	6.83×10^{-20}	2.28×10^{-18}	2.35×10^{-18}
Infinite Plane (Sv s^{-1} Bq^{-1} m^{2})	5.51×10^{-19}	2.36×10^{-17}	2.42×10^{-17}
Soil Contaminated to 1 cm	4.42×10^{-22}	1.41×10^{-19}	1.41×10^{-19}
Soil Contaminated to 5 cm	5.45×10^{-22}	3.77×10^{-19}	3.78×10^{-19}
Soil Contaminated to 15 cm	5.52×10^{-22}	5.49×10^{-19}	5.50×10^{-19}
Soil Contaminated to an Infinite Depth	5.52×10^{-22}	6.09×10^{-19}	6.10×10^{-19}

Table 7.16. Dose equivalent (ICRP-30) rate factors for external exposure ($+() to the skin for various geometries, for ^{238}U and short-lived progeny (Sv s^{-1} Bq^{-1} m^3 except where noted) [13]

Geometry	^{238}U	^{234}Th + ^{234m}Pa	Total
Air Submersion	2.91×10^{-17}	5.56×10^{-14}	5.56×10^{-14}
Water Submersion	6.83×10^{-20}	1.39×10^{-18}	1.46×10^{-18}
Infinite Plane (Sv s^{-1} Bq^{-1} m^2)	7.42×10^{-18}	9.41×10^{-15}	9.41×10^{-15}
Soil Contaminated to 1 cm	3.40×10^{-21}	7.87×10^{-18}	7.91×10^{-18}
Soil Contaminated to 5 cm	3.54×10^{-21}	8.14×10^{-18}	8.15×10^{-18}
Soil Contaminated to 15 cm	3.55×10^{-21}	8.34×10^{-18}	8.34×10^{-18}
Soil Contaminated to an Infinite Depth	3.55×10^{-21}	8.42×10^{-18}	8.42×10^{-18}

Notes to Tables 7.12 to 7.16

Air Submersion	1. To convert to mrem y^{-1} μCi^{-1} cm^3 multiply the entries by 1.168×10^{23}. 2. To scale these entries for densities other than 1.2 kg m^{-3}, multiply the entries by 1.2/D, where D is the density in kg m^{-3}.
Water Submersion	1. To convert to mrem y^{-1} :Ci^{-1} cm^3 multiply the entries by 1.168×10^{23}. 2. To scale these entries for densities other than 1000 kg m^{-3}, multiply the entries by 1000/D, where D is the density in kg m^{-3}.
Infinite Plane	1. To convert to mrem y^{-1} :Ci^{-1} cm^2 multiply the entries by 1.168×10^{21}.
Contaminated Soil	1. The assumed density is 1600 kg m^{-3}. The table entries cannot be scaled for different soil densities. 2. To convert to mrem y^{-1} :Ci^{-1} m^3 multiply the entries by 1.168×10^{23}. 3. To convert to mrem y^{-1} :Ci^{-1} g, multiply the entries by 1.868×10^{23}.

7.8.1.2.3. Internal Radiological Hazards

There is suggestive evidence that lung cancer may be induced by chronic inhalation of low levels of uranium dust [14]. However, bone sarcoma and kidney problems are considered the most likely radiological effects of internal exposure to uranium, especially to high specific activity isotopes [10, 14].

Two important parameters in the estimation of dose equivalents from intakes of radionuclides are inhalation class and the f_1 value. The inhalation class is a classification that describes how quickly the radionuclide is cleared from the lung. There are three classes: Y for years, W for weeks, and D for days. The f_1 value describes the fraction of the radionuclide that crosses the lining of the digestive system and enters the bloodstream. Both f_1 and the inhalation class depend on the chemical form of the radionuclide. The dose equivalent rate factors (h_E) below are based on class Y compounds for inhalation and an f_1 value of 0.002 for uranium, 0.0002 for thorium, and 0.001 for protactinium. Class Y was chosen based on the expected chemical form of the radionuclide and the guidance in Federal Guidance Report Number 11 [15]. The rate factors listed are based on an intake of the pure parent but include effects of the production and decay of progeny in the body. The ICRP assumes, unless evidence to contrary exists, that the progeny are metabolized as the parent [16]. For example, the effect of the ^{234m}Pa decays is included in the reported rate factors for ^{234}Th. Because of the very short half-life of ^{234m}Pa, equilibrium is quickly established, and this activity is considered in deriving the rate factor for ^{234}Th. However, for mixtures of longer-lived nuclides, even those in radioactive decay series, each nuclide should be considered individually.

Table 7.17. Committed effective dose equivalent (ICRP-30) per unit inhalation intake (Sv Bq^{-1}) for uranium and related nuclides for class Y [15]

Nuclide	Effective	Bone Surface
^{234}U	3.58×10^{-5}	1.13×10^{-6}
^{235}U	3.32×10^{-5}	1.05×10^{-6}
^{238}U	3.20×10^{-5}	1.01×10^{-6}

The bold values are the limiting dose equivalent rate factors.

Because the dose equivalent per unit intake is very much greater for the uranium isotopes and includes the effects of production of the progeny in the body, it is not necessary to include their dose equivalent factors in Table 7.17.

7.8.2. Plutonium

Plutonium was discovered in 1940 at the University of California, Berkley and named for the planet Pluto. Plutonium is found in trace amounts in nature, not as a primordial radionuclide but as an activation product of naturally occurring uranium; Pu is created by the absorption of neutrons by ^{238}U. Since Pu concentrations in pitchblende ores are on the order of one part per trillion, plutonium is considered a synthetic element.

7.8.2.1. Physical radiological properties

Plutonium is a silvery-white metal that is more reactive than uranium. It tarnishes quickly and if the oxidation is severe enough it forms loose PuO_2 powder. The melting point is 641 °C, and the boiling point is 3232 °C. Its density is about 19.8 g cm^{-3}. There are 15 isotopes of Pu; all except ^{243}Pu emit alpha radiation, and ^{241}Pu has a very low alpha emission rate. The half-lives range from about 20 minutes for ^{233}Pu to 80 million years for ^{244}Pu. The fissile isotopes are ^{239}Pu (T½ = 24,000 years) and ^{241}Pu (T½ = 14.4 years).

Table 7.18. Decay data for the three major plutonium isotopes and progeny [7]

		Major Radiation Emitted					
		"		$		(	
Isotope	Half life	MeV	%	MeV	%	MeV	%
^{239}Pu	2.4 x 10^4 y	5.10	11.5	0.007	19	0.0136	4.4
		5.14	15.1	0.010	3.5	0.113	0.05
		5.16	73.3	0.017	2.8		
				0.030	4.8		
				0.046	1.3		
^{240}Pu	6.6 x 10^3 y	5.12	26.4	0.010	8.6	0.0136	11
		5.17	73.5	0.023	19.7		
				0.040	7.2		
^{241}Pu	14.4 y	4.85	0.0003	0.021	~100	0.149	0.0002
		4.90	0.002				
^{241}Am	458 y	5.43	12.8			0.0263	2.4
		5.49	85.2			0.0595	35.7
						0.099	0.02
						0.103	0.02

Table 7.19. Specific activities of selected plutonium isotopes and ^{241}Am

Uranium Isotope	Specific Activity (TBq g^{-1})	Specific Activity (mCi g^{-1})
^{239}Pu	2.30 x 10^{-3}	62.2
^{240}Pu	8.43 x 10^{-3}	228
^{241}Pu	3.81	1.03 x 10^5
^{241}Am	1.27 x 10^{-1}	3430

Freshly made average weapon grade plutonium contains 93.4% ^{239}Pu, 6.0% ^{240}Pu, and 0.6% ^{241}Pu. Plutonium-241 decays into ^{241}Am (T_2 = 432.7 y), which can pose an external radiation hazard. In addition, because of the spontaneous fission rates of ^{239}Pu, ^{240}Pu, and ^{241}Am external neutron exposures are possible.

Table 7.20. Spontaneous fission rates for selected nuclides of interest [1, 7]

Nuclide	Spontaneous fission rate f s^{-1} kg^{-1}	Neutron emission rate n s^{-1} kg^{-1}
^{239}Pu	10	30
^{240}Pu	4.15 x 10^{5}	1 x 10^{6}
^{241}Am	600	1.5 x 10^{3}

7.8.2.2. External hazards

The major external hazards of Pu exposure result from the beta particle emitted by ^{241}Pu and the low energy gamma rays, x-rays, and electrons emitted by the Pu isotopes and by ^{241}Am, the progeny of ^{241}Pu.. Table 7.21 shows the specific gamma ray dose constants for the major Pu isotopes and ^{241}Am.

Table 7.21. External gamma dose rate constants for plutonium isotopes and selected progeny [7]

	Specific Gamma Ray Dose Equivalent Constants for a Point Source	
Uranium Isotope	mSv h^{-1} MBq^{-1} at 1 Meter	mrad h^{-1} mCi^{-1} at 1 Meter
^{239}Pu	8.145 x 10^{-6}	3.04 x 10^{-2}
^{240}Pu	2.30 x 10^{-5}	8.510 x 10^{-2}
^{241}Pu	0	0
^{241}Am	8.479 x 10^{-5}	3.137 x 10^{-1}

Tables 7.22 to 7.24 show external dose rate factors for various exposure geometries. Notes on using the tables follow Table 7.24.

Table 7.22. Effective dose equivalent (ICRP-30) rate factors for external exposure ($+() for various geometries, for ^{239}Pu, ^{240}Pu, and ^{241}Pu (Sv s^{-1} Bq^{-1} m^{3} except where noted) [13]

Geometry	^{239}Pu	^{240}Pu	^{241}Pu
Air Submersion	4.24 x 10^{-18}	4.75 x 10^{-18}	7.25 x 10^{-20}
Water Submersion	9.60 x 10^{-21}	1.11 x 10^{-20}	1.62 x 10^{-22}
Infinite Plane (Sv s^{-1} Bq^{-1} m^{2})	3.67 x 10^{-19}	8.03 x 10^{-19}	1.93 x 10^{-21}
Soil Contaminated to 1 cm	5.61 x 10^{-22}	6.20 x 10^{-22}	9.60 x 10^{-24}
Soil Contaminated to 5 cm	1.15 x 10^{-21}	7.44 x 10^{-22}	2.44 x 10^{-23}
Soil Contaminated to 15 cm	1.52 x 10^{-21}	7.84 x 10^{-22}	3.15 x 10^{-23}
Soil Contaminated to an Infinite Depth	1.58 x 10^{-21}	7.85 x 10^{-22}	3.16 x 10^{-23}

Table 7.23. Dose equivalent (ICRP-30) rate factors for external exposure ($+() to the skin for various geometries, for ^{239}Pu, ^{240}Pu, and ^{241}Pu (Sv s^{-1} Bq^{-1} m^3 except where noted) [13]

Geometry	^{239}Pu	^{240}Pu	^{241}Pu
Air Submersion	1.86 x 10^{-17}	3.92 x 10^{-17}	1.17 x 10^{-19}
Water Submersion	4.26 x 10^{-20}	9.13 x 10^{-20}	2.50 x 10^{-22}
Infinite Plane (Sv s^{-1} Bq^{-1} m^2)	3.67 x 10^{-18}	9.18 x 10^{-18}	7.06 x 10^{-21}
Soil Contaminated to 1 cm	2.20 x 10^{-21}	4.68 x 10^{-21}	1.28 x 10^{-23}
Soil Contaminated to 5 cm	2.87 x 10^{-21}	4.83 x 10^{-21}	2.95 x 10^{-23}
Soil Contaminated to 15 cm	3.31 x 10^{-21}	4.87 x 10^{-21}	3.76 x 10^{-23}
Soil Contaminated to an Infinite Depth	3.38 x 10^{-21}	4.87 x 10^{-21}	3.78 x 10^{-23}

Table 7.24. Effective dose equivalent (ICRP-30) and dose equivalent rate factors for external exposure ($+() for various geometries, for ^{241}Am (Sv s^{-1} Bq^{-1} m^3 except where noted) [13]

Geometry	Effective	Skin
Air Submersion	8.16 x 10^{-16}	1.28 x 10^{-15}
Water Submersion	1.88 x 10^{-18}	2.98 x 10^{-18}
Infinite Plane (Sv s^{-1} Bq^{-1} m^2)	2.75 x 10^{-17}	8.32 x 10^{-17}
Soil Contaminated to 1 cm	1.15 x 10^{-19}	1.62 x 10^{-19}
Soil Contaminated to 5 cm	2.18 x 10^{-19}	2.89 x 10^{-19}
Soil Contaminated to 15 cm	2.34 x 10^{-19}	3.10 x 10^{-19}
Soil Contaminated to an Infinite Depth	2.34 x 10^{-19}	3.10 x 10^{-19}

Notes to Tables 7.22 to 7.24

Air Submersion	1.	To convert to mrem y^{-1} :Ci^{-1} cm^3 multiply the entries by 1.168 x 10^{23}.
	2.	To scale these entries for densities other than 1.2 kg m^{-3}, multiply the entries by 1.2/D, where D is the density in kg m^{-3}.
Water Submersion	1.	To convert to mrem y^{-1} :Ci^{-1} cm^3 multiply the entries by 1.168 x 10^{23}.
	2.	To scale these entries for densities other than 1000 kg m^{-3}, multiply the entries by 1000/D, where D is the density in kg m^{-3}.
Infinite Plane	1.	To convert to mrem y^{-1} :Ci^{-1} cm^2 multiply the entries by 1.168 x 10^{21}.
Contaminated Soil	1.	The assumed density is 1600 kg m^{-3}. The table entries cannot be scaled for different soil densities.
	2.	To convert to mrem y^{-1} :Ci^{-1} cm^3 multiply the entries by 1.168 x 10^{23}.
	3.	To convert to mrem y^{-1} :Ci^{-1} g, multiply the entries by 1.868 x 10^{23}.

Table 7.25. Beta dose rate factors to the skin at a depth of 70 μm for ^{241}Am for various exposure geometries [11]

	Dose Rate Factor	
Immersion in contaminated water	1.8 x 10^{-8} Sv y^{-1} Bq^{-1} cm^3	7.7 μrad h^{-1} μCi^{-1} cm^3
Immersion in contaminated air	1.5 x 10^{-5} Sv y^{-1} Bq^{-1} cm^3	6.4 mrad h^{-1} μCi^{-1} cm^3
One meter above an infinite plane	0.0 Sv y^{-1} Bq^{-1} cm^2	0 mrad h^{-1} μCi^{-1} cm^2

Table 7.26. Beta dose rates from nuclides deposited on the skin to the skin at a depth of 7 mg cm^{-2} for ^{241}Am [12]

Radionuclide	Dose Rate Factor Sv y^{-1} Bq^{-1} cm^2	Dose Rate Factor rad h^{-1} mCi^{-1} cm^2
^{241}Am	2.2 x 10^{-5}	9.4

There is also the possibility of a neutron exposure from sufficiently large masses of Pu. For example, there are about 5 kg of Pu in a warhead, so the neutron emission rate from the Pu in a weapon is on the order of 3 x 10^5 n s^{-1}. At one meter, this would result in an external dose equivalent rate of about 3 μSv h^{-1} (0.3 mrem h^{-1}), if the source can be approximated as a point source.

7.8.2.3. Internal Radiological Hazards

Because most of the plutonium isotopes are alpha emitters the major radiological concern is internal contamination. The most common form of Pu that people may be exposed to is the virtually insoluble PuO_2. The three major routes of any internal contamination are inhalation, ingestion, and direct entry through a wound.

If PuO_2 is inhaled, about 20 to 60 percent is retained in the lungs [17]. This lung retention greatly depends on the size of the particle as well as the biological properties of the lung. A discussion of the retention of dust in the lungs is beyond the scope of this text. For a detailed discussion of the mechanics of dust in the lungs, see NCRP Report Number 125 [18]. The rest of the PuO_2 is removed from the body in several days. The PuO_2 that remains in the lung is removed with an effective half-life of about a year; some goes to the lymph nodes where it is retained indefinitely, some is excreted, and a very small amount deposits in the bone [10]. About 20 mg of optimally sized dust will produce death in about a month from pulmonary edema or fibrosis [17].

If ingested, the vast majority of PuO_2 passes through the digestive system rapidly and is excreted. If directly entering the blood through a wound, PuO_2 will deposit mainly in the bone and liver. Acutely lethal damage to the digestive system occurs with an ingestion of about 500 mg of plutonium [17].

The second most common form of plutonium is plutonium nitrate, which is somewhat more soluble than the oxide. Plutonium nitrate behaves much like plutonium oxide except that it clears more rapidly from the lungs.

Plutonium shares many of the toxicological properties of heavy metals; however, the chemical hazard is negligible compared to the radiation hazards. Plutonium is not very toxic as toxicity is commonly defined; fast acting and fatal in small doses. At low levels commonly encountered the effects of Pu exposures may not be seen for many years, if at all.

The table below shows the committed effective dose equivalent factors for ^{239}Pu, ^{240}Pu, ^{241}Pu, and ^{241}Am; the isotopes found in weapons grade plutonium. These numbers are based on the least soluble chemical form of the isotope.

Table 7.27. Committed effective dose equivalent (ICRP-30) per unit inhalation intake (Sv Bq^{-1}) for plutonium and related nuclides for class Y [15]

Nuclide	Effective	Bone Surface
^{239}Pu	**8.33×10^{-5}**	8.21×10^{-4}
^{240}Pu	**8.33×10^{-5}**	8.21×10^{-4}
^{241}Pu	1.34×10^{-6}	**1.78×10^{-5}**
^{241}Am (Class W)	1.20×10^{-4}	**2.17×10^{-3}**

The bold values are the limiting dose equivalent rate factors.

The limiting factor in each case is the dose equivalent to the bone surface. This means that the limits are set to prevent non-stochastic effects (effects with an apparent threshold) to the bone surfaces.

7.8.3. Tritium

Tritium is a radioactive isotope of hydrogen; it is often abbreviated as T, and its official abbreviation is ^{3}H. Hydrogen was first identified in 1766 by Cavendish and named by Lavoiser. Hydrogen is the most abundant element in the universe and is thought to be the building block of all the elements. On earth, most of the hydrogen combines with oxygen to form water, but it is also found in organic matter. Trace amounts of hydrogen (< 1ppm by volume) exist in the atmosphere.

Tritium was discovered in 1934 from the bombardment of deuterium with accelerated deuterium ions [1]. Tritium is formed in nature from cosmic ray interactions with nitrogen, oxygen, lithium, and other exotic interactions. Tritium is also produced in light and heavy water reactors and nuclear weapon detonations. Tritium is used in fusion weapons as well as luminous paints, and it has found a use as a radiological tracer.

7.8.3.1. Physical and Radiological Properties

Tritium is the only radioactive isotope of hydrogen. It contains one proton and two neutrons and has a half-life of about 12.5 years. Tritium behaves very similarly to hydrogen except for the physical effect of its greater mass. It diffuses very rapidly in the environment and exchanges with stable hydrogen. The specific activity of pure tritium is 357 TBq g^{-1} (9650 Ci g^{-1}). Tritium (^3H) decays by beta emission to helium (^3He). The betas have a maximum energy of 18.6 keV and an average of 5.685 keV, and cannot penetrate the dead layer of skin.

7.8.3.2. Radiobiological and Toxicity Concerns

Elemental hydrogen (H_2) is relatively inert; hence, tritium incorporated in molecular hydrogen as HT is relatively inert. The elemental gas is inhaled and exhaled with only about 0.005% of the activity depositing in the lung [6]. However, when incorporated into water vapor (HTO), tritium distributes throughout the body. The uptake of tritiated water vapor is 100%. When exposed to a cloud of HTO, about one third of the uptake will be through skin absorption and the remaining will be inhaled.

Exposures to very high concentrations of tritium can cause intakes large enough to induce acute radiation symptoms. An accidental exposure leading to a multicurie dose of tritium induced nausea and exhaustion and the eventual death of a victim [9]. Other estimates put the LD-50[28] at about 10 Ci, which corresponds to about 1 mg of pure tritium [1]. This is about the same mass of a lethal dose of the nerve agent sarin [1].

7.8.3.3. External Radiological Hazards

The external radiation hazard from exposure to tritium is extremely small; in fact, because the beta particles emitted cannot penetrate the dead layer of skin, then only external hazard is from inhaled tritium gas irradiating lung tissue. The effective dose equivalent rate per unit concentration (h_E) to tritium gas is

$$h_E = 1.19 \text{ x } 10^{-15} \text{ Sv h}^{-1} \text{ Bq}^{-1} \text{ m}^3 \text{ (4.40 mrem h}^{-1} \text{ :Ci}^{-1} \text{ cm}^3\text{). [15]}$$

7.8.3.4. Internal Radiation Hazards

Tritium gas, like hydrogen gas, is relatively inert; only about 0.005% of inhaled tritium deposits in the lung. However, when incorporated in water vapor, it spreads uniformly and rapidly throughout the water in the body. The effective dose equivalent per unit inhalation and ingestion intake (h_E) to tritiated water vapor is

$$h_E = 1.73 \text{ x } 10^{-11} \text{ Sv Bq}^{-1} \text{ (6.4 x } 10^{-2} \text{ mrem :Ci}^{-1}\text{). [15]}$$

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[28] LD-50 is the dose to which 50 % of those exposed respond, and it is used as an index of relative effectiveness of a given agent in eliciting a particular response. For example, when death of an experimental animal is the biological endpoint, the 50 % dose is called the LD-50 dose [19].

Dose equivalent factors for other tritiated compounds are not available; however, under most environmental conditions tritium gas is quickly oxidized to water vapor.

7.9. Summary of identified sources from the production of nuclear weapons

This chapter identifies possible sources of radiation exposure and contamination in the production and use of nuclear weapons and lists countries with capability of producing them. Nuclear weapons are recognized as fission-only and fission-fusion types of weapon. Radiation dispersal weapons are also acknowledged in this chapter as simply conventional weapons used to disperse radioactive material into the environment.

Table 7.28 includes identified nuclides in the production of nuclear weapons. However, in the event of a nuclear detonation, many other radionuclides will result from activation. Prompt neutrons, prompt gamma rays, fission fragments and fission products are also radiation sources from the production of nuclear weapons.

Table 7.28. Summary of Radiation Sources from the Production of Nuclear Weapons

Isotope	Radiation	Half- life	Precaution level (s)
^{3}H	$	12.3 y	E-T
^{137}Cs	β, γ	30.2 y	X-E-I
^{210}Po	", γ	138.4 d	X-I
^{234m}Pa	β, γ	1.18 m	X-I
^{231}Th	β, γ	25.5 h	X-I
^{232}Th	", γ	1.4E10 y	X-I
^{234}Th	β, γ	24.1 d	X-I
^{234}U	α, γ, n	2.44E5 y	X-I-U
^{235}U	α, β, γ, n	7.04E8 y	X-I-U
^{238}U	α, γ, n	4.5E9 y	X-I-U
^{234m}Pa	β, γ	1.17 m	X-E
^{239}Pu	α, β, γ, n	2.4E4 y	X-E-I
^{240}Pu	α, β, γ, n	6.6E3 y	X-E-I
^{241}Pu	α, β, γ, n	14.4 y	X-E-I
^{241}Am	α, β, γ, n	458 y	X-E-I

References:

1. Web: URL: http//www.enivronlink.org/issues/nuketesting/hew/usa/weapons/pal.htm -Nuclear Weapons Frequently Asked Questions (Sublette, Carey). , 1997.

2. Sublette, C.: Nuclear Weapons Frequently Asked Questions, Version 2.1, www.envirolink.org/issues/nuketesting/hew, May 16, 1997, 1997.

3. DOE: Linking Legacies: Connecting the Cold War Nuclear Weapons Production Processes to the Environmental Consequences. Washington, DC: U.S. Department of Energy, Office of Environmental Management, 1997.

4. Web: URL: http://www.milnet.com/milnet/ - Encyclopedia of Military Information , 1997.

5. NARP: Nuclear Weapon Accident Response Procedures. Washington, DC: U.S. Department of Defense, 1990.

6. Eisenbud, M.and Gesell, R. *Environmental Radioactivity from Natural, Industrial and Military Sources*, 4th ed. New York: Academic Press, 1997.

7. Shleien, B., Slaback, J.L.A.and Birky, B.K. *The Health Physics and Radiological Health Handbook*, 3rd ed. Baltimore, Maryland: Williams & Wilkins, 1998. (Shleien, B., ed.)

8. Brodsky, A.: *Review of Radiation Risks and Uranium Toxicity with Application to Decisions Associated with Decommissioning Clean-up Criteria*. Hebron Connecticut: RSA Publications, 1996.

9. Conklin, J.J.and Walker, R.I.: Eds. Military Radiobiology: Academic Press, 1987.

10. BEIR: Health risks of radon and other internationally deposited alpha-emitters. . Washington, DC: National Research Council Committee on the Biological Effects of Ionizing Radiations National Academy of Sciences Press, 1988.

11. Kocher, D.C. and Eckerman, K.F.: Electron dose-rate conversion factors for external exposure of the skin. *Health Physics Journal*, 1981; 40(April): 467-475.

12. Kocher, D.C. and Eckerman, K.F.: Electron dose-rate conversion factors for external exposure of the skin from uniformly deposited activity on the body surface. *Health Physics Journal*, 1987; 53(No. 2): 135-141.

13. Eckerman, K.F.and Ryman, J.C.: External exposure to radionuclides in air, water, and soil. . Washington, D.C.: U.S. Environmental Protection Agency, 1993.

14. Mossman, K.L. and Mills, W.A.: Eds., *The Biological Basis of Radiation Protection Practice*. Baltimore, Maryland: Williams and Wilkins, 1992.

15. Eckerman, K.F., Wolbarst, A.B.and Richardson, A.C.B.: Limiting values of radionuclide intake and air concentration and dose conversion factors for inhalation, submersion, and ingestion. Washington, D.C.: U.S. Environmental Protection Agency, 1988.

16. ICRP: Limits for Intakes of Radionuclides by Workers : International Commission on Radiological Protection, Pergamon, Oxford, 1979.

17. Sutcliffe, W.G., Condit, R.H., Mansfield, W.G., Myers, D.S., Layton, D.W.,and Murphy, P.W.: A Perspective on the Dangers of Plutonium: Lawrence Livermore National Laboratory, 1995.

18. NCRP: Deposition, Retention, and Dosimetry of Inhaled Radioactive Substances. Bethesda, Maryland: National Council on Radiation Protection and Measurements, 1997.

19. Cember, H.: Introduction to Health Physics, 3rd ed. New York: McGraw-Hill, 1996.

Appendix A. Radiation Protection and Precautions Levels

The reduction of radiological exposure starts with the identification of the sources (by using this technical guide), continues with the selection of appropriate precautions and course of action, and ends with the implementation of a selected response or protocol. This guide is very important to the entire process of reducing the exposure to radiological agents.

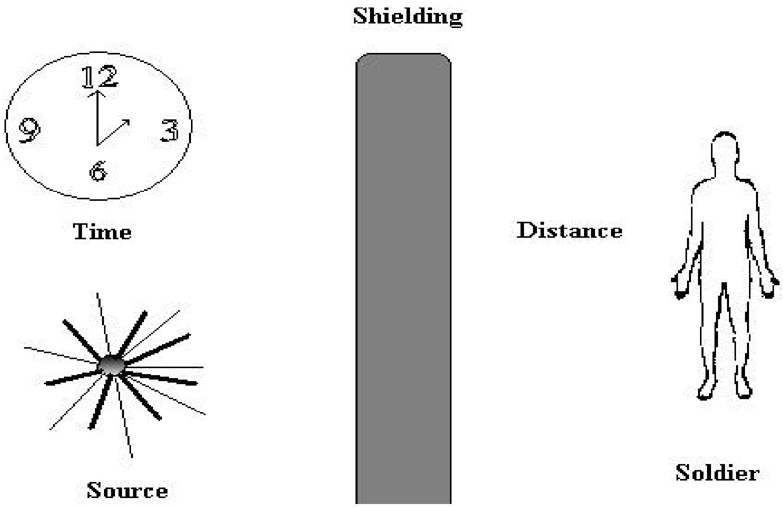
Possible radioactive sources of exposure or contamination, of both civilian and military origin, have been identified. This was done to accommodate probable scenarios that can be encountered by soldiers during both peacetime operations and war missions. Other documents deal with the handling of these identified sources, preventive measures, decontamination procedures, and risk assessment [1-10]. Dealing with known radiological sources is a job for qualified and trained personnel. However, to avoid or minimize the exposure of soldiers to radiological sources several precautions can be taken.

This appendix includes general precaution levels that can be used to reduce the exposure to identified radiation sources or risk of contamination. Precaution levels included in this appendix are based on the basic principles of radiation protection and the principle that dictates that all exposures should be as low as reasonably achievable (ALARA).

A.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. Precaution levels for external sources of radiation are derived from these concepts as they are illustrated in Figure A.1. 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. That is, the radiation exposure at twice the distance would have decreased to one fourth its original value. 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, etc., and would need to improvise in order to acquire the necessary shielding. This is why it is important to know how to properly shield a specific type of radiation (alpha, beta, gamma, and neutron), as we have identified in this technical guide.

Figure A.1. Illustration of the time, distance and shielding concept



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 A.2 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. The 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[29]. Low levels of beta radiation can be stopped completely by about a one-half inch of water, a smaller thickness of plastic, or less than one quarter of an inch of glass. Another common shielding material for beta sources is aluminum. Leather gloves can greatly reduce the beta radiation dose. Gamma and x-rays are shielded with denser materials, such as lead or steel. Lead, which is a very good absorber for gammas, is a poor shielding material against neutrons.

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.

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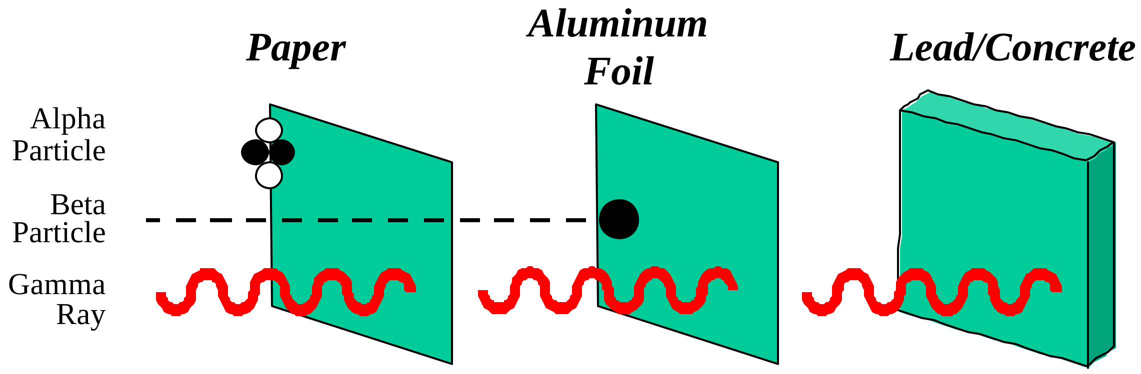
[29] X-rays are produced whenever electrons of high energy strike a heavy metal target like tungsten. When electrons hit this material, some of the electrons will approach the nuclei of the metal atoms and are deflected. This deflection causes the energy of the electron to decrease. The decrease in energy appears as photons or electromagnetic radiation called ***bremsstrahlung,*** a German word for Abraking 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.

Figure A.2. Illustration of the shielding of alpha, beta and gamma radiation sources



The following table includes examples of shielding materials, the type of radiation for which they are used and the advantages and disadvantages of using them.

Table A.1. Example of shielding materials [11]

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 semirigid and needs support for large sections. Lots of thickness would be needed for gammas. Lots of thickness would be needed for gammas.

Shielding material	Radiation	Advantages	Disadvantages
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 for neutron shielding and it is stable at elevated temperatures.	It activates and large shields must be reinforced to avoid cracks. Shields can have voids.
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.

To reduce the individual exposure to ionizing radiation, one must be aware of the principles of radiological protection. The judicious use of time, the imposition of shielding and maximization of distance between a radiation source and an individual will minimize the dose.

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

Before determining which measures to take in the event of radiological contamination, one must clearly distinguish between the possibility of external and internal contamination. External contamination can occur when the radioactive material is airborne, and when it is in contact with clothing, or surface of the skin. One can dispose of the clothing, clean surface and isolate from airborne radioactivity to eliminate these types of external contamination; however, the skin has to be treated and shielded or 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 [2-6, 8, 10, 12]. 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. Decontamination generally involves clothing that is made of plastic garments and/or paper suits (Tyvek), which are discarded at the end of the operation when leaving a contaminated area. Therefore, the risk for contamination of the individuals is reduced. The following are some of the general rules that can be followed as precautions to avoid further external contamination:

Table A.2. General precautions for minimizing or avoiding external contamination

1. If it is suspected that a soldier has been in contact with an identified contaminant a radiation survey should follow.
2. If contamination is confirmed, it is recommended that contaminated clothing be discarded, rather than trying to clean it with soaps and chemical agents (detergents with certain additives, such as citrus acid) to attempt decontamination.
3. Contaminated hands should be washed thoroughly for two to three 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.
4. If precaution 3 does not remove all dirt and contamination, it is recommended to scrub the hands for a period of at least eight minutes with a liquid or cake soap, hand brush and warm water. During this eight 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.
5. If there is contamination of the skin and a few decontamination efforts do not work and the skin starts to become thin, they should be discontinued.
6. If the integrity of the skin is damaged and contamination is suspected, there is a potential for internal contamination and precautions in A.3 should be applied.

An example of external contamination can be the contamination of the hands with fission products. In this case it is recommended to use titanium oxide (TiO_2) as follows:

Table A.3. Precautions for minimizing contamination of the hands with fission products

1. 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.
2. 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 fingernails.
3. The rinse should be done with lukewarm water and followed by a thorough washing with soap and water and a hand brush.
4. 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.

Another example worth including in this section is the use of potassium permanganate ($KMnO_4$) to remove external plutonium contamination. This is done as follows:

Table A.4. Precautions for minimizing external contamination with plutonium

1. An equal volume of a saturated solution of $KMnO_4$ must be mixed with 1 percent sulfuric acid solution and poured over wet hands, covering the nails and cuticles thoroughly.
2. The entire surface must be rubbed lightly with a brush without bending the bristles out of shape.
3. 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.)
4. Freshly prepared 5 percent 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 ml of water.)
5. The procedure 1-4 may be repeated several times without appreciable harm to the skin if each washing is limited to about 2 minutes.
6. 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.

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

Internal contamination may occur via inhalation, ingestion, or injection, through a wound, or absorbed through the skin (see Figure A.3). 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 ingested, inhaled, injected or absorbed and how it is distributed within the body, its biological half-life[30] and effective half-life[31]. The later is a combination of its physical and biological half-lives.

As a precautionary measure to avoid internal contamination, soldiers must wear protective clothing when performing a task in a contaminated environment and it is required to do so. Examples are the use of a mask, hood, helmet, gloves, footwear covers, and protective clothing or MOPP (Mission Oriented Protective Posture) gear upon entering a contaminated area, or an area where there are fallout deposits [9]. It must be emphasized that spread of contamination to clean areas should be avoided.

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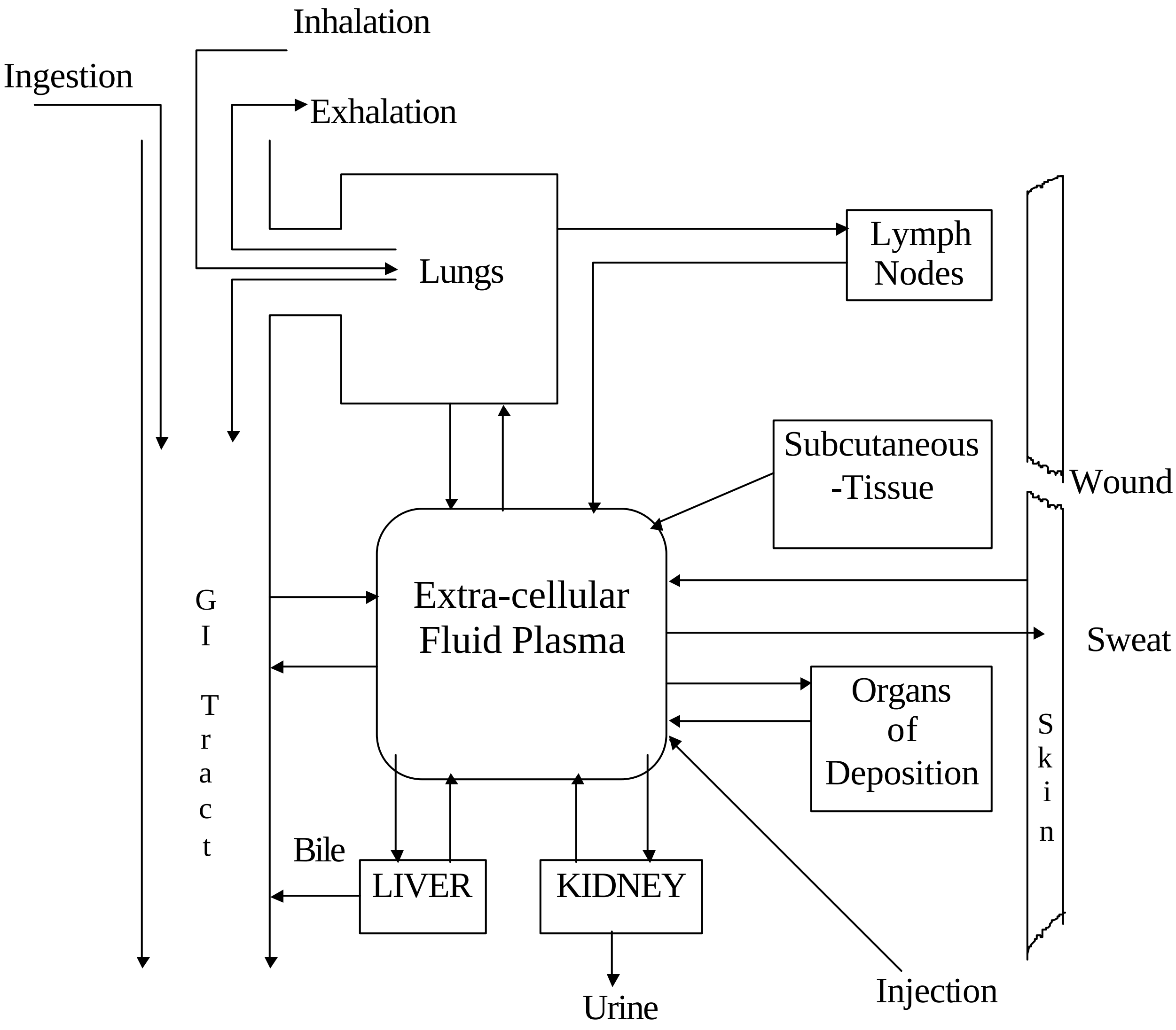
[30] Biological half-life is the time that the body would take to eliminate one half of the radionuclide.

[31] The effective half-life is 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 and biological half-lives. $1/T_{1/2EFF} = 1/T_{1/2RAD} + 1/T_{1/2BIO}$.

Figure A.3. Illustration of the possible pathways of internal contamination



A.3.1. Precautions Recommended for Working in a Contaminated Area

The following are some general precautions for soldiers encountering a contaminated area:

Table A.5. Precautions for entering a contaminated area

1. Assigned duties in contaminated radiation areas must be completed promptly to minimize exposure.
2. 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.
3. Protective wear is to be used when required.
4. Radioactive materials should be isolated and shielded to reduce exposures to individuals.
5. Maintaining maximum distance between a radioactive source and the body can significantly reduce exposure.

The following table includes techniques for reducing internal contamination. These include several elements for which dose reduction techniques have some effect. All these techniques require medical supervision for administration.

Table A.6. Techniques for reducing internal contamination [13]

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

Understanding the elimination of radioactive isotopes is an important issue when dealing with potential contamination of personnel. A radioactive material must be eliminated from the body to remove its hazard. Detoxification, which is effective against materials that are chemical hazards, will not be effective in the case of radioactive materials because contamination is not modified by chemical changes. 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 (diethylenetriamine pentaacetic acid), if administered soon after exposure, are effective in enhancing the elimination of certain radioisotopes. These materials are not very effective for radioisotopes that have been incorporated and fixed in organs and tissues, for example to the bone or thyroid. Under conditions of nuclear war, chelation therapy is very unlikely to be used.

The rate at which a material is eliminated is usually expressed as the biological half-life. During each successive half-life, an additional one-half of the radio-contaminant is removed from the body, analogous to the physical half-life. However, not all materials follow a simple exponential elimination process, but this method of expression is sufficiently accurate to be applicable to most soluble isotopes. An exception that must be noted is the retention of insoluble heavy metals such as plutonium in the lungs and in bone. The rates of loss under these circumstances are not exponential and are very slow.

The biological half-time may be variable. A prime example of this is body water, the turnover of which can be as short as 4 days to as long as 18 days, depending upon the state of hydration, volume of intake, and renal function [8]. Some isotopes cannot be cleared from the body as rapidly, and there is no adequate treatment available at present for increasing the rate of removal of a mixture of isotopes. For example, a mixture of isotopes would be incorporated into the body as a result of ingesting fallout contaminated food and water.

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.

A.3.2. Precautions when Dealing with Equipment Containing Radioactive Sources

As previously identified in this guide, there are equipment, commodities, or instrumentation that contain radioactive material and a common precaution is to follow applicable general safety rules. The following are common rules that apply to personnel working with equipment containing radioactive material.

Table A.7. Precautions for handling equipment containing radioactive sources

1. 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.
2. Always wash hands after handling radioactive materials or sources with non-abrasive soap, even if disposable gloves were used.
3. 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.
4. Chain of command must be informed of radiological handling operations.

A.4. Precautions when Dealing with Tritium Sources [14, 15]

Since tritium is found in many Army commodities, this appendix has included some precautions to avoid or minimize exposure. Over 99% of the tritium in light sources is tritium gas. Tritium oxide, which is readily absorbed by the body, poses no radiation threat 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, if it is suspected that the Pyrex tube containing the tritium gas has been broken or is leaking. The lack of illumination is an indication that the source may be damaged. To test for illumination of the light source, one can follow the following simple steps:

Table A.8. Illumination Test for Equipment Containing Tritium Sources

1. 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.
2. View the device in low light after your eyes have become accustomed to the dark.
3. If there is no evidence of illumination, consider the light source to be broken.

A suspicion of damage to the tritium source or leakage is raised when not all of the sources are illuminated during the illumination test. 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 A.4 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, the local NBC personnel must be notified, and the following actions must be taken under their direction:

Table A.9. Precautions for dealing with a broken tritium source

1. Anyone who may have touched or handled the broken Pyrex tube should wash as soon as possible with non-abrasive soap and luke warm water.
2. Personnel handling the device should wear rubber or latex gloves.
3. The device must be immediately double wrapped in plastic, sealed, packaged, and shipped to designated place.
4. The outside container must be labeled “BROKEN TRITIUM DEVICE - DO NOT OPEN”.
5. 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 NBC personnel, and then hands should be washed well.
6. Personnel who may have handled the broken tritium device should report to the health clinic for a tritium bioassay[32]. The optimum bioassay sample time is approximately 4 hours after the exposure. A minimum of 2 to 4 hours is necessary for tritium to reach an equilibrium and only after this minimum time should a urine sample be taken [14].
7. Personnel should drink lots of fluid/water to enhance the tritium biological elimination from the body.
8. The area where the tritium contamination has occurred must be cordoned off and restricted until a wipe test[33] 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.

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

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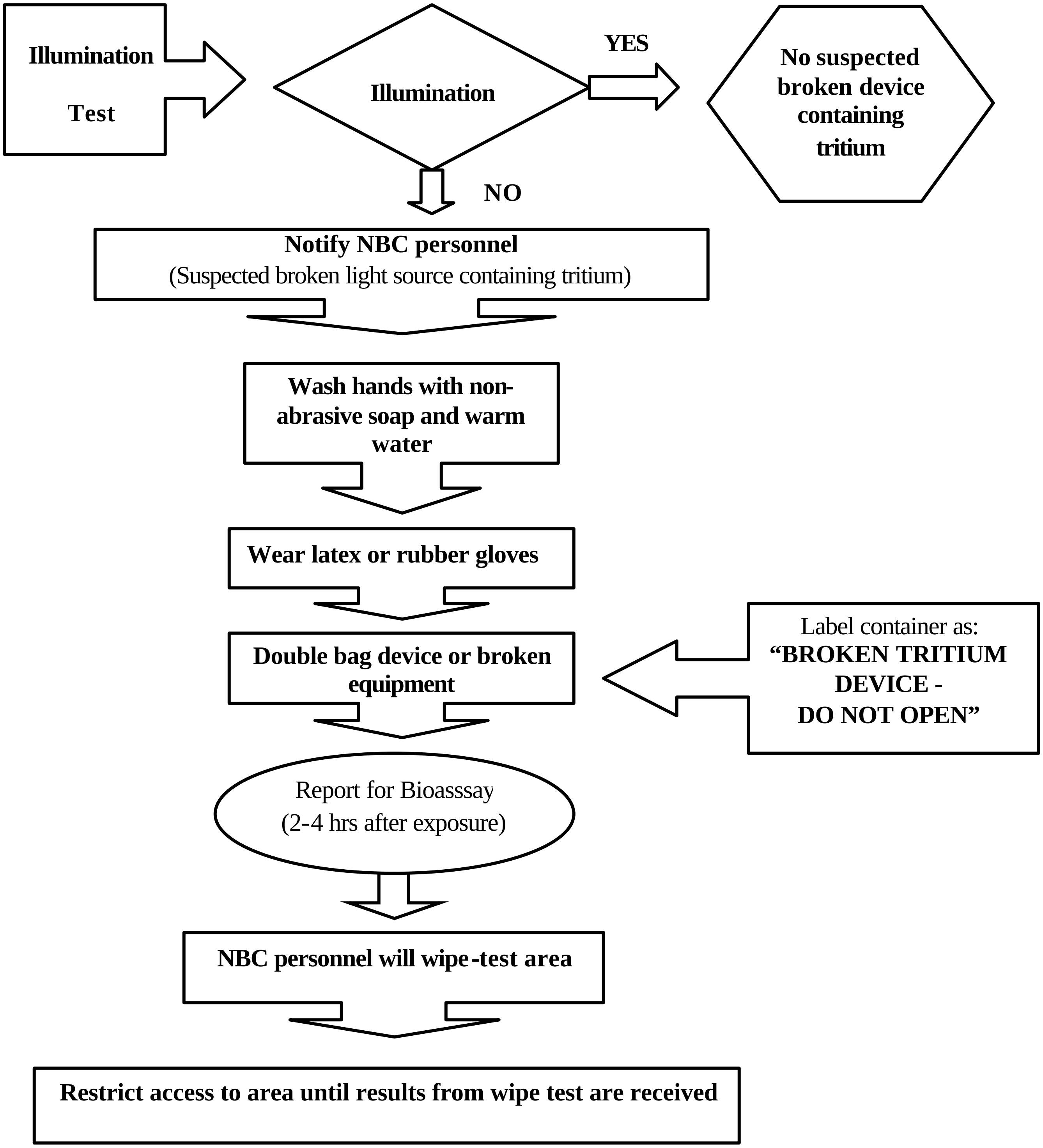
[32] Bioassay refers to the determination of kinds, quantities or concentrations, and, in some cases, the locations, of radioactive material in the human body, whether by direct measurement (in vivo counting) or by analysis and evaluation of materials excreted or removed from the human body.

[33] 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.

Figure A.4. Flow chart indicating precautions when dealing with broken tritium source



A.5. Precautions when Dealing with DU

Personnel should stay at least 50 meters from any vehicle struck by DU munitions or containing DU armor that has been struck by armor piercing rounds. DU munitions and armor are safe if intact; that is, if they are unfired or undamaged.

There are four basic situations in which special precautions may be required to protect from DU exposure. The first is being within 50 meters 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 meters 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 nature of 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, there are some standard protective measures that can be taken:

Table A.10. Precautions to minimize or avoid DU contamination

1. Wear respiratory protection
2. Keep exposed skin covered
3. Brush off clothing and equipment to remove potential contamination
4. Wash hands before eating and shower when available
5. If suspected DU exposure (internal intake via ingestion, inhalation, or wound) bioassay must be recommended

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.

A.5.1. The Nature of the Potential DU Hazard

In the limited scenarios described above, DU could potentially cause health effects. There are two basic mechanisms responsible for these health effects: radioactivity and heavy metal toxicity. The external radiation effects of DU are minimal[34]. Most of the radiation emitted by DU is weak and cannot penetrate the skin and a layer of clothing, and what does is well below the U.S. safety standards. Following standard safety precautions and observing good personal hygiene mitigates health effects. The internal radiation effects (i.e., once the DU gets inside your

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[34] Although external radiation effects of DU are minimal, the ^{234m}Pa, progeny of ^{238}U, has a 2.28 MeV (max) beta that may be of concern.

body by inhalation, ingestion or through wounds) are of more importance. Breathing in the DU dust is of most concern. Heavy metal toxicity is of significance only when internal exposure has occurred. Like any other heavy metal, such as lead and tungsten, the 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.

Health effects become important in the four scenarios mentioned above. One must remember that brief exposures are safe, and that standard safety and hygiene procedures will ensure soldier safety.

A.6. Determination of Precaution Levels

The precaution levels found in Table A.11 were determined by taking into account information on the minimization of exposure and avoidance of contamination, as stated in previous sections. These precautions have further been defined for grouped radioisotopes in their order of chemical and radiological toxicity, type of radiation emission, and contamination levels. Further consideration can be given to removable and fixed contamination possibilities and estimated risk.

Since external contamination can lead to internal contamination, it is often observed that both precautions in Sections A.2 and A.3 may be common to some identified sources. For example, an identified plutonium source that has externally contaminated a soldier must be treated as indicated in Section A.2; however, there may be the possibility for internal contamination and measures should be taken as indicated in Section A.3.

These precaution levels can be linked with the Radiation Exposure State (RES) categories[35] to assess the dose or potential risk from exposure or contamination. That is, given an identified potential source by using this technical guide, appropriate precautions can be taken. If further data is available regarding the radiation level, these precaution levels can be matched to a specific RES category that would dictate the recommended course of action.

NATO RES categories did not consider the intake of radioactive material. However, we do consider internal exposure when computing the cumulative dose that is shown in Table A.12 of this document[36]. Appendix H includes examples of dose assessments for cases of internal contamination and external exposure. The first example is a scenario in which there is internal contamination from the inhalation of weapons grade uranium. Precaution levels X, I and U can be applied. The resulting dose of 0.149 mSv (14.9 mrem) can be assumed to be the total dose that is referred to in the RES category table (Table A.12). The 0.149 mSv, representing a dose of 0.0149 cGy, corresponds to an RES category 0, NO RISK. The second example is a scenario of an external exposure to a 1 mCi source of ^{238}U at a distance of 80 cm. Precaution levels of X, I and U apply. The resulting dose of 0.50 mSv (50.47 mrem) is the total dose that is referred to in the RES category table. The 0.50 mSv, representing a dose of 0.05 cGy, corresponds to an RES category 1A, NORMAL RISK. The third example is a scenario involving weapons-grade plutonium. Precaution levels for plutonium are X, E and I; level U can also be applied. The resulting dose of 0.64 Sv (640 mSv, 64 rem), representing a dose of 64 cGy, corresponds to an RES category 1E, SIGNIFICANT RISK. Recommended course of action can be derived from Table A.12.

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[35] Radiation Exposure State (RES) categories are defined in NATO Ace Directive No. 80-63 [16].

[36] Original NATO document did not consider internal exposure [16].

Table A.11. Guidance for precaution levels

Precaution level	Definition
X	Potential external exposure. Apply precautions in section A.1.
E	Potential external contamination. Apply precautions in section A.2.
I	Potential internal contamination. Apply precautions delineated in section A.3.
T	Potential tritium exposure. Apply precautions in section A.4.
U	Potential DU exposure. Apply precautions in section A.5.

Table A.12. Modified table for guidance low level radiation operational exposure [16]

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)
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)
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

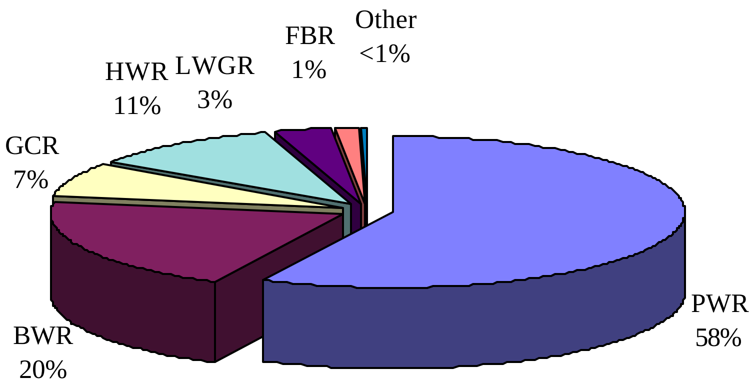
NOTES:

1. Dose is uniform to the entire body due to whole body radiation and including internal contamination.
2. 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.
3. The use of the measurement Millisieverts (mSv) is preferred in all cases. However, due to the fact that normally the military has only the capability to measure Centigray (cGy), as long as the ability to obtain measurements in mSv is not possible, ACE forces will use cGy.
   1 cGy = 10 mSv
4. Risk is of long term health consequences, primarily induction of fatal cancer starting two years post exposure. Total lifetime risk is assumed to be four to seven percent per 100 cGy (= 1000 mSv). This is in addition to the 20-25% 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.
5. It must be noted that higher radiation dose rates produce proportionally more other health risks than the same total dose given over a longer period.
6. 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 human life.
7. During peacetime, this dose shall not be exceeded except to save human lives.
8. RES category 1E covers a wide range of dose and its lower level (25 cGy = 250 mSv) is the peacetime maximum operational dose in many NATO nations. This category is normally only applicable in wartime. Intentional exposure to doses in this category (25-70 cGy = 250-700 mSv) requires additional justification.

Appendix B. Power Reactor Types

By 1999 there it was a total of 494 nuclear power plants, 444 of which were in operation in 1997 and 433 in 1999 [17, 18]. Figure B.1 is a pie chart representing the distribution of these plants by reactor type.

Figure B.1. Worldwide nuclear power plant distribution by type



PWR: Pressurized Water Reactor
BWR: Boiling Water Reactor
GCR: Gas Cooled Reactor
HWR: Heavy Water Reactor
LWGR: Light Water Graphite Reactor
FBR: Fast Breeder Reactor

Typical components of nuclear power reactors are:

1.) ***The reactor pressure vessel***. In most reactors the fuel is contained within a single pressure vessel. However in some designs fuel rods are contained within individual pressure tubes. Figures B.2 and B.3 include pictorial representations of the pressure vessel for a typical PWR and a BWR. The control rod mechanisms in the pressurized water reactors are located at the top of the reactor core. By contrast, the control rod mechanisms in the boiling water reactors are at the bottom of the reactor core.

Figure B.2. Pressure vessel of a typical PWR (overall height = 13.12 m (43 ft), outer diameter, including nozzles = 6.99 m (22.92 ft))

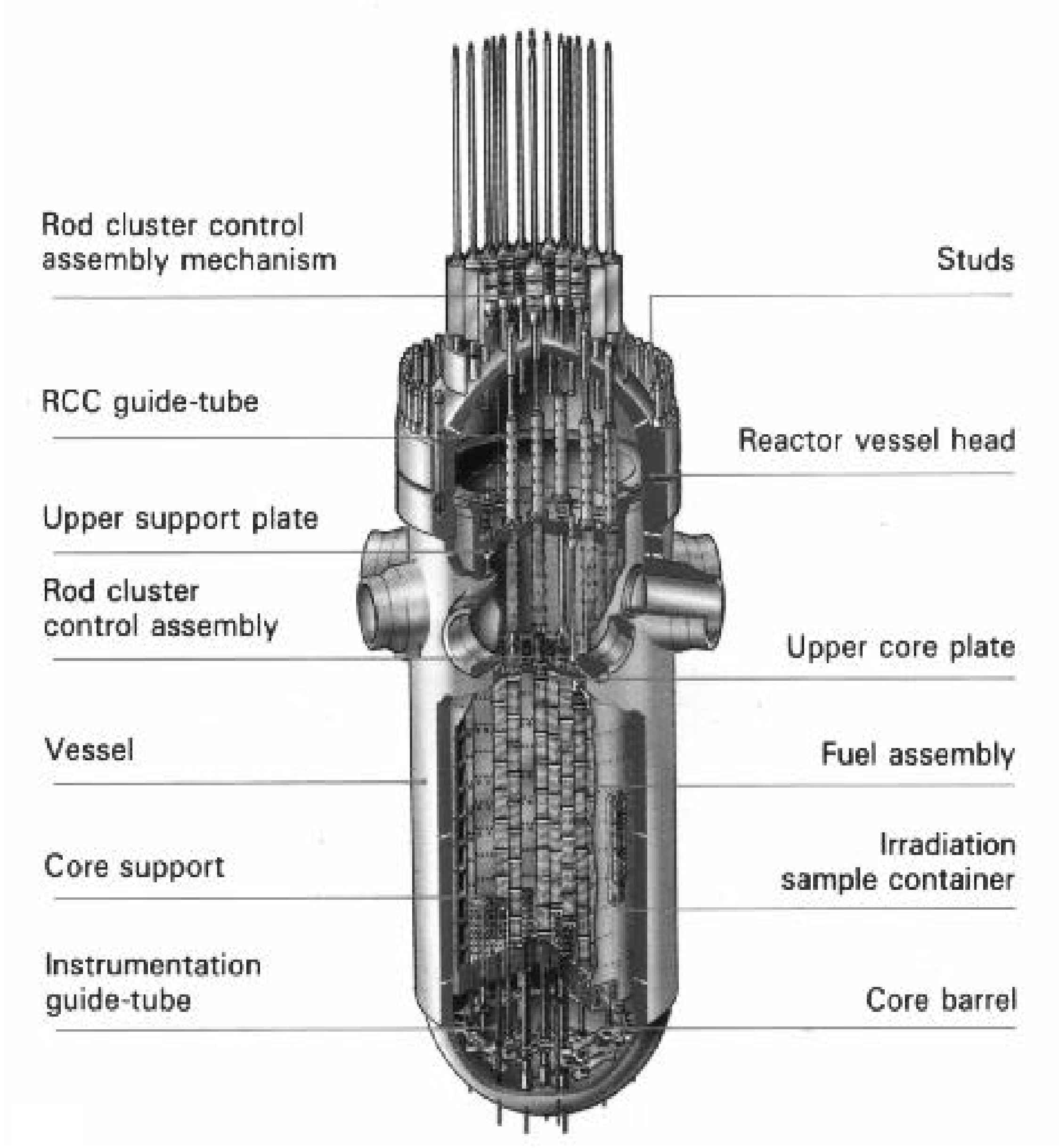
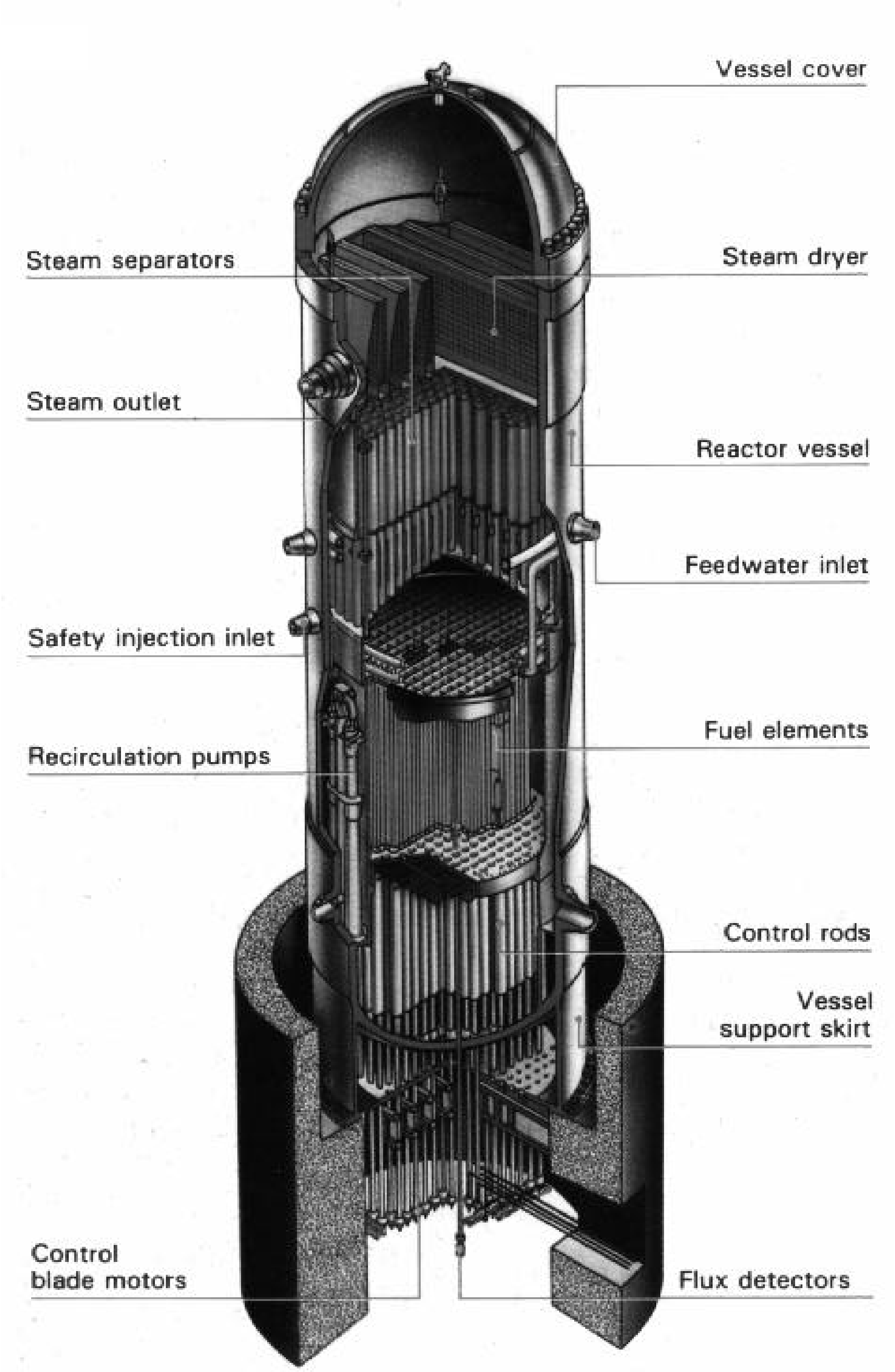
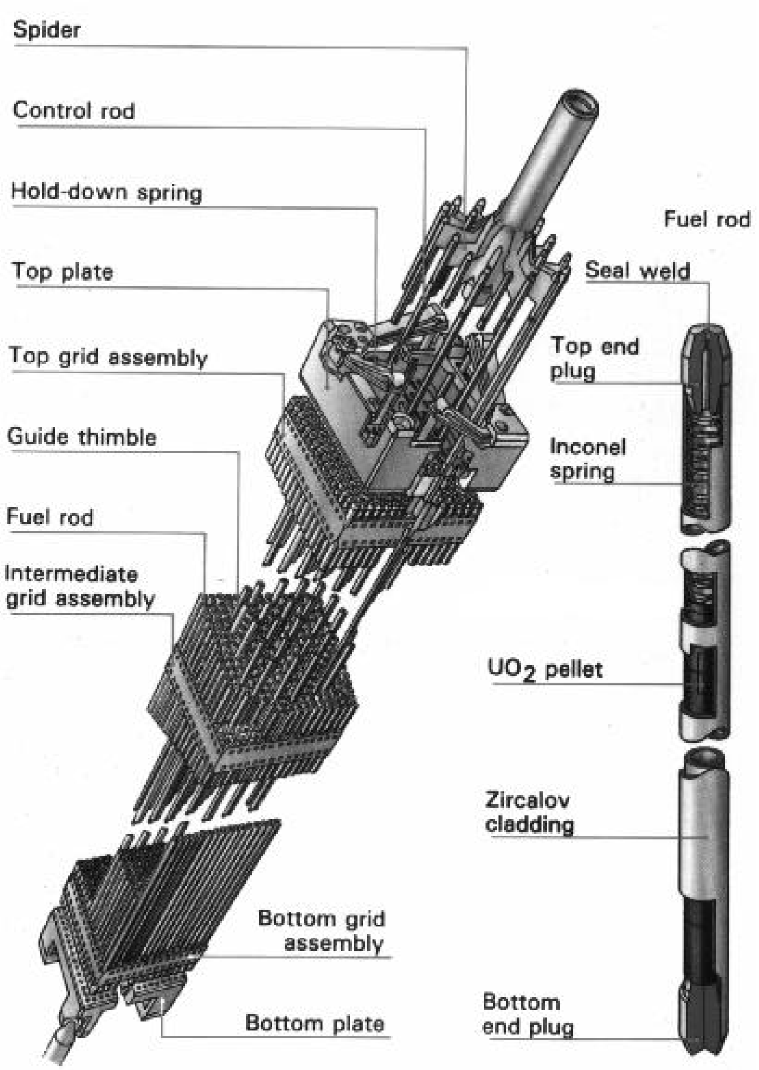


Figure B.3. Vessel of a typical BWR reactor (overall height = 21.65 m (71 ft), inner diameter = 6.05 m (19.83 ft))



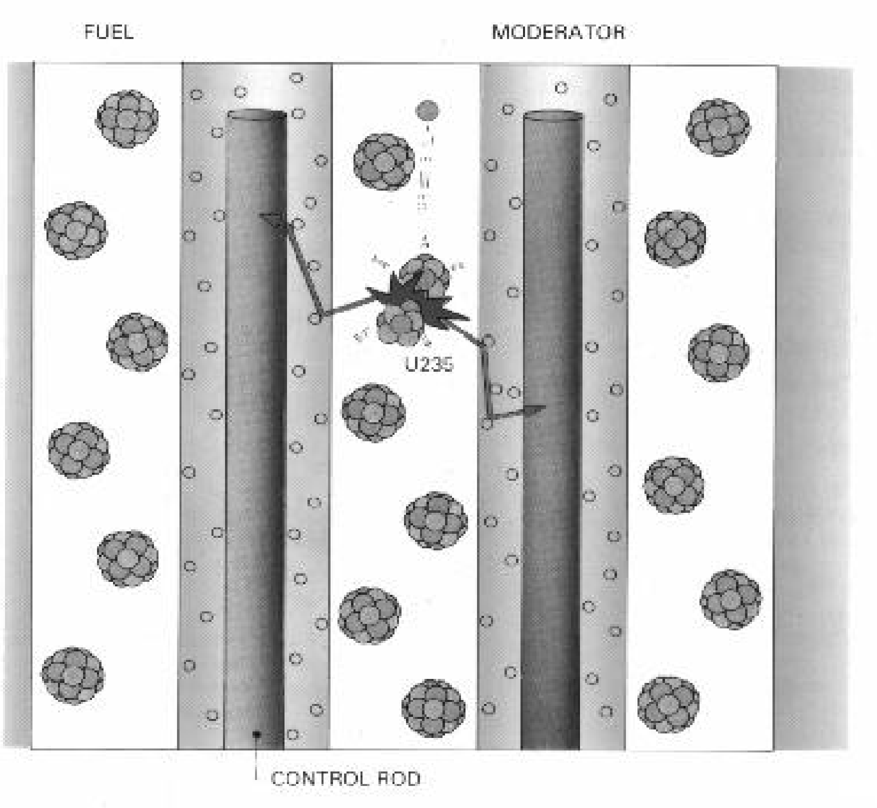
2.) ***The fuel.*** The fuel is usually an arrangement of pellets of enriched uranium oxide in zircaloy (a strong, anti-corrosive material) rods. These fuel rods are placed in the core. Figure B.4 shows an example of a fuel rod assembly and cross-section of a rod for a typical PWR.

Figure B.4. A fuel rod and its assembly (assembly dimensions = 20.32 cm x 20.32 cm (8 in x 8 in), active height = 3.81 m (12.5 ft), active diameter = 3.63 m (11.91 ft))



3.) ***The moderator.*** The moderator is used to slow down the fast moving neutrons produced by fission. This allows them to be captured by other nuclei so that the fission process continues. The moderator may be in the form of a solid, such as graphite, or a liquid, such as water. Figure B.5 is a representation of the role of the moderator in a reactor. The fast neutrons emitted by nuclear fission lose their energy and slow down in successive collisions with the nuclei neutrons across the moderator (hydrogen, deuterium or graphite). The chain reaction in the core of the reactor is started, adjusted or stopped by withdrawing or inserting a neutron absorber, such as boron. The control rods are inserted so as to absorb the neutrons emitted and arrest the chain reaction.

Figure B.5. Illustration of the moderator of a typical reactor



4.) ***The control rods.*** These control rods are made of neutron absorbing materials, such as cadmium or boron and are strengthened with steel. They can be moved into or out of the reactor core to control the rate of fission reaction or stop it completely.

5.) ***The coolant.*** The coolant is a liquid or gas circulating through the reactor, transferring heat away from the core.

6.) ***The steam generator.*** The steam generator is part of the cooling system of a PWR. It separates steam from the coolant and directs it to the turbines to generate electricity. Figures B.6 and B.7 include a picture of a u-tube steam generator and a once-through steam generator, respectively.

Figure B.6. A U-tube steam generator (overall height = 20.73 m (68 ft), upper shell outer diameter = 6.77 m (22.2 ft), lower shell outer diameter = 4.82 m (15.8 ft)

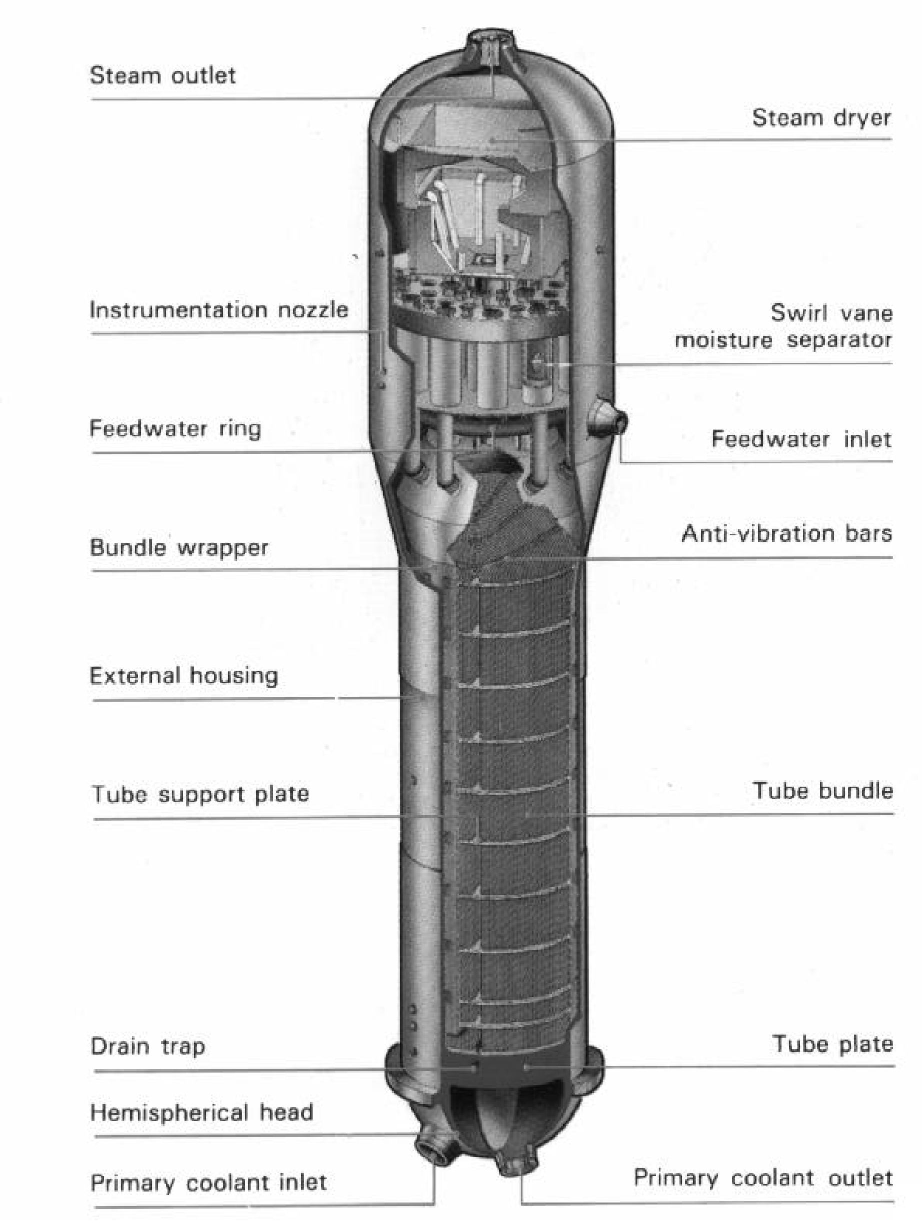
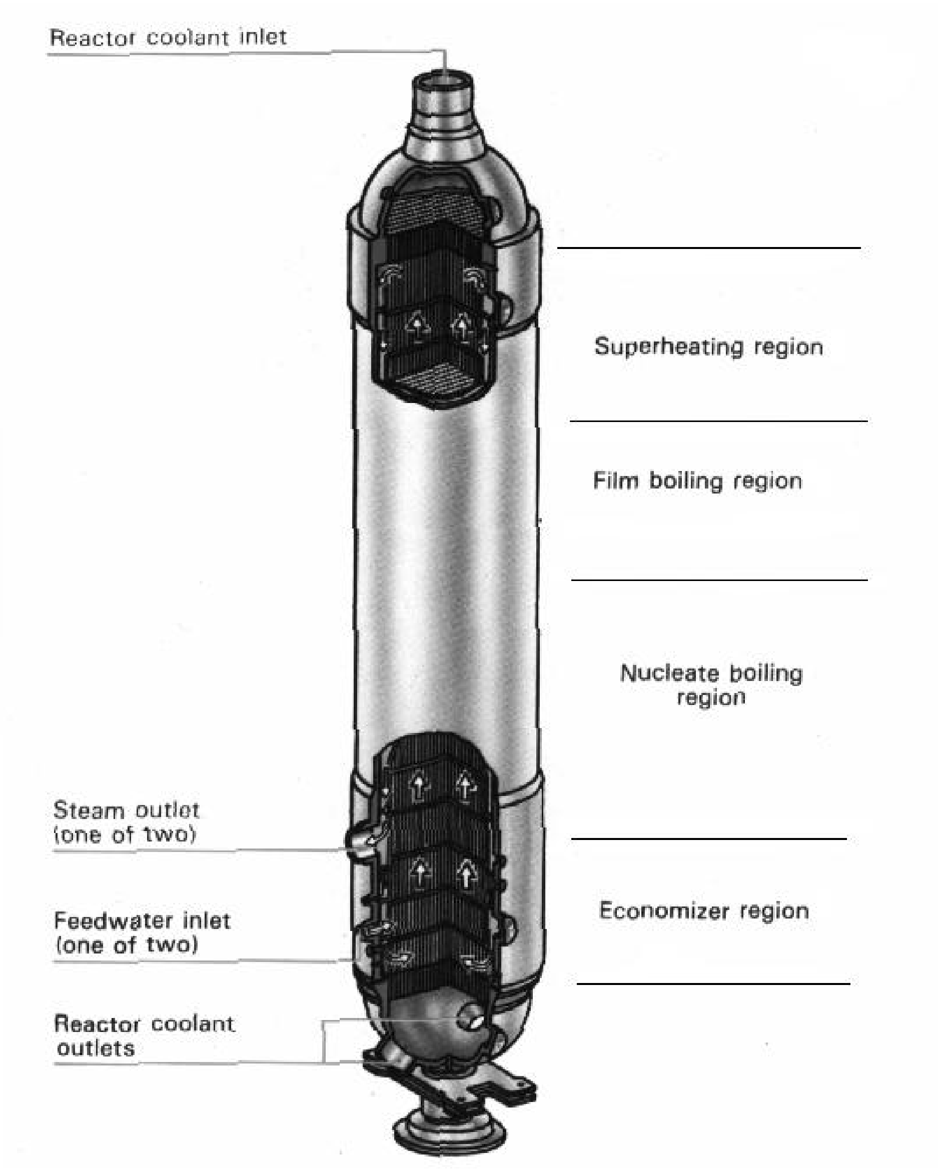


Figure B.7. A once-through steam generator (overall height = 23.01 m (15.5 ft), shell inner diameter = 3.53 m (11.58 ft))



7.) ***The containment****.* Reactors are contained inside a casing that acts as a radiation shield and is designed to prevent the release of radioactivity into the environment. Lack of containment is a design weakness of some Soviet designed reactors.

8.) ***Others.*** Other important components include the reactor pumps, turbines, pressurizer (in PWRs), demineralizers, and many other systems and components.

Other main components are the pumps and all other equipment that are part of the primary and secondary loops in most reactors. Demineralizers, turbines, condensers, dryers, shielding structures, water treatment systems, other systems, corresponding piping and many other systems are among these components.

Table B.1 includes typical characteristic parameters associated with the various nuclear reactor designs. These can be used to identify parameters and reactor components in the absence of documentation and to predict and locate possible sources of radiation within the power plants. The data included in this table can also serve as a key to predict values such as the radiation from a fuel assembly, radiation flux from a reactor core, the predicted dose from possible exposure to these parameters and other health physics computations [19].

Table B.1. Typical nuclear reactor parameters

Parameter	PWR (W)	PWR (B & W)	PWR (CE)	BWR	Candu (PHW)	GCFR	HTGR	LMFBR
Fuel Type	UO_2	UO_2	UO_2	UO_2	UO_2	PuO_2, UO_2	UC, ThO_2	PuO_2, UO_2
Coolant	H_2O	H_2O	H_2O	H_2O	D_2O	He	He	Na
Structural Material	Zircaloy	Zircaloy	Zircaloy	Zircaloy 2	Zircaloy 4	316SS	Graphite	316SS
Moderator	H_2O	H_2O	H_2O	H_2O	D_2O	-	Graphite	-
Core Parameters								
Active height(cm)	366	363	381	376	410	148	634	91
Equivalent active diameter (cm)	337	352	363	366	680	270	844	222
Height / diameter	1.09	1.03	1.05	1.03	0.60	0.55	0.75	0.41
Active core volume (l)	32,800	37,600	40,000	63,910	130,000	8,510	354,000	6,300
Fuel weight (kg)	90,200	94,900	103,000	138,000	80,000	28,000	39,000	19,000
Fuel Assemblies								
Type	Square bundles	Square bundles	Square bundles	Canned-square bundles	Pressure tube bundles	Hexagonal canned bundles	Hexagonal graphite prisms	Hexagonal canned bundles
Number of assemblies	193	205	241	732	473	347	3944	394
Fuel element array	17 x 17	17 x 17	16 x 16	8 x 8	pressure tubes	hex	132 pins	hex
Assembly dimension (cm)	21.4 x 21.4	21.7 x 21.7	20.3 x 20.3	14 x 14	8 x 50	17 x 17	35 x 79	12 x 12
Number of fuel elements per assembly	264	264	236	63	28	225	132	217
Fuel Elements								
Type	Clad rod	Clad rod	Clad rod	Clad rod	Clad rod	Vented clad rod	Graphite UC, ThO_2 rod	Wire-warped clad rod
Outside diameter (cm)	0.94	0.96	0.97	1.25	1.52	0.805	1.56	0.579
Fuel pellet diameter (cm)	0.819	0.823	0.825	1.056	1.44	0.739	1.56	0.66

Parameter	PWR (W)	PWR (B & W)	PWR (CE)	BWR	Candu (PHW)	GCFR	HTGR	LMFBR
Thermal hydraulics								
System pressure (bar)	155	155	155	70	89	86	50	14
Coolant flow (10^6 kg/hr)	62	68	72	47	23.9	10	5	50
Inlet temperature (^{o}C)	300	300	296	269	249	332	337	380
Outlet temperature (^{o}C)	326-332	333	328	285	293	642	750	552
Maximum fuel temperature (^{o}C)	1788	2021	1882	1829	1500	2200	1410	2000

W: Westinghouse
B & W: Badcock and Wilcox
CE: Combustion Engineering
PHW: Pressurized Heavy-water Reactor
GCFR: Gas cooled fast reactor
HTGR: High Temperature Gas-cooled Reactor
LMFBR: Liquid Metal Fast Breeder Reactor
316SS: Stainless Steel # 316
CR: Criticality Ratio

B.1. Pressurized Water Reactors (PWR)

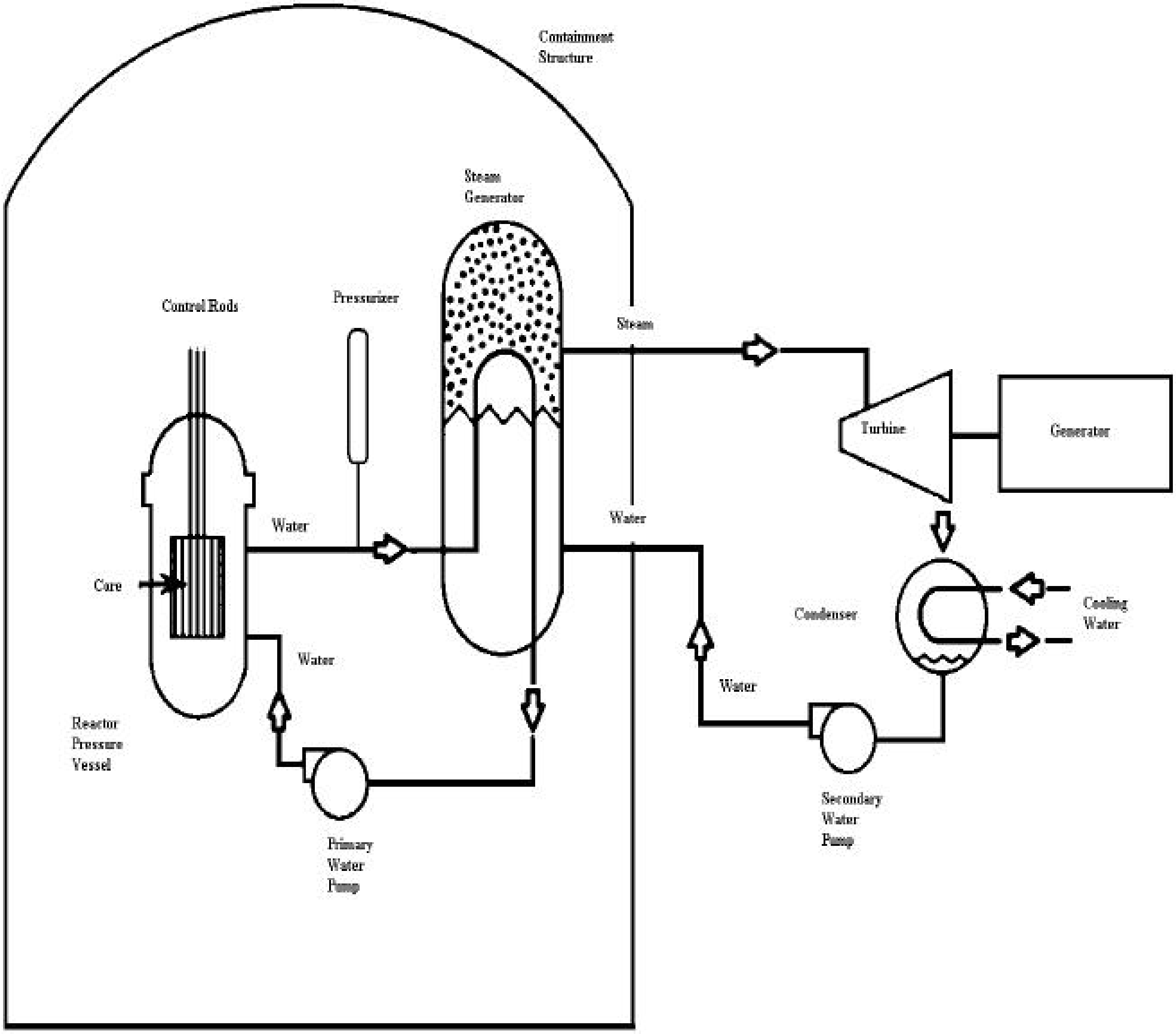
Pressurized water reactors are the most common types of reactors in the world. In the beginning of 1999, there were 288 PWRs in the world, representing fifty-eight percent of all the nuclear power plants; of these, 251 plants are? still in operation [18]. The pressurized water reactor has two main loops. A primary loop runs through the reactor vessel and the steam generator and is contained in the containment structure. A secondary loop runs though the steam generator, turbine and condenser. A tertiary loop can be identified if one considers the water flow that runs from a reservoir through the condenser. Figure B.8 illustrates these loops in a typical PWR.

The main components of the primary loop are the vessel, the steam generators, the pressurizer, the pumps and associated piping. The coolant flowing through this loop is called the primary coolant. Sources of high radiation can be identified at each component of this loop.

The main components of the secondary loop are the steam generators, the turbine, the condensers, the secondary pumps and the associated piping. Heat is transferred to the secondary loop via steam generators. This loop is maintained at a lower pressure, at which steam is generated. Each steam generator constitutes a branch of the primary loop and a branch of the secondary loop. The steam drives the turbines from the secondary loop and the exhaust steam is condensed into liquid water in the condensers. The condensed water is pumped as feed water for the steam generators. A certain amount of radioactivity may be present in the water in the secondary loop, but unless there is a leak in the steam generator (common failure of tubes), the secondary loop (and the steam) should be non-radioactive.

The condensers have a branch of the secondary loop and a branch that links it to a tertiary loop. Water is condensed and pumped back to the steam generator of the secondary loop. The counterflow in these condensers has a leg that is commonly fed from a water reservoir.

Figure B.8. The pressurized water reactor



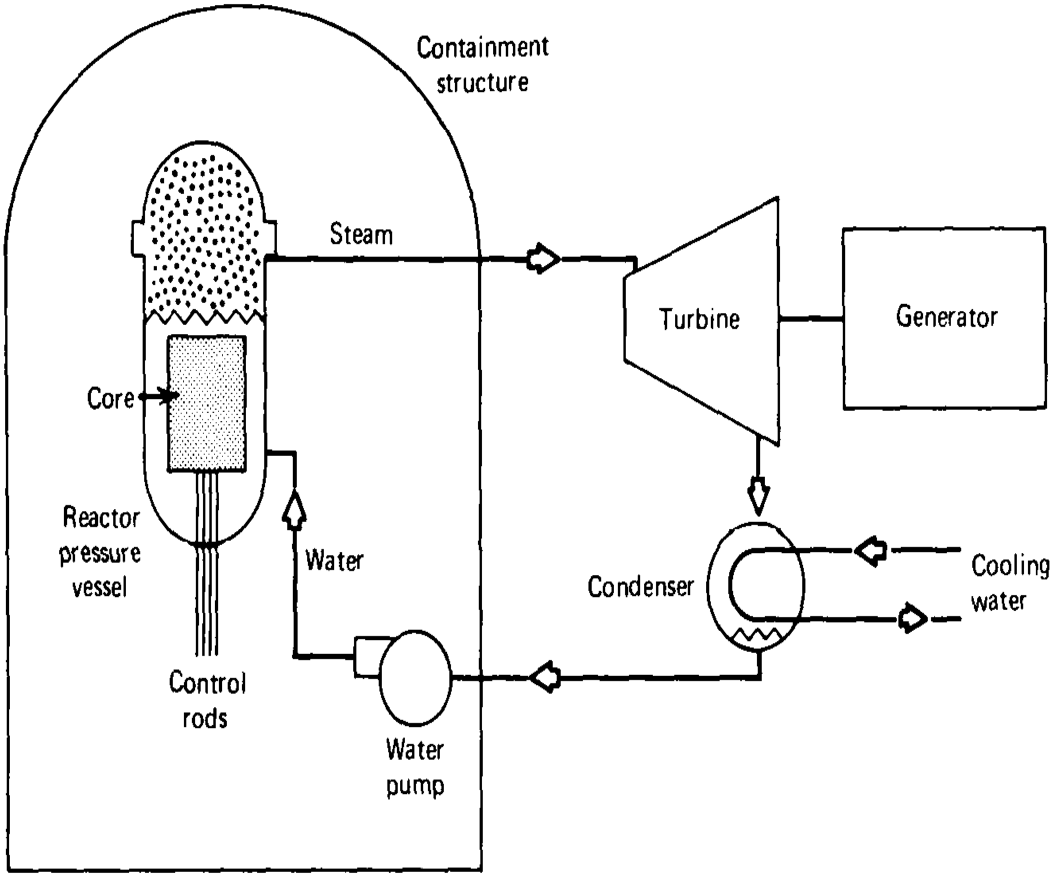
B.2. The Boiling Water Reactors (BWR)

In a BWR, the water that is heated by the core turns directly to steam in the reactor vessel, and the same steam is used to power the turbine-generator. Therefore, this type of reactor has only one loop. In this loop water boils and steam is produced within the reactor core. Consequently, there is no need for a separate steam generator. The loop includes the reactor vessel and recirculating pumps (within the primary containment), the turbines, condenser, pumps and related piping (in a secondary type of containment). A secondary loop can be identified in the same fashion as in the PWR tertiary loop, by looking at the water that flows from a reservoir and through the condenser. Figure B.9 sketches the main components of a BWR power plant.

The water of the BWR is not borated as it is in the PWRs, but reactivity compensation is obtained by adding the neutron absorber gadolinium (as its oxide) to a small number of fuel elements. The gadolinium acts as a burnable poison, which is gradually consumed as the reactor operates [20].

The steam that drives the turbines will contain some gaseous and volatile fission product because of pinhole leaks in the cladding of fuel rods. However, BWR systems take steps to reduce their activity before discharge, such as the use of demineralizers.

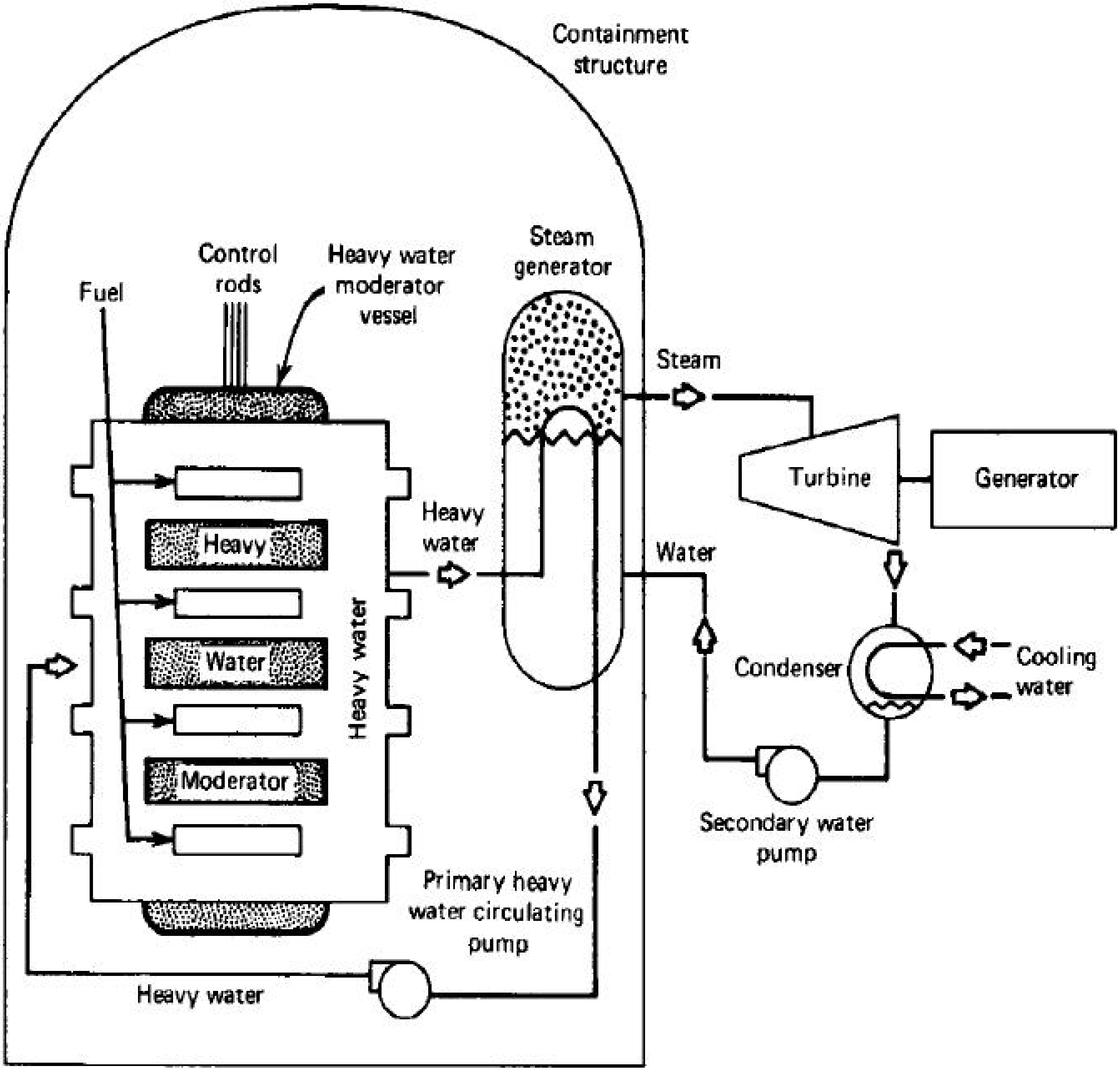
Figure B.9. The boiling water reactor



B.3. The Heavy Water Reactors (HWR)

Moderation of heavy water is not as efficient as light water (the absorption cross section of D_2O is very small); therefore, the ratio of moderator-to-fuel is five to eight times that of an LWR [21]. Since a large volume of moderator is required, the system is usually designed with a low-pressure tank (the calandria) filled with cold D_2O moderator. The fuel bundles are located in cylindrical tubes or channels that are cooled by D_2O at high pressure and horizontally transverse this tank (vessel). The coolant is piped to a steam generator to remove the heat and pumped back to the inlet of the fuel-bearing channels. The Canadian nuclear power system is based on the use of natural uranium fueled reactors moderated by D_2O. This Canadian Deuterium Uranium (CANDU) reactor system is represented in Figure B.10.

Figure B.10. A heavy water reactor



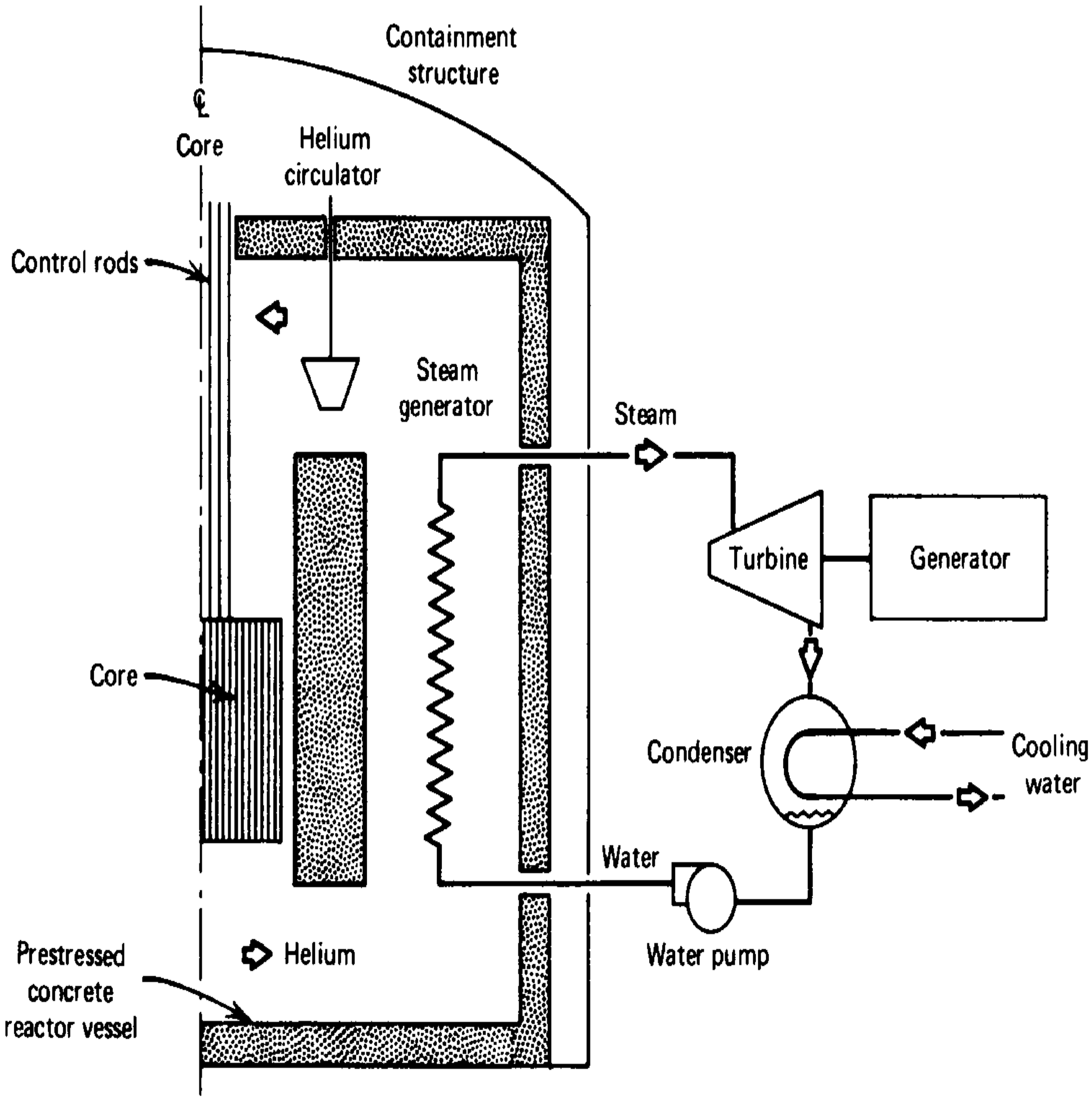
B.4. High-temperature Gas-cooled Reactors (HTGR)

The HTGRs are double-loop systems like the PWRs, with gas as a coolant instead of water. The gas used is helium, which is circulated through pipes in the primary loop by huge blowers. The gas is kept under a pressure of about 4.8 MPa (700 psi, 48.3 bar) and can achieve much higher temperatures than water. In some designs, the gas can be heated as much as 750 ^{o}C (1400 ^{o}F). As a result, the steam produced from the water in the secondary loop, which powers the turbines, can have temperatures as high as 538 ^{o}C (1000 ^{o}F). This higher temperature leads to improved thermal efficiency. That is, more electric power is generated for the same amount of heat obtained from the fuel.

The core of an HTGR is made up of a number of hexagonal graphite blocks stacked in close-packed columns. Vertical holes are drilled in the blocks for insertion of some 10,000 fuel rods and for passage of the coolant gas. The fuel rods are made of graphite containing separate particles of highly enriched uranium dioxide (or carbide, or a combination of the two) and of thorium dioxide (or carbide). The combination of fissile ^{235}U and fertile ^{232}Th is roughly equivalent to uranium of about 5 percent enrichment in ^{235}U [22]. Some of the ^{232}Th is converted into fissile ^{233}U during reactor operation.

The steam generator in an HTGR plant is similar to a conventional water tube boiler. The feedwater flows under pressure through a bank of tubes that are surrounded by helium gas, which has been heated in the reactor core. The HTGR steam can be superheated because the water is heated by hot gas rather than by hot water, as in the steam generator from a PWR. The steam leaves the generator at a temperature of about 538 ^{o}C (1000 ^{o}F) and a pressure of about 16.5 MPa (2400 psi, 163 bar) [23]. Figure B.11 is a representation of an HTGR.

Figure B.11. A high-temperature gas-cooled reactor



B.5. The Fast Breeder Reactors (FBR)

The fuel material in a water-cooled thermal power reactor generally contains about 3 percent of ^{235}U. The remaining 97 percent (by weight) is usually the fertile ^{238}U. Therefore, in normal operation of the reactor, ^{239}Pu is formed as a consequence of the capture of neutrons by ^{238}U. As it accumulates, ^{239}Pu serves as an alternative to ^{235}U in the fission process. A converter reactor is a reactor in which fertile specie is changed into fissile material, while generating heat by fission. Examples of this type of reactor are the water- cooled reactors.

In a thermal reactor, the ^{239}Pu formed is less than the ^{235}U consumed. However, in a breeder reactor, the ^{239}Pu generated from ^{238}U can exceed the quantity of fissile material used in operating the reactor. That is, the breeder reactor produces energy while producing more fissile material than is consumed. The breeding of ^{239}Pu from ^{238}U can only be achieved in a fast reactor; however, the breeding of the fissile material ^{233}U from ^{232}Th is theoretically possible in a thermal reactor. The requirement for breeding is that there should be more than two neutrons available for every neutron absorbed in fissile material. One of the neutrons is needed to maintain the fission chain, whereas the remainder can be capture by the fertile species to generate new fissile material.

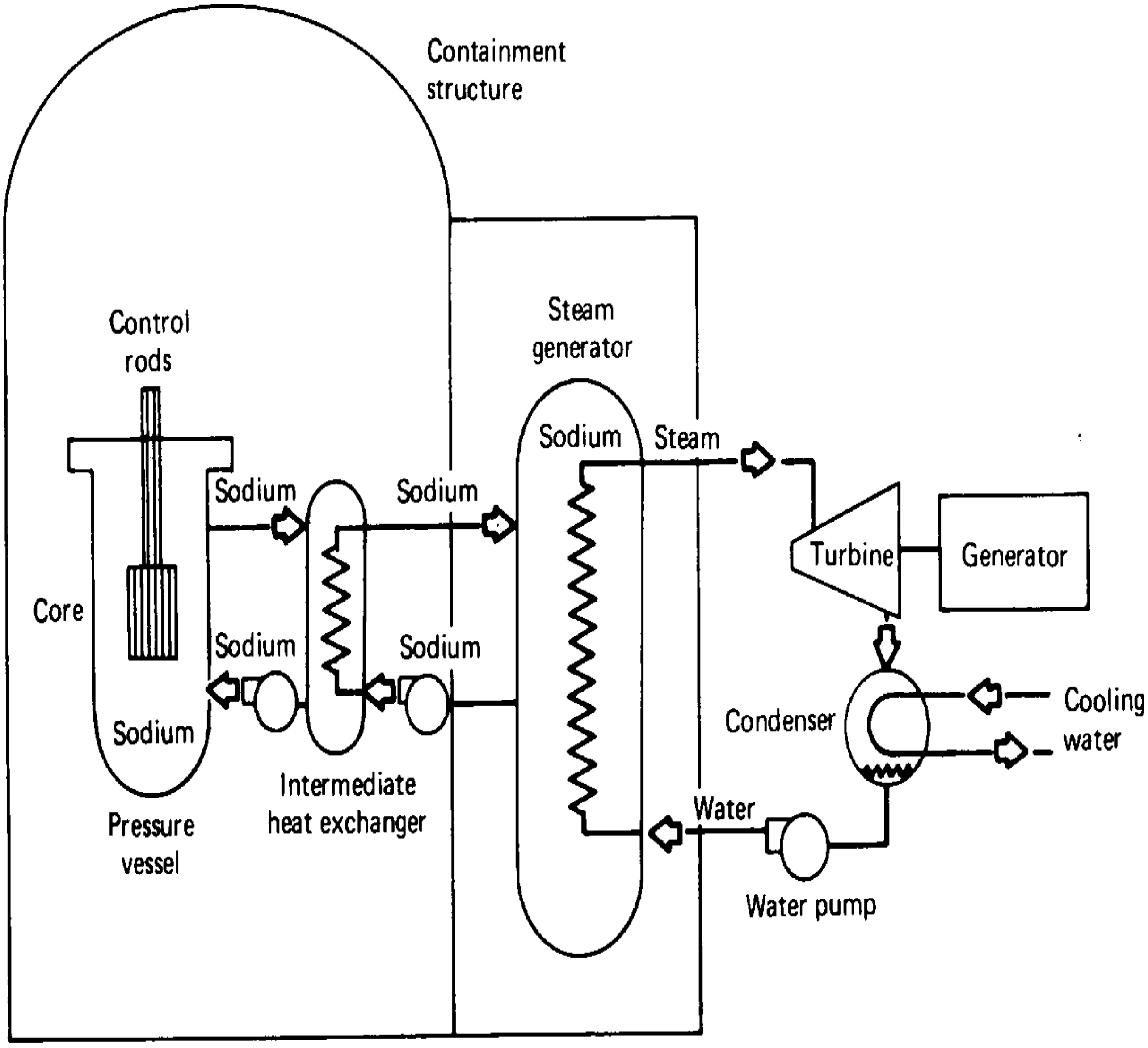
Breeder reactors are designed similar to previously described designs. However, the fertile specie is included in the reflector (the breeding blanket), as well as in the fuel elements. The fertile nuclide is converted into fissile nuclide by neutrons in the rector core and also by many of those that escape into the surrounding blanket. If breeding occurs, the total amount of fissile species produced in the core and blanket exceeds that consumed in the release of energy [24]. The liquid metal fast breeder reactor is an example of a breeder reactor.

B.5.1. The Liquid Metal Fast Breeder Reactor (LMFBR)

The fuel in an LMFBR is a mixture of about 85 percent uranium dioxide and 15 percent plutonium dioxide. The uranium may be normal uranium (99.3 % ^{238}U), or it may consist of the depleted residues (99.7 to 99.8 % ^{238}U) from a gaseous diffusion plant. The fuel rods consist of long, thin stainless-steel tubes packed with pellets of mixed (U and Pu) oxides. The core contains a large number of fuel rods separated by channels to permit flow of the molten sodium coolant for heat removal. Conversion of ^{238}U to ^{239}Pu occurs within the core as well as in a breeding blanket (reflector) of natural (or depleted) uranium dioxide that surrounds the core [24]. No moderator is needed since fast neutrons are required to achieve breeding.

In its passage through the reactor core, sodium captures neutrons to a small extent and is partly converted into a radioactive isotope. The heated sodium coolant leaving the reactor is consequently slightly radioactive. To provide protection to operators, steam generation involves an intermediate stage. Heat from the radioactive coolant is first transferred to non-radioactive sodium in a well-shielded heat exchanger (intermediate heat exchanger, IHX). Steam is then produced from feed-water in a heat-transfer steam generator that uses the high-temperature non-radioactive sodium. This steam generator operates on the same principle as that in a PWR system [23]. Figure B.12 is a sketch representation of an LMFBR.

Figure B.12. The liquid metal fast breeder reactor



There are two types of LMFBR, and their classification is derived from the detailed manner in which the intermediate sodium loop is arranged. These are the loop-type LMFBR and the pool-type LMFBR [25]. Figure B.13 is a representation of the loop-type LMFBR. The core, blanket and control rods are located in the reactor vessel, which is surrounded by a safety tank.

In this system, the IHX and all other components of the heat transfer system are located external to the reactor vessel. All components in the primary loop are heavy shielded because the sodium in the primary loop is radioactive. An atmosphere of nitrogen is maintained in the primary loops of this type of reactor[37]. The top part of the reactor vessel, which is above the sodium, and the

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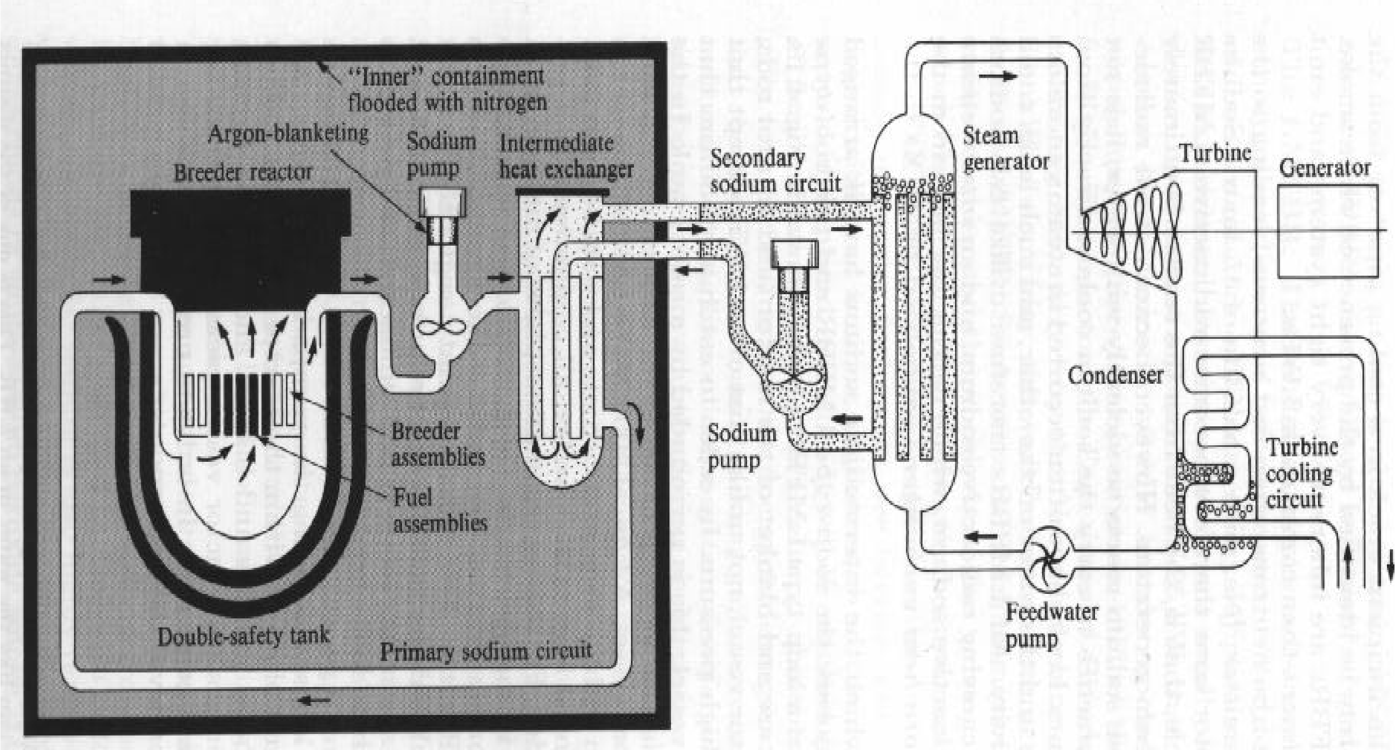
[37] Sodium does not react with nitrogen and therefore, it is used to reduce the likelihood of fires involving radioactive sodium [26].

primary pumps are made inert with argon[38]. The sodium in the secondary loops is not radioactive and neither is the water or steam.

Figure B.13. Loop-type LMFBR power plant



The pool-type LMFBR is distinguished from the loop-type LMFBR in that all of the primary loops (including the core, blanket, pumps, and the IHXs) are located within the reactor vessel. Sodium is circulated by the pumps through the core and blanket, and then through the IHXs. The sodium from the secondary system enters the reactor vessel, picks up the heat from the IHXs and continues to the steam generators. The sodium in the IHXs is heavily shielded; therefore, it is not radioactive[39]. Figure B.14 is a schematic of the pool-type LMFBR power plant.

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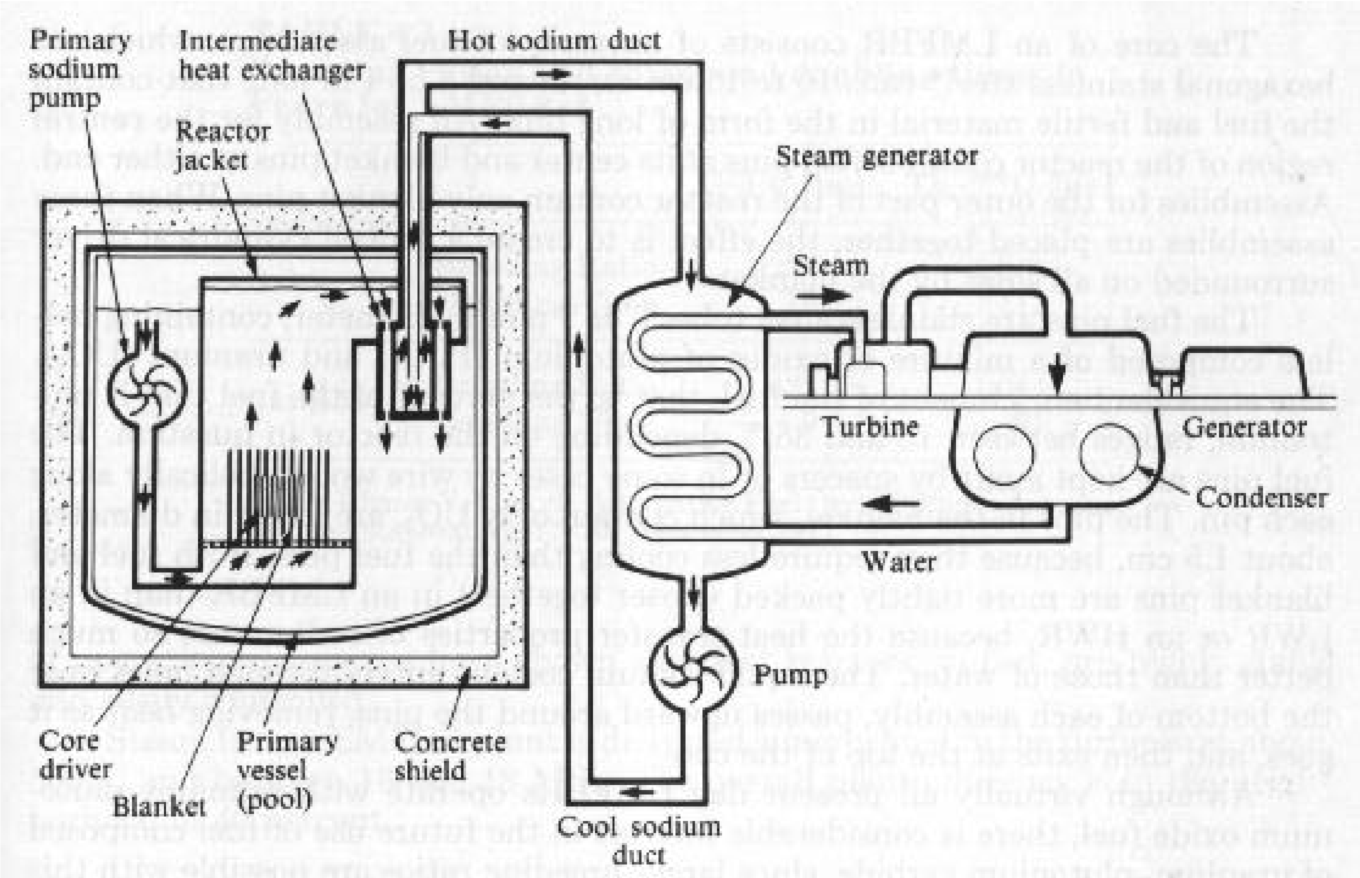
[38] Argon is used to make the system inert and also avoid the likelihood of fires involving radioactive sodium.

[39] The sodium leaving the IHXs is carefully shielded from the reactor neutrons, in order to prevent the sodium from becoming radioactive [26].

Figure B.14. A pool-type LMFBR



B.6. The RBMK (“Reactor Bolchoe Molchnastie Kipiachie”, High Power Boiling Water reactor) Reactor

The RBMK reactor was developed by the Soviet Union using a graphite pile as moderator and boiling water as coolant. An array of pressure tubes traversing the graphite core contains the fuel, which is 1.8 to 2.0 percent enriched uranium (^{235}U) with a zircaloy-niobium cladding. The core of the RBMK is a graphite 7 m high cylinder with 12 m in diameter [27]. Light water passes vertically through each of the fuel channels. Then the water, with a void (steam) fraction of about 14.5 percent, passes through steam separators to the turbine.

The most serious defect of the RBMK reactors is its positive coefficient of reactivity[40]. If the liquid coolant changes to less dense steam during an accident, reactivity would increase and the reactor can become uncontrollably supercritical. Another important defect of this type of reactor is the absence of a full containment structure. Thick walls of concrete, that enclose most of the coolant system, provide partial containment to the reactor building. However, the floor of the reactor is not enclosed and the roof of the reactor building is constructed as an ordinary industrial structure and is not designed to contain a pressure surge. A vapor-suppression pool is located beneath the reactor and it may be useful in the event of sudden depressurization of the coolant circulating system. The reactor core is not contained within a pressure vessel, as it is the case for LWRs [28]. A cross section of this type of reactor can be observed in Figure B.15. At the center of the structure one can find the reactor core.

The main parts numbered in this plant are: the main circulating pumps (1), the steam separators (2), vapor-suppression pools (3), concrete pad (4), and the fuel handling machine (5).

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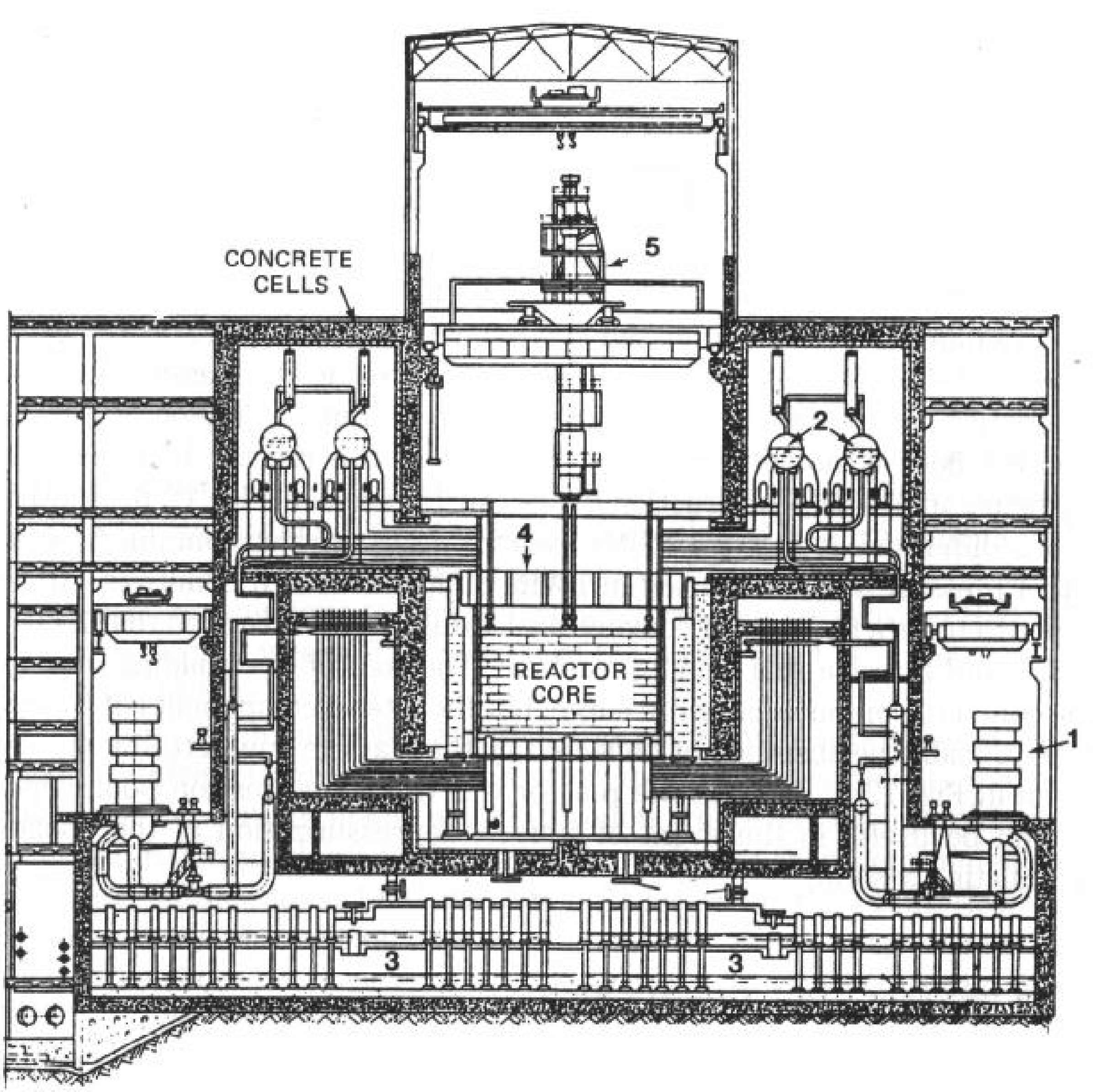
[40] Reactivity refers to the reactivity of a reactor (D) and it is dependent on the multiplication factor k, which is specific to a reactor. If a reactor has a $k > 1$, it is said to be supercritical and the reactivity D is positive. When a reactor is subcritical, $k < 1$ and reactivity D is negative.

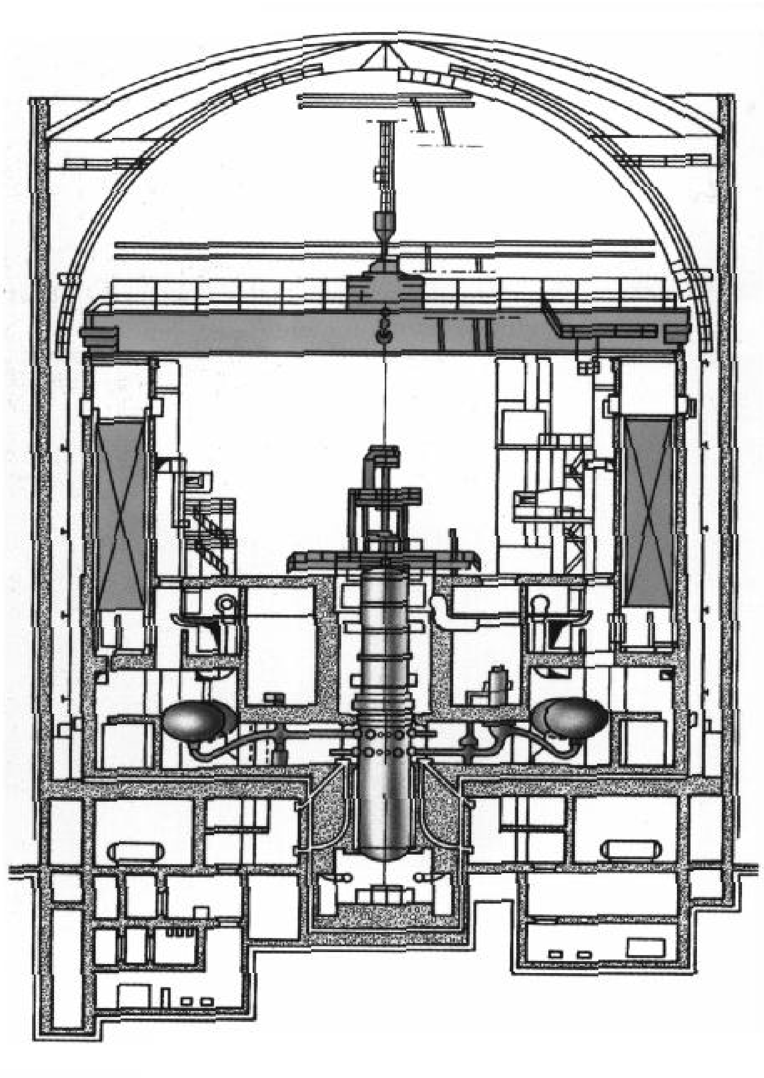
Figure B.15. The representation of an RBMK reactor



B.7. The "Vode Vodjanie Energitcheskie Reactor", VVER (Water-water power reactor)

The VVER reactor is a pressurized water reactor developed by the former U.S.S.R. This reactor is similar to the PWR design previously discussed; however, the steam generators are horizontal and smaller. The operating pressure of this reactor is about 123 bars, and its fuel enrichment varies from 2.2 percent to 3.6 percent ^{235}U. The containment of this type of reactor is usually a steel-lined reinforced concrete building. Chambers filled with 1,000 tons of ice are provided inside the containment to bring down temperature and pressure in the event of primary system pipe break [23]. Figure B.16 is a sketch representation of this type of reactor.

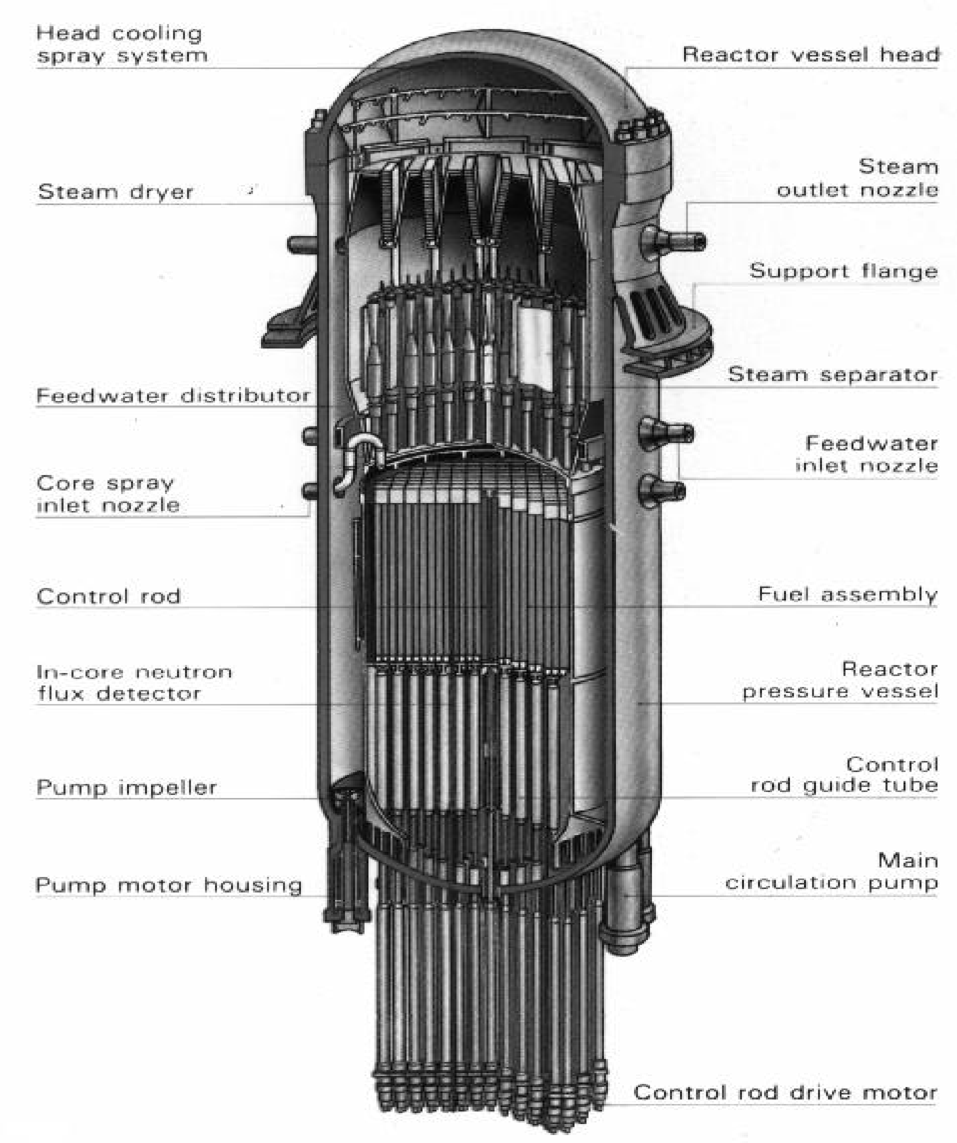
Figure B.16. Sketch of a VVER reactor



B.8. The Advanced Boiling Water Reactors (ABWR)

A new generation of reactor is emerging in European and Asian countries and is expanding to the rest of the world. These are the Advanced Boiling Water Reactors (ABWR), which include improvements to the common BWR design. In this design the re-circulation loops are eliminated and the pumps are integrated inside the reactor vessel [23]. Additionally, the control rod mechanism has two operating modes: the hydraulic mode for reactor trips, and the electric mode for manual movements. Figure B.17 is a pictorial representation of this type of reactor.

Figure B.17. Model of an advanced boiling water reactor



B.9. Radioactivity Barriers in Light Water Reactors

There are multiple barriers against the escape of radioactive fission products to the environment in light water nuclear power reactors, the most common type of reactors. They may vary within design but are sufficiently alike to be considered together. These barriers are important because they protect against unplanned exposures and help contain and control potential sources of environmental contamination that can be found throughout nuclear power reactors.

The first barrier is the reactor fuel itself. This fuel of light water reactors, for example, consists of uranium dioxide formed into cylindrical pellets of precise dimensions (roughly 1.5 cm [0.6 in] long and somewhat smaller diameter). These pellets are made by compressing the powdered oxide and then heating it until it sinters to a dense, ceramic-like material with a high melting point (2860 ^{o}C [5180 ^{o}F]). Solid fission products that are formed within the fuel cannot escape. Volatile fission products, notably radioisotopes of iodine, xenon, and krypton are released slowly from the ceramic material, thus allowing them time to decay to some extent.

The second barrier is the fuel cladding. The cladding prevents the escape of the volatile fission products to the environment. The cladding consists of a long tube made of a corrosion-resistant zirconium alloy (Zircaloy), into which the fuel pellets are packed. The empty spaces, including the annular gap between the pellets and the surrounding tube, as well as the space above the pellets, are filled with helium. The tubes are sealed and after inspection and testing are assembled into bundles that make up the reactor core in LWRs.

The third barrier is in the primary coolant system. Although different between PWRs and BWRs, it essentially consists of the reactor vessel and associated pumps and piping for both types of reactors. This forms a barrier to the fission products that may leak from the fuel rods. The reactor vessel and associated components are built and tested to exceptionally high standards to ensure integrity of the primary coolant boundary.

The fourth barrier is the primary containment structure. Although a break in the primary coolant boundary is not a common event, this containment serves as an additional safety feature to contain any fission products and prevent their escape to the environment. Containments are different for PWRs and BWRs but in all cases are made of steel surrounded by a thick layer of concrete and are pressure-tested to ensure a very low leak rate.

Appendix C. Radioactive Waste from the Nuclear Fuel Cycle

Wastes from the nuclear fuel cycle are categorized in a number of ways, including high, medium, or low-level waste. These wastes come from a number of sources and include:

1.) essentially non-radioactive waste resulting from mining,
2.) low-level waste produced at all stages of the fuel cycle,
3.) intermediate-level waste produced during reactor operation and by reprocessing , and
4.) high-level waste, which is spent fuel and waste containing fission products from reprocessing.

Milling wastes contain long-lived radioactive materials and progeny in low concentrations and toxic materials such as heavy metals; however, the total mass activity of radioactive elements in milling waste is less than in the original ore. These wastes require safe management in order to isolate them from the environment or to ensure that releases are limited to reduce environmental impact. Commonly, shallow burial in engineered facilities is used to dispose of milling wastes. The enrichment process leads to the production of depleted uranium (DU). This is uranium in which the concentration of ^{235}U is significantly less than the 0.7% found in nature [29]. Small quantities of this material, which is primarily ^{238}U, are used in applications where high density material is required, including radiation shielding and the production of MOX. While ^{238}U is not fissionable it is a low specific activity radioactive material and some precautions must be taken in its storage or disposal.

As a general rule, one can classify waste to determine the appropriate treatment or disposal. Table C.1 includes a general classification of these wastes.

Table C.1. Classification of waste

Waste	Definition
Below-Regulatory-Concern	This is waste that is classified below-regulatory-concern from a regulatory point of view. That is, a value of equivalent dose, RAM concentration, or other related quantity, at or below which there is no further regulatory concern (de minimus). This concept, from a scientific point of view, means that the value of increment of the equivalent dose or RAM concentration (above background), is deemed trivial or of no concern in decision making. The NCRP has set the bases at 1 mrem/yr as the Negligible Individual Risk Level (NIRL). The NRC allows the disposal of very low level waste by release into sanitary sewer, the disposal of oil by incineration, and the exception for the disposal of ^{14}C and ^{3}H (10CFR20).

Waste	Definition
By-product Material	(1) “Any radioactive material (except special nuclear material) yielded in, or made radioactive by, exposure incident to the process of producing or utilizing special nuclear material”, or (2) “The tailings or wastes produced by the extraction or concentration of uranium or thorium from ore processed primarily for its source material content, including discrete surface wastes resulting from uranium solution extraction processes. Underground ore bodies depleted by these solution extraction operations do not constitute "by-product material" within this definition” (10 CFR 20).
Hazardous Waste	A subset of solid wastes that pose substantial or potential threats to public health or the environment and meet any of the following criteria identified in 40CFR260 and 40CFR261: $is specifically listed as a hazardous waste by the EPA $exhibits one or more of the characteristics of hazardous waste (ignitability, corrosivity, reactivity, and/or toxicity); $is generated by the treatment of hazardous waste; or is contained in a hazardous waste.
Heavy Metal (Resource Conservation and Recovery Act, RCRA Metals)	A common hazardous waste; can damage organisms at low concentrations and tends to accumulate in the food chain. Examples are lead, chromium, cadmium, and mercury.
High Level Radioactive Waste (HLW)	The radioactive waste material that results from the reprocessing of spent nuclear fuel, including liquid waste produced directly from reprocessing and any solid waste derived from the liquid that contains a combination of transuranic and fission product nuclides in quantities that require permanent isolation. HLW is also a mixed waste because it has highly corrosive components or has organics or heavy metals that are regulated under RCRA. HLW may include other highly radioactive material that the NRC determines by rule and requires permanent isolation.
Transuranic Radioactive Waste (TRU)	TRU waste contains more than 100 nanocuries of alpha-emitting transuranic isotopes, with half-lives greater than twenty years, per gram of waste, except for (1) high-level radioactive waste; (2) wastes that the DOE has determined, with the concurrence of the EPA, that does not need the degree of isolation required by EPA's high level waste rule (40 CFR 191); or (3) waste that has been approved for disposal on a case-by-case basis in accordance with NRC's radioactive land disposal regulation (10 CFR Part 61). TRU is not generally found outside the DOE complex and is mainly produced from the reprocessing of spent nuclear fuel, nuclear weapons production, and reactor fuel assembly. TRU wastes mainly emit alpha particles as they decay. DOE categorizes TRU as either Contact Handled (CH) or Remote Handled (RH) with RH being the more radioactive of the two.

Waste	Definition
Low-Level Radioactive Waste (LLRW or LLW)	LLRW is waste that satisfies the definition of LLRW in the Low-Level Radioactive Waste Policy Amendments Act of 1985 (LLRWPAA). The LLRWPAA defines LLRW as "radioactive material that: (A) is not high-level radioactive waste, spent nuclear fuel, or byproduct material as defined in section 11e.2 of the Atomic Energy Act of 1954, and (B) the NRC, in accordance with definition (A), classifies as low-level radioactive waste. LLRW is also defined by the broadest category of waste. It encompasses materials that are slightly above natural radiation background levels to highly radioactive materials that require extreme caution when handling (Greater than Class C – GTCC). Examples of sources of LLW are: 1) Fuel-related activities 2) Reactor operations 3) Industrial establishments 4) Research laboratories 5) Medical establishments 6) Radiopharmaceutical companies Specific examples include: contaminated items, such as clothing and tools, swipes, trash, and liquids containing radioisotopes.
Mixed Waste (MW)	MW contains both hazardous waste and radioactive waste (as defined by Atomic Energy Act and its amendments). It is jointly regulated by the NRC or the NRC's Agreement States in the United States and the EPA or EPA's RCRA Authorized States. The fundamental and most comprehensive statutory definition is found in the Federal Facilities Compliance Act (FFCA) where Section 1004(41) was added to the RCRA: The term “mixed waste” means waste that contains both hazardous waste and source, special nuclear, or byproduct material, defined in the Atomic Energy Act of 1954.
Low-Level Mixed Waste (LLMW)	LLMW is waste that contains LLRW and hazardous waste.
Mixed Transuranic Waste (MTRU)	MTRU contains both Transuranic (TRU) and hazardous wastes. Approximately 55% of DOE's TRU is MTRU.

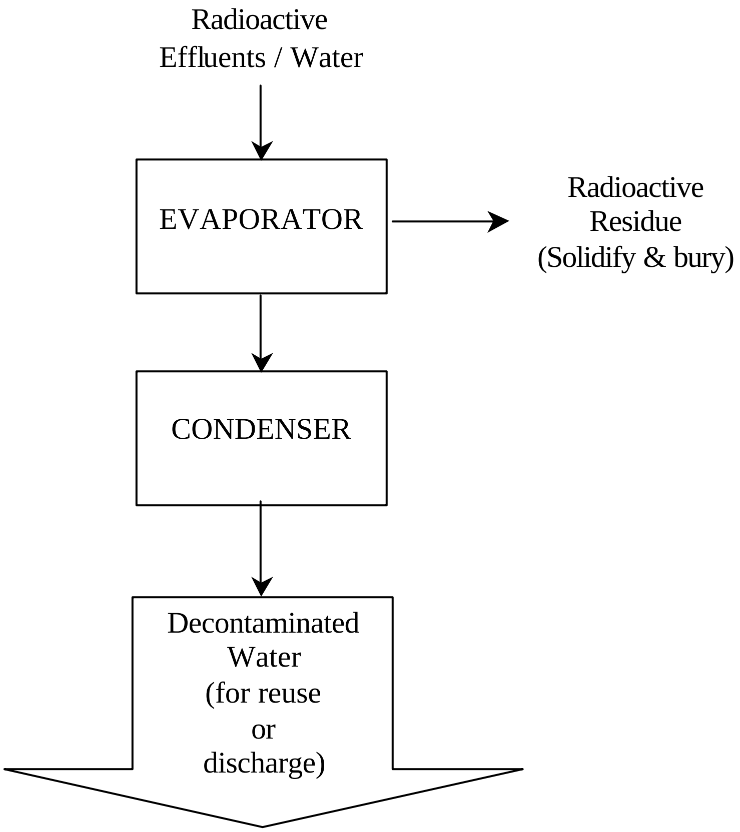
C.1. Waste in PWRs

The PWR is the most common nuclear power plant design in the world. Therefore, its waste has become the most common type of radioactive waste from nuclear power plants. These are generated from liquid, solid and gaseous effluents and are indexed as such.

C.1.1. Liquid Wastes from PWRs

Radioactive liquid waste is commonly decontaminated (decrease in radioactivity) by evaporation or by means of demineralizer. In the evaporation process, water is boiled off and the steam is condensed. The evaporator residue contains most of the radioactive material and it can be disposed in a controlled manner. The condensed water is essentially (although not completely) free of dissolved solids, but it will contain nearly all of the tritium. Tritiated water is vaporized and subsequently condensed with the ordinary water in the evaporator. Figure C.1 is a schematic representation of decontamination by evaporation.

Figure C.1. Decontamination by evaporation

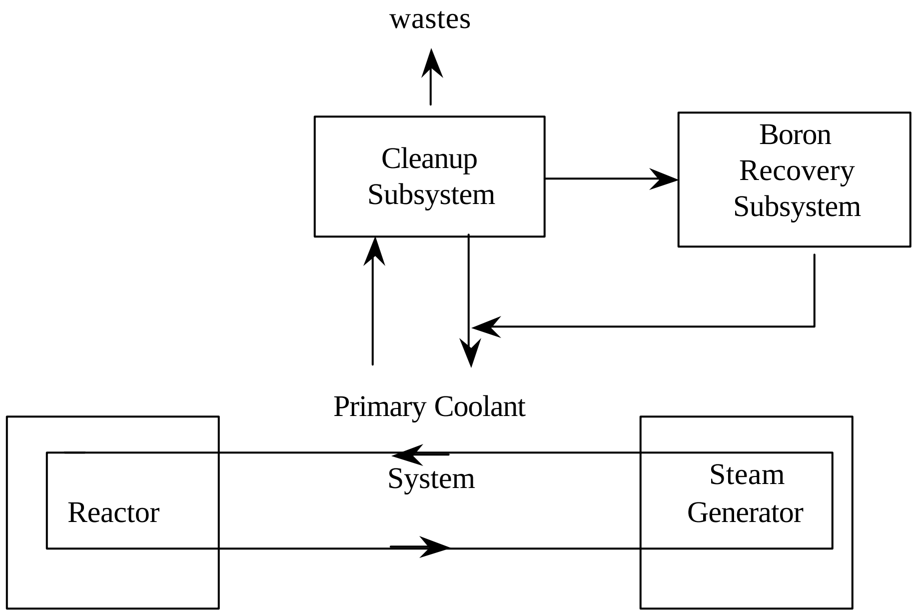


The demineralizer contains an ion-exchange resin, similar to the material used in household and industrial water softeners. Most of the dissolved matter is removed and retained by the resin when a radioactive solution is passed through the demineralizer. Elements such as cesium, yttrium, and molybdenum are removed relatively slowly by demineralizers; tritium is essentially unaffected. Although less effective, demineralizers are preferred over evaporators because of their simplicity.

The chemical and volume control system (CVCS) of a PWR plays an important role in decreasing the radioactivity in the liquid effluent. It consists of two main subsystems: the reactor coolant water cleanup system and the boron recovery subsystem. This is illustrated below in Figure C.2. A bypass in the main (primary) coolant circuit permits some of the water to be diverted continuously through the cleanup/purification subsystem. The water is cooled and passed through a demineralizer in order to remove dissolved substances, including fission and activation products (but not boric acid), before being filtered and returned to the coolant circuit. Most of the radioactivity is then retained by the ion-exchange resin in the demineralizer.

The concentration of boric acid used for shim control in a PWR must be decreased during the course of operation. Water is evaporated and steam is condensed, resulting in a condensate that is free of boron and is returned to the primary circuit. Accumulated radioactive materials in the boric acid residues are disposed of with solid wastes.

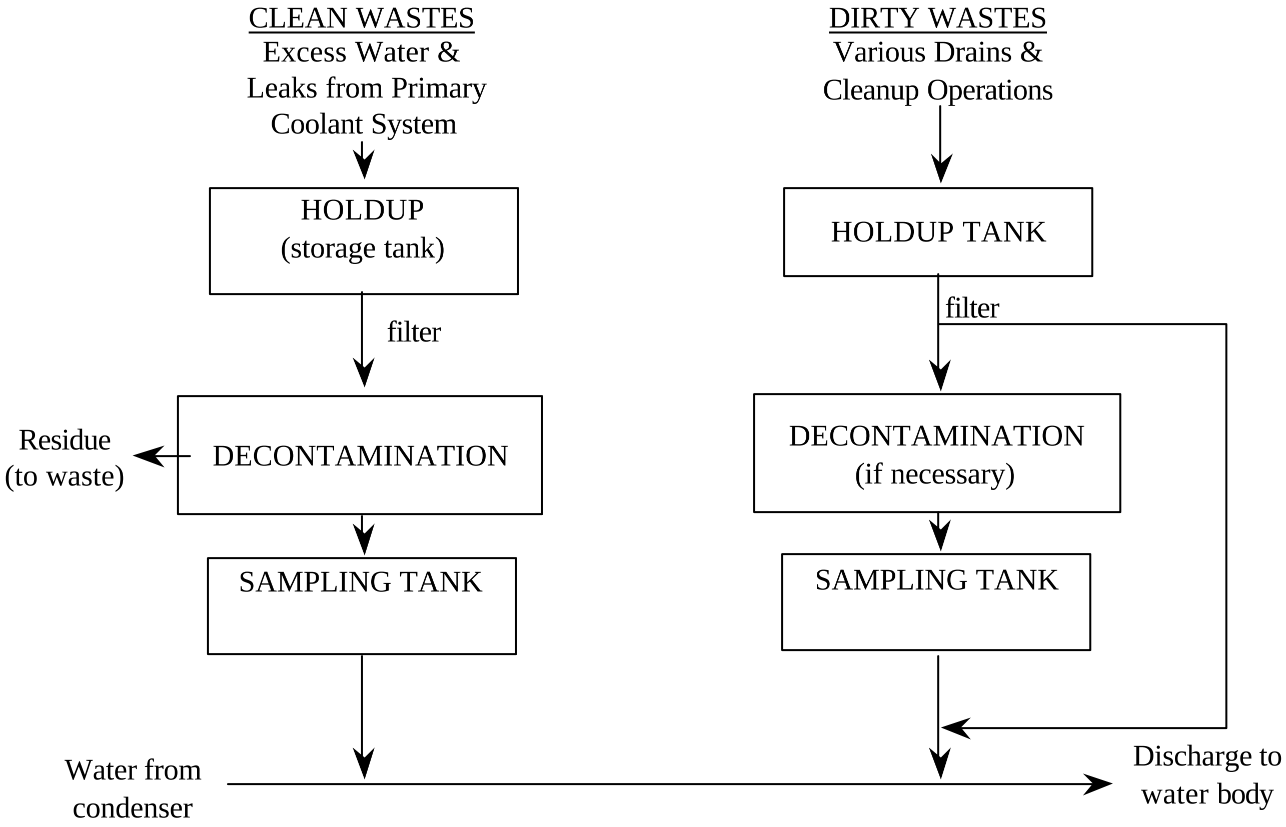
Figure C.2. Simplified flow diagram of the PWR CVCS system



Most PWR facilities classify their waste as clean, dirty, and laundry wastes. The terms clean and dirty refer to the chemical purity of the water and not to the amounts of radioactivity. The primary system wastes are also called clean wastes and originate in the primary coolant circuit, having the highest level of radioactivity of all the liquid wastes. However, the water is essentially pure, apart from the radioactivity. The clean water waste is composed of excess water from the CVCS system, pump-seals valve leakages, and any other liquid that may have leaked or that have been released for the primary coolant system. A holdup tank is used to collect liquid for about 30 days in order to allow radionuclides of short half-life decay. Contents of the tank are filtered and then decontaminated by evaporation or demineralization, or both.

Part of the decontaminated water is retained for use as primary coolant. The remainder is diluted with clean water (e.g., from the turbine condenser) and after being tested for radioactivity, it is discharged at a controlled rate into an adjacent water body [20]. Figure C.3 outlines the liquid radioactive waste system of a PWR.

Figure C.3. Liquid radwaste system of a PWR



One would normally expect to find radioactive impurities in the primary loop of a PWR. Ideally, if steam generators from PWRs are completely free from internal leaks, there is no reactivity in the "blow down" (withdrawal of water from secondary system in steam generators). Therefore, both liquid water and steam could be discharged without further treatment. However, small holes develop in the miles of tubing in the steam generators, and radioactive material in the primary coolant can leak into the secondary system and thus appears in the blowdown. The concentration of salts in the secondary system water gradually increases as a result of the presence of normal impurities in the water from the leakage from the primary to secondary flow defective tubes in the condenser. Moderate leakage rates (e.g., up to about 76 liters (20 gal)/day) in the steam generator tubing can be tolerated. But if the leakage becomes too large, faulty steam generators are normally shut down and tubes are plugged [24].

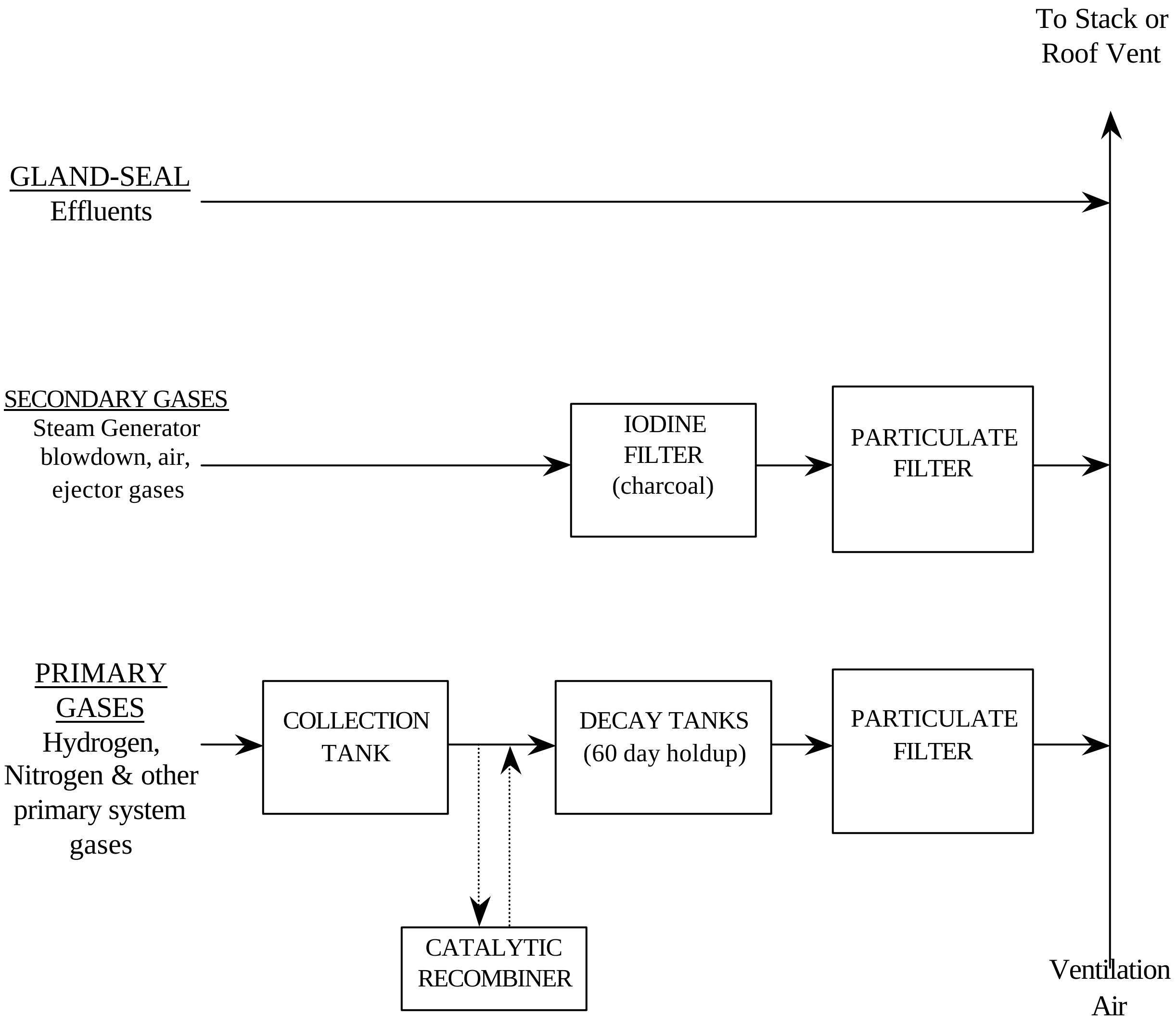
C.1.2. Gaseous Wastes from PWRs

Gaseous effluents from power plants contain noble gases such as krypton and xenon, iodine, and particulate matter. Particulates are reduced by filtering gas through a HEPA filter, prior to discharge. A charcoal filter removes part of the iodine. The noble gases are difficult to remove, and they are held up for a time to permit the activity to decrease by radioactive decay. Radioactive gaseous waste sources in PWRs include gases from the primary and secondary systems, and building ventilation gases. Figure C.4 outlines the gaseous radioactive waste system of a typical PWR.

The primary system gases include fission product gases (and vapors) vented from the CVCS and from the liquid waste holdup tanks. Hydrogen and nitrogen are also present because of the decomposition of water near the core into hydrogen and oxygen (radiolysis), and the usage of nitrogen to avoid the formation of an explosive mixture of hydrogen and atmospheric oxygen.

Many PWR designs collect the primary system gases in a storage tank and compress them into one of several decay tanks where the gases are held for an average period of about 60 days [22]. Krypton-85, ^{133}Xe, ^{133}I and tritium are the radionuclides that remain present in appreciable amounts and are filtered and mixed with large volumes of ventilation air prior to discharge through the stack. In some PWR plants however, primary waste gas is decreased by removing the hydrogen component by mixing the gases with oxygen and passing them through a catalytic recombiner to form water.

Figure C.4. Gaseous radwaste system of a PWR



Secondary system gases are:

1) gases released during steam generator blowdown,
2) gases from an air ejector, which are removed continuously from the low-pressure (exhaust) side of the turbine by means of steam jet, and
3) steam used to seal the turbine gland and prevent the entry of air (gland-seal effluent).

If there is no leakage from the steam generator tubes, radioactivity in the secondary waste gases is not significant and gases can be discharged after being mixed with ventilation air. However, most PWRs filter gases through charcoal to decrease the iodine content. They are then filtered to remove particulate matter and discharged with the ventilation air by way of a roof vent or stack.

Large volumes of ventilation air are part of the gaseous wastes, most of which is from auxiliary buildings where the radioactivity level is very low. This air is often discharged directly after filtration, but some plants use charcoal to remove iodine prior to discharge [20].

C.2. BWR Waste

Waste produced in a BWR plant differs from the waste produced in a PWR for several reasons. BWRs do not use boric acid in the reactor water as shim control; consequently, there is much less tritium formed. Steam is generated in the reactor vessel; therefore, radioactive gases (and vapors) that have escaped from defects in the fuel cladding or that were formed by neutron activation will be carried by the steam into the turbine. Finally, the BWR design does not allow for the use of hydrogen gas to suppress radiolytic decomposition of the water; hence, the gases removed from the low-pressure side of the turbine contain substantial volumes of hydrogen and oxygen.

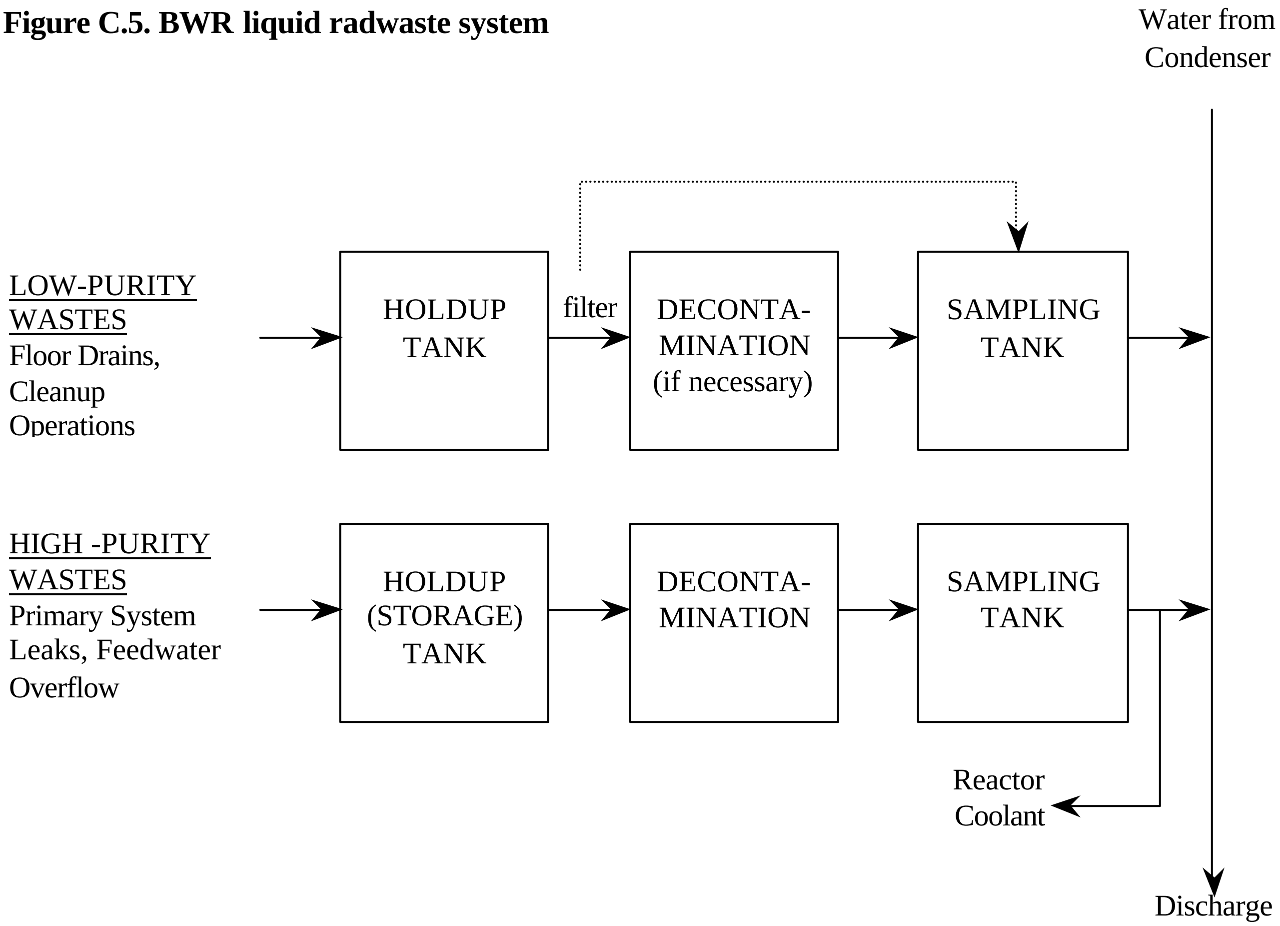
C.2.1. Liquid Wastes from BWRs

Liquid waste from BWRs differs from that of PWR and can be categorized into three general classes: the high-purity (or low solid), the low-purity (high-solid) wastes, which are equivalent to the clean and dirty wastes from PWRs respectively, and the laundry wastes. The laundry type of waste is treated in the same fashion as in the PWRs.

The high-purity (clean) wastes consist of the purest water with the highest radioactivity concentration. These arise from the reactor coolant water that has leaked from the primary system equipment (e.g., pumps and valves), from the overflow of the feedwater tank, and others. Liquids are held in storage (or holdup) tank, where partial decay occurs. The wastes are then filtered and demineralized. Part of the decontaminated liquid may be discharged after dilution with clean turbine condensed water and after being sampled for radioactivity. However, most of the liquid is retained for reuse as reactor coolant.

The low-purity (dirty) wastes consist of wastes from various floor drains, which are also collected in a storage tank. Some BWR designs allow for liquids to stand for a time and are then filtered and discharged with the condenser water, provided the radioactivity concentration is sufficiently low. Common practice, however, is to follow filtration and demineralization or evaporation prior to disposal. Water may then be discharged after dilution, or if purified by evaporation, it can be used as makeup for the reactor coolant as required [20]. Figure C.5 outlines the liquid radioactive waste system of a BWR.

Figure C.5. BWR liquid radwaste system



C.2.2. Gaseous Wastes from BWRs

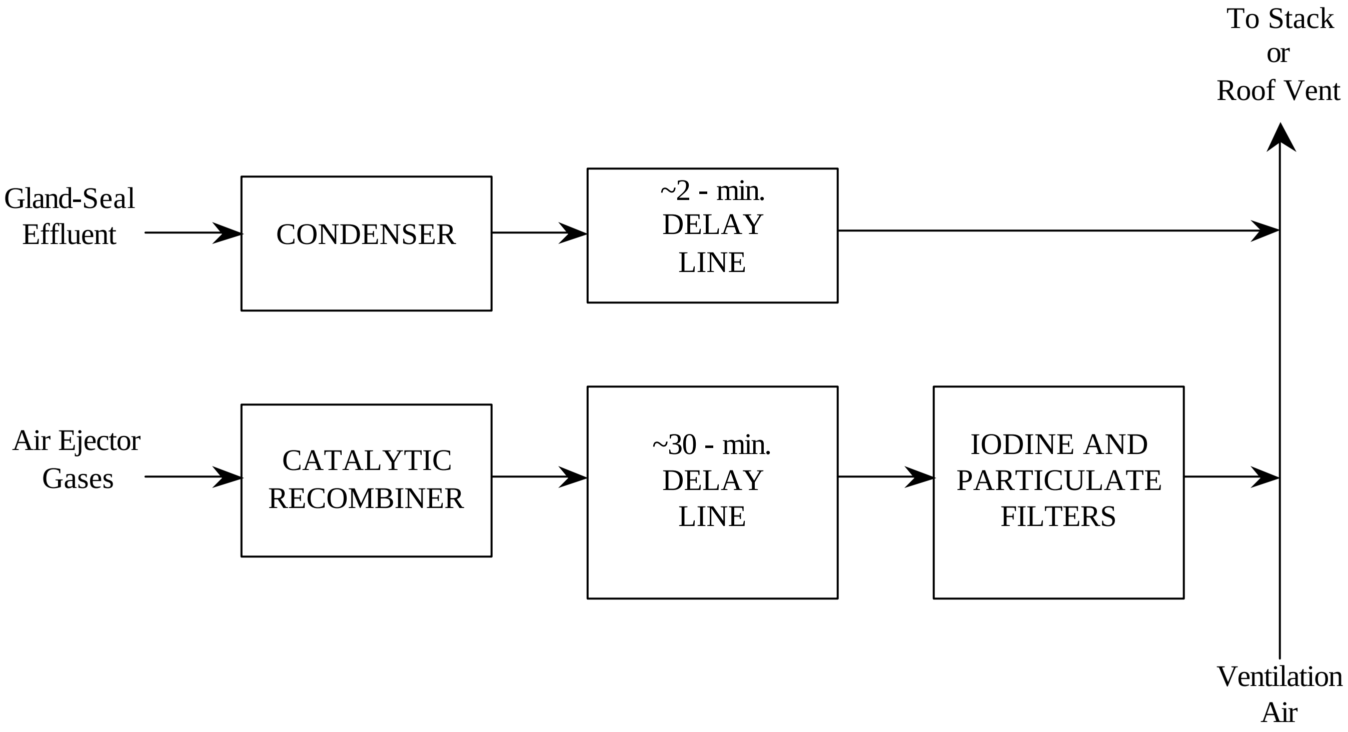
BWRs produce three types of gaseous waste: 1) the steam-jet air-ejector gases, 2) the gland-seal effluent, and 3) the building ventilation air. The steam-jet air-ejector gases consist of gases removed from the steam jet from the exhaust side of the turbine. This carries most (more than 99 percent) of the radioactive noble gases and iodine escaping from the fuel, as well as large amounts of hydrogen and oxygen produced by radiolysis of the reactor water. Therefore, the volume of steam-jet-ejector gases from a BWR is considerably greater than that from a PWR.

Most BWR designs pass the air-ejector gases through a catalytic recombiner in which the hydrogen and oxygen gases recombine to form water. After condensation of the water vapors, the remaining gases have about one-fifth of the original volume. These gases enter a delay line (a long, wide, convoluted pipe), where they are held for about 30 minutes to permit radionuclides with short half-lives to decay. From the delay line, gases pass on to charcoal beds at ambient temperature. The charcoal selectively removes (adsorbs) the noble gases and then gradually releases (desorbs) them. The net effect is to cause these gases to move slowly through the charcoal beds, which thus serve as an effective holdup system. Iodine radioisotopes are largely retained by the charcoal. Gases emerging from the charcoal beds are filtered to remove particulate matter and are mixed with large volumes of ventilation air. After being tested for radioactivity, these gases can be discharged to the atmosphere.

Gland-seal effluents from a BWR are more radioactive than those from a PWR because of the greater radioactivity of the steam used to provide the seal. However, the total radioactivity content is relatively small, and hence the gases remaining after condensation are usually held for about 2 minutes. If radioactivity levels are sufficiently low, these gases are then mixed with ventilation air prior to discharge.

Building ventilation air has low radioactivity and large volumes are discharged. This air is used to reduce the concentration of noble gases and iodine in the gaseous effluents entering the atmosphere [29]. Figure C.6 includes a block diagram representing the gaseous radioactive waste system of a BWR.

Figure C.6. BWR gaseous radwaste system



C.3. Solid Waste in LWRs

Apart from the waste resulting from the fuel and reactor components itself, solid waste from LWRs arise mainly from the spent ion-exchange (demineralizer) resins, discarded filter material (including charcoal), and evaporator residues. The latter are often slurries rather than solids, but they are generally solidified (e.g., by being mixed with cement).

C.4. Other Waste Sources from Reactors in Submarines

Naval nuclear power plants were discussed in Appendix B. Decommissioning nuclear-powered submarines has become a major task for the U.S. and Russian navies. After defueling, U.S. practice is to cut the reactor section from the vessel for disposal in shallow land burial as low-level waste. In Russia the whole vessels, or the sealed reactor sections, remain stored afloat indefinitely [30-32].

Naval yards contain possible sources of radioactive sources and contamination. As an example, one can look at the Russian naval program. Including Sevmash, there are six naval yards in Murmansk and Arkhangelsk counties. Sevmash is the only yard that constructs nuclear submarines. As part of servicing the submarines, the yards carry out operations in defueling, refueling, general maintenance, repair and work in the dry dock where the vessels' hulls and structures are attended. Therefore, in the event a soldier encounters this type of facility, it is primal to have a tool of recognizing risk associated with it.

There are several floating docks stationed at the various bases. The Russian naval northern fleet also has a number of service ships that assist in conducting minor maintenance and repair work on the submarines. Aside from servicing, repairing and maintaining nuclear submarines and vessels, naval yards serve as storage for liquid and solid radioactive waste. An example is the naval yard Shkval, close to the city of Polyarny. Figure C.7 is a picture from this naval yard, which is capable of processing 3-4 nuclear submarines at the same time. Figure C.8 is a picture of the naval yard Safonovo, which is located south of Severomorsk in the Murmansk Fjord and has several large floating docks. In this photograph, maintenance work on the hull of a Typhoon class nuclear submarine is being carried out. Figure C.9 is a picture of the naval shipyard Sevmorput, which is located in the Rosta Township in the northern district of Murmansk. Spent nuclear fuel assemblies are transferred at the shipyard from Northern Fleet service ships to railroad cars which will transport them further to a reprocessing facility. Sevmorput also has a storage facility for fresh nuclear fuel.

Figure C.7. The naval yard of Shkval

Figure C.8. Naval yard Safonovo

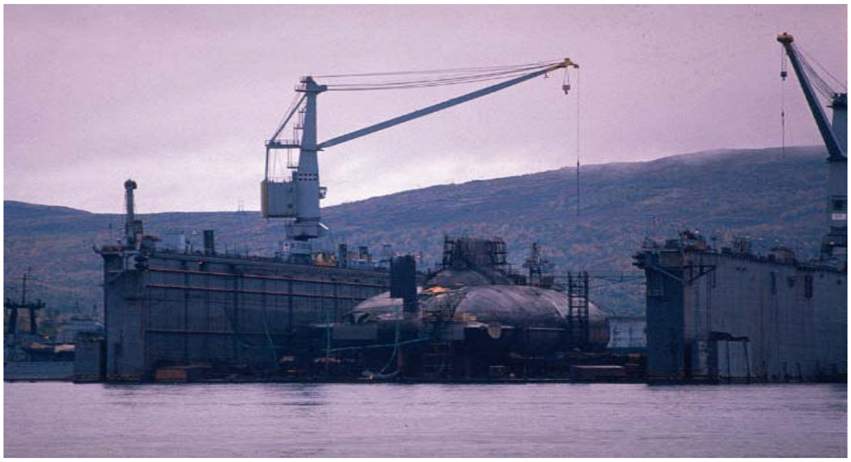


Figure C.9. Sevmorput naval shipyard

As an example of the potential for exposure or contamination from the naval process of nuclear waste one can look at Figure C.10. This is a picture of an Echo-II class nuclear submarine, as it is moored at one of the piers at the naval shipyard Sevmorput, only a few hundred metres away from the closest apartment buildings in the Rosta township. The submarine has two reactors on board. In 1991, the county authorities in Murmansk prohibited the removal of spent fuel assemblies from nuclear submarines at Sevmorput on the grounds that an accident during this type of operation could affect large parts of Murmansk and over half a million inhabitants.

Figure C.10. Picture of nuclear submarine at the naval shipyard Sevmorput

Appendix D. Sources from Nuclear Plant Accidents

To predict radionuclide contamination/emission from a power plant one can look at the previous accidents and releases involved. Among other accidents, one can list the Windscale accident of 1957, the Oak Ridge Pu release of 1959, the explosion of an Army low power reactor in 1961, the 1974 Browns Ferry fire, the Three Mile Island 1979 accident, and the 1986 Chernobyl accidents. Possible accidents are continuously being studied in the industry to assure safety of power plants and compliance with today's regulations.

D.1. The Windscale Accident

The Windscale (now called Sellafield) station is comprised of two air-cooled, graphite-moderated, natural-uranium reactors, primarily employed for plutonium production (the reactor was also used for the production of ^{210}Po by neutron bombardment of bismuth, [33]). In October of 1957, the core of one of the reactors was partially consumed by combustion, which resulted in the release of fission products to the surroundings [34].

The cause of the fire can be summarized as follows:

1.) As a result of neutron bombardment the carbon atoms were displaced from their natural position in the crystal lattice of the graphite blocks.
2.) Under the action of thermal agitation, many of the atoms returned to the original position, but not all of them. This has a number of effects on the physical properties of the graphite, including dimensional growth, which may occur linearly to about 3 percent.
3.) At a temperature of about 200 ^{o}C (the normal operating temperature for this type of reactor) potential (stored) energy accumulated in the graphite.
4.) From time to time, and to avoid dire consequences due to the release of this energy, the pile is "annealed" (its temperature is raised above the normal operating temperature and the energy is dissipated in a limited release of heat). This operation was performed too quickly and resulted in oxidation of the fuel in 150 channels and multiple cladding failures.
5.) The metallic uranium and graphite began to react with air and a substantial portion of the core was destroyed.
6.) Radioactive fission products escaped outside the plant. The activity of the aerosols released in this accident was estimated at 30,000 Ci, 20,000 of which was from iodine [33].

There were no acute health effects as result of this accident. However, for 2 weeks, all milk produced on farms within a few kilometers of the plant was collected and withdrawn from consumption. The principal fission products released during the fire were: ^{131}I, ^{137}Cs, ^{89}Sr and ^{90}Sr [33]. The seriousness of this incident led to the shutdown of the Windscale reactors.

D.2. The Oak Ridge Plutonium Release of 1959

In November of 1959, in one of the shielded cells of a radiochemical-processing pilot plant at Oak Ridge National Laboratory, a chemical explosion occurred during the decontamination of an evaporator. The explosion is thought to have resulted from the formation of explosive compounds, such as picric acid, when concentrated hot nitric acid was mixed with a proprietary decontaminating agent that contained phenol. A small quantity of this solution had been left in the equipment because of the omission of a normal water wash. Therefore, an explosion occurred when the nitric acid was introduced into the evaporator and was brought to the boiling temperature. The explosion resulted in plutonium contamination of the pilot-plant building, nearby streets, and building surfaces. The adjacent air-cooled graphite reactor building became contaminated when plutonium was drawn into the ventilation system. Quantities of ^{95}Zr and ^{95}Nd were also released [28].

D.3. The explosion of an Army Low Power Reactor

In January of 1961, an explosion occurred at an Army low-power reactor at the National Reactor Testing Station in Idaho (currently named the Idaho National Engineering Laboratory, or INEL). The reactor was a direct-cycle BWR designed to operate at 3 MWt and was fueled with enriched uranium plates with aluminum cladding. The explosion resulted when the withdrawal of a single control rod (the reasoning for the removal of the rod is not publicly known) caused the reactor to go into the prompt critical condition [28].

Although there were three casualties related with this accident, all of the radioactive material, with the exception of ^{131}I, was contained within a three-acre plot. An estimated 10 Ci (0.37 TBq) of ^{131}I was released to the environment.

D.4. The Browns Ferry Fire

In 1974, there was a fire at the Browns Ferry, Alabama nuclear power plant. The plant comprises three 1,065 MW BWR units. At the time of the fire one unit was in service, a second was undergoing startup tests, and the third was under construction. A worker in the second unit was checking the direction of ventilation airflow in an electrical cable gallery. The candle used for this check accidentally started a fire, which spread rapidly through the gallery and the control room of the unit in operation. The accident had no external consequences but caused serious damage inside the plant.

The “common mode failure” concept, used in nuclear power plants, was introduced by this accident because of its potential to affect several safety systems, previously thought to be independent. The method to guard against the loss of a function vital to plant safety has been “redundancy”. That is, the function is performed by two completely independent systems.

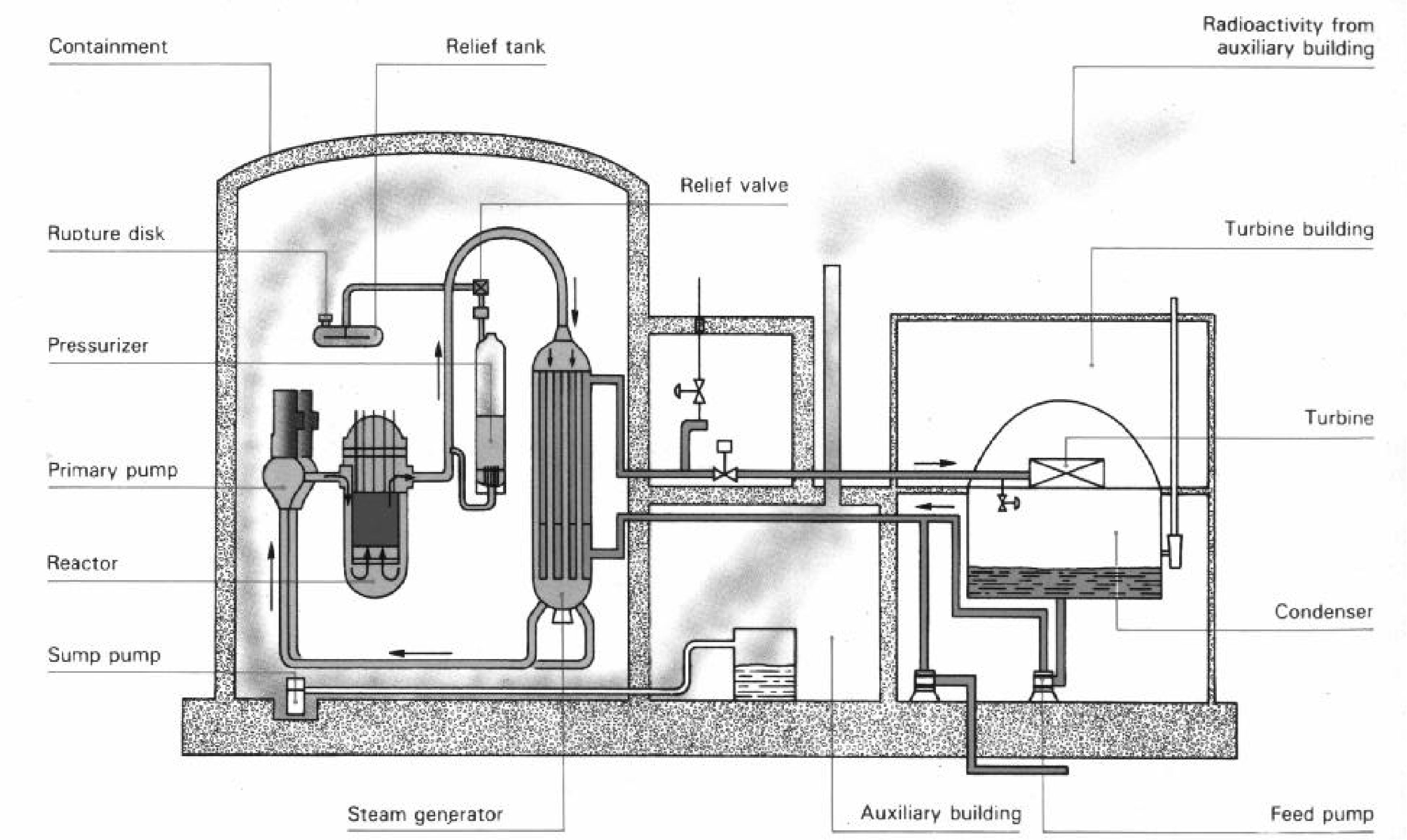
Common mode failure may result from an external event, such as an aircraft crash, flooding, or earthquake. It may also be ensued from an internal cause, for example, a fire, projected components, broken pipes, etc.

D.5. The Three Mile Island (TMI) Accident

The Three Mile Island accident started on March 28, 1979 in Pennsylvania. Figure D.1 is an illustration of the TMI 904 MWe PWR power plant accident. In this accident pressurized water escaped from the primary system through the pressurizer relief valve and filled the relief tank until it burst, spilling water into the reactor building. A portion of the water floated to an adjacent building. Gaseous released occurred through the discharge stack from the second building.

The start of the TMI accident was in an auxiliary component from the secondary system. The incident in this system led to loss of feedwater supply to the steam generators, which remove the heat produced by the nuclear reaction. A reactor shutdown (the normal response to this condition) was initiated. The primary system pressure rose, opening the pressurizer relief valve. What the operator did not know, however, was that this valve had failed to close once the temporary overpressure had been relieved. As a result, the primary system pressure continued to fall, automatically actuating the safety injection pumps. The operator shut down these pumps by erroneously judging the situation. Pressure began to drop and the coolant began to boil. Part of the primary system was filled with a mixture of water and steam, leading to severe vibration in the primary coolant pumps and prompting the operator to shut down those pumps too. Soon thereafter, the reactor coolant boiling uncovered the reactor core, and residual heat removal ceased. The fuel cladding started to fail and part of the fuel melted, carrying fission products through the primary system into the pressurizer relief tank via the open relief valve. This relief tank, which was designed only for short-term operation, filled up and burst open under the rising pressure. Fission gases were released into the containment, actuating all the radioactivity alarms. Radioactive water, spilling from the tank, flowed down to the bottom of the reactor building, where it was to be collected for removal to an auxiliary building. After hours in the confused maneuvering, the operator finally restored water injection to the reactor and reflooded the core. The reaction between the water and the cladding alloy, whose temperature had risen in the absence of coolant, led to the formation of hydrogen. The hydrogen gas, mixed with air in the containment, caused an explosion (with no serious consequences). Shortly thereafter, the operator at last closed the relief valve to restore more stable circulation through the reactor. Some of the rare fission gases, such as xenon and krypton, had escaped through the ventilation filters before the operator isolated the containment. But there was no uncontrolled release of iodine or aerosols, which were all trapped in the water and the filters. The accident had no biological effects in the surrounding population.

Figure D.1. TMI plant layout



D.6. The Chernobyl Accident

The Chernobyl power station is located in the Ukraine, about 90 miles from Kiev. The 1000 MWe, water-cooled, graphite-moderated RBMK type reactor (Unit 4) was destroyed in the accident. The accident occurred on April 26, 1986, not during normal operation but during the running of a test. The test was intended to assess the reactor's safety margin in a particular set of circumstances. The test, which had to be performed at less than full reactor power, was scheduled to coincide with a routine shutdown of the reactor. The electricity used to run the power station, for example, to power the pumps that circulate the coolant, is usually supplied from a grid. If the source of electricity should fail, most reactors are able to derive the required electricity from their own production. However, if the reactor is operating but not producing power, for example when in the process of shutting down, some other source of supply is required. Generators are generally used to supply the required power, but there is a time delay while they are started. The test carried out at Chernobyl-4 was designed to demonstrate that a coasting turbine would provide sufficient power to pump coolant through the reactor core while waiting for electricity from the diesel generators. The circulation of coolant was expected to be sufficient to give the reactor an adequate safety margin.

The following is the set of events that led to the Chernobyl accident. The scheduled shutdown of the reactor started and gradual lowering of the power level began (April 25, 01:06). The lowering of the reactor power halted at 1600 MW(t) (03:47). At 14:00 hours, the emergency core cooling system (ECCS) was isolated (part of the test procedure) to prevent it from interrupting the test later. The fact that the ECCS was isolated did not contribute to the accident; however, had it been available it might have reduced the impact slightly. The power was due to be lowered further; however, the controller of the electricity grid in Kiev requested the reactor operator to keep supplying electricity to enable demand to be met. Consequently, the reactor power level was maintained at 1600 MW(t) and the experiment was delayed. At 23:10, power reduction was recommenced and at 24:00 there was a work shift change. At 00:05 on April 26, power level had been decreased to 720 MW(t) and continued to be reduced, in continuing preparation for the test. The safe operating level for a pre-accident configuration in an RBMK is about 700 MW(t) because of the positive void coefficient associated with this type of reactor. At 00:28 the power level was about 500 MW(t). Control was transferred from the local to the automatic regulating system. Either the operator failed to give the "hold power at required level" signal, or the regulating system failed to respond to this signal. This led to an unexpected fall in power, which rapidly dropped to 30 MW(t). At approximately 00:32 hours, the operator retracted a number of control rods in an attempt to restore the power level. Station safety procedures required that approval of the chief engineer be obtained to operate the reactor with fewer than the effective equivalent of 26 control rods. It is estimated that there were less than this number remaining in the reactor at this time. At 01:00, the reactor power had risen to 200 MW(t) and at 01:03 an additional pump was switched into the left hand cooling circuit in order to increase the water flow to the core (part of the test procedure). At 01:07, an additional pump was switched into the right hand cooling circuit (part of the test procedure). Operation of additional pumps removed heat from the core more quickly. This reduced the water level in the steam separator and at 01:15 the automatic trip systems to the steam separator were deactivated by the operator to permit continued operation of the reactor. The operator increased the feed water flow at 01:18 in an attempt to address the problems in the cooling system. Some manual control rods were withdrawn at 01:19 in order to increase power and raise the temperature and pressure in the steam separator. Operating policy required that a minimum effective equivalent of 15 manual control rods be inserted in the reactor at all times. At this point it is likely that the number of manual rods was reduced to less than this (probably eight). However, automatic control rods were in place, thereby increasing the total number. At 01:21:40, the feed water flow rate was reduced to below-normal by the operator to stabilize steam separator water level, decreasing heat removal from the core. Spontaneous generation of steam in the core began 01:22:10. At 01:22:45, indications received by the operator, although abnormal, gave the appearance that the reactor was stable.

The beginning of the actual test was at 01:23:04, when the turbine feed valves were closed to start turbine coasting. At 01:23:10 the automatic control rods were withdrawn from the core. An approximately 10 second withdrawal was the normal response to compensate for a decrease in the reactivity following the closing of the turbine feed valves. Usually this decrease is caused by an increase in pressure in the cooling system and a consequent decrease in the quantity of steam in the core. The expected decrease in steam quantity did not occur because of the reduced feed-water to the core. At 01:23:21, steam generation increased to a point where because of the reactor's positive void coefficient, a further increase of steam generation would have led to a rapid increase in power. Steam in the core began to increase uncontrollably at 01:23:35. The emergency button (AZ-5) was pressed by the operator at 01:23:40. Control rods started to enter the core and the insertion of the rods from the top concentrated all of the reactivity in the bottom of the core. At 01:23:44, the reactor power rose to a peak of about 100 times the design value. At about 01:23:45, fuel pellets started to shatter, reacting with the cooling water to produce a pulse of high pressure in the fuel channels, which ruptured at about 01:23:49. Two explosions occurred at 01:24. One was a steam explosion; the other resulted from the expansion of fuel vapor. The explosions lifted the pile cap, allowing the entry of air, which reacted with the graphite moderator blocks to form carbon monoxide. This flammable gas ignited and a reactor fire resulted.

As a result, about 8 of the 140 tons of fuel, which contained plutonium and other highly radioactive materials (fission products), were ejected from the reactor along with a portion of the graphite moderator, which was also radioactive. These materials were scattered around the site. In addition, cesium and iodine vapors were released both by the explosion and during the subsequent fire.

The main factors that led to the accident at Chernobyl can be summarized as follows:

1) Non-routine operation of the reactor.
2) Violation of operating regulations, including the removal of most of the control rods.
3) Positive void coefficient characteristic of the reactor.
4) Apparent lack of knowledge by the station staff of the characteristics of the reactor.
5) Inadequate control rod design.

Appendix E. Accelerators and Clinical Radiation Generators

Basically, an accelerator takes a charged particle, speeds it up using electromagnetic fields, and impacts 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 accelerators and cyclic. In a linear accelerator, the particle beam travels in a straight line. In a cyclic accelerator the beam travels in 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 E.1 below. Table E.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 77) [35].

Table E.1. Basic accelerator types [35]

General	Type
Direct[41] (Potential Drop)	1. Electrostatic High Voltage a. Belt-charging (e.g., Van de Graaf) b. Rotating cylinder charging system 2. High Voltage Transformers a. Transformer rectifier set b. Voltage multiplying (e.g., Cockcroft-Walton generator) c. Cascaded transformer system
Indirect (Cyclic)	1. Linear Beam Trajectory a. Ion linear accelerator b. Electron linear accelerator 2. Circular or Spiral Beam Trajectory a. Cyclotron (Ions only) b. Synchrotron (Ions or electrons) c. Betatron (Electrons only) d. Microtron (Electrons only)

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[41] For accelerating ions either a single stage or tandem accelerator may be used. Electrons are generally accelerated in a single stage.

Table E.2. Applications of particle accelerators [35]

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

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

Table E.3. Radiation concerns in the vicinity of particle accelerators [11, 36]

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 E.4 gives rough guidelines concerning the activation of target materials and materials surrounding the accelerator.

Table E.4. Guidelines for activation near particle accelerators [11, 36]

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 E.5 gives a summary of radionuclides often found near accelerators. Although many nuclides are listed in many cases the radionuclides are fixed, and only the external radiation is of concern. The exception is for hydrocarbons, especially lubricants and plastics, that 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 E.5. Activation products often found near accelerators [37]

Exposed Material	Radionuclides	Half Life
Hydrocarbons	^{7}Be	53.6 days
	^{11}C	minutes
Duralumin (aluminum alloy)	As above, and	
	^{18}F	110 minutes
	^{22}Na	2.6 years
	^{24}Na	15 hours
Steel	As above, and	
	^{42}K	12.5 hours
	^{43}K	22.4 hours
	^{44}Sc	3.92 hours
	^{44m}Sc	2.44 days
	^{46}Sc	84 days
	^{47}Sc	3.43 days
	^{48}Sc	1.83 days
	^{48}V	16 days
	^{51}Cr	27.8 days
	^{52}Mn	5.55 days
	^{52m}Mn	21.3 minutes
	^{54}Mn	300 days
	^{56}Co	77 days
	^{57}Co	270 days
	^{58}Co	72 days
	^{55}Fe	2.94 years
	^{59}Fe	45.1 days
Stainless Steel	As above, and	
	^{60}Co	5.27 years
	^{57}Ni	37 hours
	^{60}Cu	24 minutes
Copper	As above, and	
	^{65}Ni	2.56 hours
	^{61}Cu	3.33 hours
	^{62}Cu	9.8 minutes
	^{64}Cu	12.8 hours
	^{63}Zn	38.3 minutes
	^{65}Zn	245 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 [37]. Because these are airborne radionuclides, ventilation rates are very important in controlling the concentrations. The half- lives of all the radionuclides listed are on the order of minutes or seconds, except ^{7}Be (53.6 days) and ^{41}Ar (1.9 hours).

E.1. Clinical Radiation Generators and Accelerators

Even in the present era of the megavoltage beams, there is still some use for the lower-energy beams, especially in the treatment of superficial skin lesions. X-ray therapy in the kilovoltage range is divided into subcategories by the NCRP [38]. Everyone of these generators can represent a radiation hazard and therefore are addressed in this guide.

E.1.1. Grenz-ray Therapy

Grenz-ray therapy is a term used to describe treatment with beams of very soft (low energy) x-rays at potentials below 20 keV. Such radiations are no longer used in radiotherapy because of the very low depth of penetration. However, this equipment may still be found and should be handled with care, since it can deliver a dose to the skin.

E.1.2. Contact therapy

Contact therapy machines operate at potentials of 40 to 50 kV and facilitate irradiation of accessible lesions at very short source (focal point) to surface distances (SSD). The machines operate typically at a tube current of 2 mA. Applicators available with such machines can provide an SSD of 2.0 cm or less. These units usually have a 0.5- to 1.0- mm thick aluminum filter interposed in the beam to absorb the very soft component of the energy spectrum.

Since the SSD is very short and the machine operates at low voltage, the contact therapy beam produces a very rapidly decreasing depth dose in tissue. For this reason, the skin surface is maximally irradiated when the beam is incident on a patient, but the underlying tissues are spared to an increasing degree in depth. The quality of the radiation for these machines is not deeper than 1 to 2 mm. The beam is almost completely absorbed with 2 cm of soft tissue.

E.1.3. Superficial therapy

Superficial therapy applies the treatment of x-rays produced at potentials ranging from 50 to 150 kV. Filtration thickness (usually 1- to 6- mm of aluminum) is added to harden the beam to a desired degree. The degree of hardening or beam quality can be expressed as the HVL. Typical HVLs used in the superficial range are 1- to 8- mm of aluminum.

The superficial treatments are usually given with the help of applicators or cones attachable to the diaphragm of the machine. The SSD typically ranges between 15 to 20 cm. The machine is usually operated at a tube current of 5 to 8 mA.

E.1.4. Orthovoltage therapy or Deep therapy

Orthovoltage therapy or deep therapy describes treatment with x-rays produced at potentials ranging from 150 to 500 kV. Most orthovoltage equipment is operated at 200 to 300 kV and 10 to 20 mA. In order to achieve HVLs between 1 and 4 mm Cu, various filters have been designed. A movable diaphragm, consisting of lead plates, permits a continuously adjustable field size. The SSD is usually set at 50 cm.

E.1.5. Supervoltage Therapy

Supervoltage therapy or high-voltage therapy is achieved with x-rays in the range of 500 to 1000 kV. In the beginning usage of this machine it became apparent that conventional transformers were not suitable for producing potentials much above 300 kV. Insulation of the high-voltage transformers was a major problem. Therefore, the newer machines would have a resonant transformer in which the voltage is stepped-up in a very efficient manner.

E.1.6. Megavoltage therapy

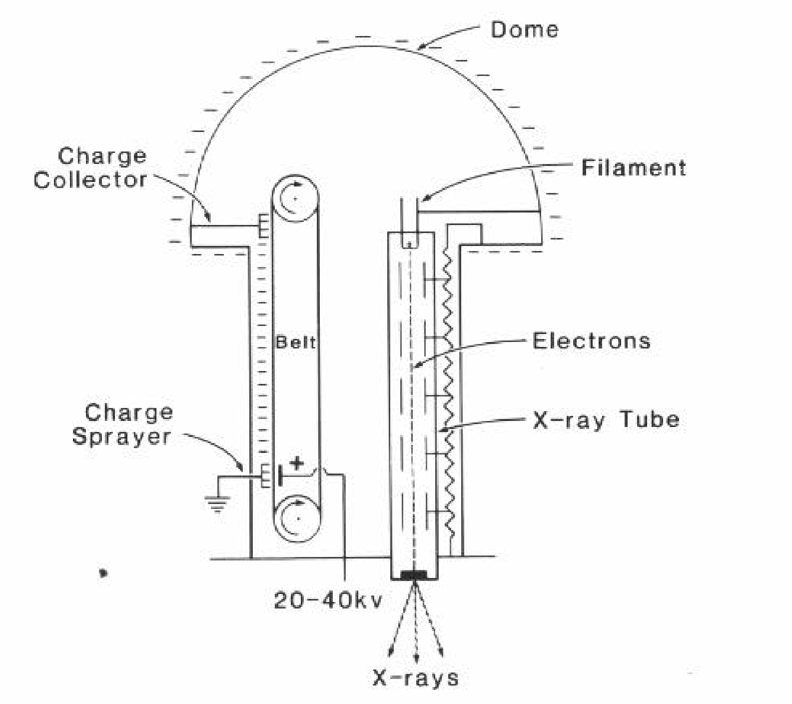
Megavoltage beams are those x-ray beams of 1 MV or greater. Gamma ray beams, produced by radionuclides are also commonly included in this category, if their energy is 1 MeV or greater. Examples of clinical megavoltage machines are accelerators such as Van de Graaff generators, linear accelerators, betatron and microtron, and teletherapy gamma ray units, such as cobalt-60.

E.1.6.1. The Van de Graaff generator

The Van de Graaff machine is an electrostatic accelerator designed to accelerate charged particles. In radiotherapy, the unit accelerates electrons to produce high-energy x-rays, typically 2 MV. Figure E.1 includes a schematic representation of a Van de Graaff generator. In this machine a 20 to 40 kV is applied across a moving belt of insulating material. A corona discharge takes place and electrons are sprayed onto the belt. These electrons are carried to the top and removed by a collector connected to a spherical dome. As the negative charges collect on the sphere, a high potential is developed between the sphere and the ground. This potential is applied across the x-ray tube, consisting of a filament, a series of metal rings, and a target. The rings are connected to resistors to provide a uniform drop of potential from the bottom to the top. X-rays are produced when the electrons strike the target [39].

Van de Graaff machines are capable of reaching energies up to 10 MV, limited only by size and required high-voltage insulation. Normally, a mixture of nitrogen and CO_2 gas provides insulation. The generator is enclosed in a steel tank and is filled with the gas mixture at a pressure of about 20 atmospheres.

Figure E.1. The Van de Graaff generator



E.1.7. Linear Accelerators

The linear accelerator (LINAC) is a device that uses high-frequency electromagnetic waves to accelerate charged particles such as electrons to high energies through a linear tube. The high-energy electron beam itself can be used for treating superficial tumors, or it can be made to strike a target to produce x-rays for treating deep-seated tumors.

There are several types of linear accelerator designs, but the ones used in radiotherapy-accelerated electrons either by traveling or stationary electromagnetic waves of frequency in the microwave region. A typical medical linear accelerator is represented in Figure F.2. This figure shows the major components and auxiliary systems. A power supply provides DC power to the modulator, which includes the pulse-forming network and a switch tube known as hydrogen thyratron. High-voltage pulses from the modulator section are flat-topped DC pulses of a few microseconds in duration. These pulses are delivered to the magnetron or klystron[42] and simultaneously to the electron gun. Pulsed microwaves, produced in the magnetron or klystron are injected into the accelerator tube or structure via a waveguide system. At the proper instant, electrons produced by an electron gun, are also pulse injected into the accelerator structure.

The accelerator structure consists of a copper tube with its interior divided by copper discs or diaphragms of varying aperture and spacing. This section is evacuated to a high vacuum. As the electrons are injected into the accelerator structure with an initial energy of about 50 keV, the electrons interact with the electromagnetic field of the microwaves. The electron gains energy from the sinusoidal electric field by an acceleration process analogous to that of a surf rider.

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[42] Magnetron and klystron are devices for producing microwaves. Klystrons have a longer life span than magnetron and are capable of delivering higher power levels required for high energy accelerators and are preferred as the beam energy approaches 20 MeV or higher.

As high-energy electrons emerge from the exit window of the accelerator structure, they are in the form of a pencil beam of about 3 mm in diameter. In the low-energy LINACS (up to 6 MV) with relatively short accelerator tube, the electrons are allowed to proceed straight on and strike a target for x-ray production. In the higher-energy LINACS, however, the accelerator structure is too long and, therefore, is placed horizontally or at an angle. The electrons are then bent through a suitable angle (usually 90^{o} to 270^{o}) between the accelerator structure and the target. The precision bending of the electron beam is accomplished by the beam transport system consisting of bending magnets, focusing coils, and other components [40]. Figure E.3 shows a picture of an isocentered LINAC.

Figure E.2. Diagram of a typical medical linear accelerator (LINAC)

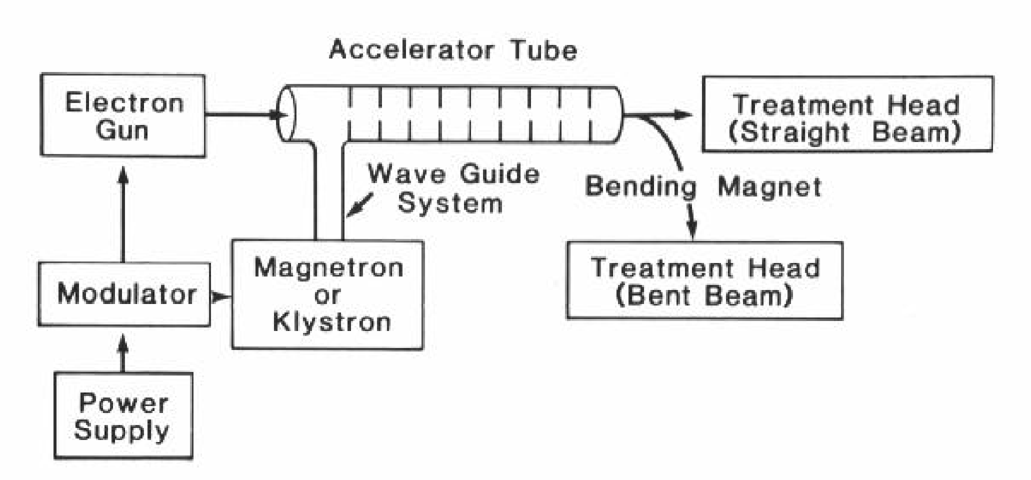

Figure E.3. Picture of an isocentrically mounted linear accelerator

Appendix F. Accelerators and Irradiator Accidents

Accidental exposures to radioactive materials typically involve much higher levels of exposure to a smaller population than the general public. Industrial accidents involving accelerators or irradiators can be extremely dangerous. Accidents range widely in magnitude of exposure and area of effect. For example, an accident at an irradiation processing plant may involve a single person but an exposure in the range of tens of gray (1000's of rads). An accidental exposure is not limited to either an intense single person exposure or a wide spread low-level contamination incident, but both aspects may be found in a single accident.

Several organizations and individuals have reviewed past industrial accidents in a "lessons learned" exercise so that similar accidents may be avoided in the future. In 1996, the International Atomic Energy Agency (IAEA) published "Lessons Learned from Industrial Accidents in Industrial Irradiation Facilities" that summarizes 8 accidents at irradiation plants and analyzes their causes [41]. These are summarized below in order to show examples of possible exposures to sources in irradiators and accelerators.

F.1. Stimos, Italy - May 1975

In this incident, an unskilled worker crawled through an opening in the conveyor system used to transport sacks of grain to the irradiation chamber. Although there were no sacks loaded, the ^{60}Co source was not shielded and the irradiator was unattended. The source activity was about 500 TBq (13,500 Ci). The dose was in the range of 8-24 Gy (800-2400 rad) received in about 1 to 4 minutes. The worker died 13 days later.

F.2. Kjeller, Norway - September 1982

In response to an alarm, a maintenance worker turned off the alarm and entered the irradiation chamber. The indicator panel indicated that the source was shielded, but a radiation monitor showed high radiation levels. The worker neglected to use a portable radiation detector. He remained in the chamber for several minutes while a ^{60}Co was exposed. The source activity was in the range of 2.22 to 3.7 PBq (60,000 to 100,000 Ci). The worker received a whole body dose of about 22 Gy (2200 rad). He died 13 days later from acute radiation injuries.

F.3. San Salvador, El Salvador - February 1989

A night shift operator heard the source transit alarm; this meant that a fault had occurred. The source was then lowered automatically into the storage pool from the irradiation position. Even after resetting the transit alarm, it continued to sound indicating that the source was not fully down. After "manipulating" several control features - in effect bypassing safety interlocks - and waiting several minutes, he entered the irradiation chamber. He did not check the portable radiation monitor. He was unable to free the jammed rack; so, he got 2 untrained workers from another department to help him. After the rack was freed and lowered into the storage pool, they noticed the Cerenkov glow and quickly left the chamber. The workers were exposed to dose rates of about 2 Gy min^{-1} (200 rad min^{-1}) at the middle of the body. These dose rates were very non-uniform. Overall, the first worker received about 8.1 Gy (810 rad), the second about 3.7 Gy (370 rad), and the third about 2.9 Gy (290 rad). All three workers suffered radiation burns and

other symptoms of acute radiation exposure. The first worker died after about 6.5 months; the second worker had both legs amputated above the knee and after 7 months was recovering with a good prognosis; the third worker had less severe symptoms and was recovering well.
The IAEA has written a separate document covering this accident [42].

F.4. Sor-Van, Israel - June 1990

After a jam occurred in the transport mechanism, three indicators on the control panel showed: (1) the jam warning light, (2) the source down indicator, and (3) a high gamma radiation alarm. The operator who arrived from home when called decided that the source down indicator was correct. He bypassed the radiation alarm to open the door to the irradiation chamber. The source in the chamber was 12.6 PBq (340,000 Ci) of ^{60}Co. He was in the chamber for about one minute and "felt a burning in his eyes and a strange pounding sensation in his head." (IAEA 96a) He got scared and left the chamber. His dose was estimated to be 10 to 15 Gy (1000 to 1500 rad.). He died 36 days later, despite intense medical treatment.

F.5. Nesvihz, Belarus - October 1991

In this accident, an operator and his assistant were working the night shift at the irradiation plant. The assistant became aware of a transport linkage decoupling in the system. The incidents that followed are unclear. In any event, the operator entered the chamber to fix the linkage. The report states (IAEA 96a), "After about 1 minute, he developed an acute headache and pain in his joints and gonads." He then noticed that the source (about 28.1 PBq or 760 kCi of ^{60}Co) was exposed. The dose rate from the rack was estimated to be about 15 Gy s^{-1} (1500 rad s^{-1}). He ran from the chamber and told his assistant that he had been irradiated. It was estimated that his whole body dose was 11 Gy (1100 rad). He died 113 days after the incident despite specialized medical treatment.
The IAEA has written a separate document covering this accident [43].

F.6. Illinois, USA - February 1965

This accident involved exposure to a beam of 10 MeV electrons at an industrial irradiator. A worker entered the irradiation chamber to put a mold to be irradiated on a conveyor belt near the output of the accelerator. He entered the room through a gap under a door that had interlocks to shut down the accelerator. The worker was exposed to the electrons from the accelerator. Table F.1 summarizes the doses received by the exposed worker.

Table F.1. Summary of doses from the Illinois accident in 1965

Body Location	Dose in Gy (rads)
Parts of the Right Hand	420 - 2400 (42,000 - 240,000)
Parts of the Right Foot	3 - 290 (300 - 29,000)
Parts of the Right Leg	up to 290 (29,000)
Skin on the Right Side of the Body	2.45 - 3.25 (245 - 325)
Interior of the Body	0.002 - 0.05 (0.2 - 5)

The worker developed serious radiation burns on the right hand, wrist, and leg. After 138 days the right arm was amputated just above the elbow and the right leg was amputated just above the knee after 6 months.

F.7. Maryland, USA - December 1991

This accident occurred at a 3 Megavolt (MV) potential drop accelerator. Electrons are produced at one end of the accelerator and are accelerated across the potential drop. A characteristic of this class of accelerator is *cold* or *dark* current. Whenever the accelerator is inactive for a long period with the accelerating voltage on, an electron current can still exist even if the source is off.

The accelerator in Maryland was off line for 3 days during maintenance. During testing after repairs, the accelerator was brought on line and run for about 15 to 20 minutes. After this test run, the operator returned to the accelerator room to inspect the window on the accelerator. Ammeter readings indicated about 50 µA of cold current. Needless to say, several alarms were ignored. The operator reported being in the accelerator room for about 1 to 3 minutes. Three months after the exposure [41], "the four digits of the right hand and most of the four digits of the left hand had to be amputated."

F.8. Hanoi, North Vietnam - 1991[43]

The director of the accelerator center was involved with experiments using the accelerator. At the start of the second in a series of experiments, the director returned to the experimental set up to adjust the sample position. He did this unbeknownst to anyone else at the time. During the readjusting, the accelerator was operated with a beam current of about 6 µA at an energy of about 15 MeV. The total time that the accelerator was on was estimated to be 2 to 4 minutes; the actual exposure time to the director's hands could not be estimated. After the accident, it was estimated that the director received about 10 to 25 Gy (1000 to 2500 rad) to the left hand, 10 to 50 Gy (2000 to 5000 rad) to the right hand, and roughly 1.5 Gy (150 rad) to the upper whole body. After much medical treatment, the right hand was amputated at the wrist and the fourth and fifth fingers of the left hand were amputated.

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[43] The IAEA has written a separate document covering this accident [44].

Appendix G. Postings in a Nuclear Environment

This appendix includes a summary of posting signs, symbols and flags used in a nuclear environment. The proper understanding of their meaning can allow the deployed personnel to determine the presence or proximity to a radioactive source.

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
G.1	Posting requirements in the United States, found in the Title 10 of the Code of Federal Regulations (10 CFR 20) [45].
G.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 C.1.
G.3	Postings required for the transportation of radioactive materials in the United States found in Title 49 of the Code of Federal Regulations [46]. 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.
G.4	Contamination marking signs used by the Department of the Army [10].
G.5	Threat Markers (former Warsaw Pact) [10].

Table G.1 Posting requirements [45]

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)	$ 5 mrem in any one hour at 30 cm from any radiation source.	CAUTION RADIATION AREA	
High Radiation Area (external)	$ 100 mrem in any one hour at 30 cm from any radiation source or surface.	CAUTION HIGH RADIATION AREA	
Very High Radiation Area	$ 500 rads (a lethal absorbed dose) in any one hour at 1 meter 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	

ALI and DAC are defined in the table below:

Table G.2. ALI's and DAC's [47, 48]

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).

$$\text{DAC Bq/m}^3 \;=\; \text{ALI } / \text{ 2400 Bq/m}^3$$

Table G.3. Requirements for the packing and transportation of radioactive materials [46]

Type			**Label**
Packaging			
Name / Contents	Radiation Level at Package Surface (RL)	Transport Index (TI)	
White-I Label includes contents and activity	RL # 0.005 mSv/h (RL # 0.5 mrem/h)	TI = 0	
Yellow-II Label includes contents, activity, and in boxed TI	0.005 mSv/h < RL # 0.5 mSv/h (0.5 mrem/h < RL # 50 mrem/h)	0 < TI # 1.0	
Yellow-III Label includes contents, activity, and in boxed TI	0.5 mSv/h < RL # 2 mSv/h (50 mrem/h < RL # 200 mrem/h)	1.0 < TI # 10	
Yellow-III[44]	2 mSv/h < RL # 10 mSv/h (200 mrem/h < RL # 1000 mrem/h)	TI > 10	

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[44] This Yellow-III type of package must be shipped under exclusive use provisions, as detailed in 49 CFR, section 173.441(b) [46].

Type	**Label**
Transportation	
Function	Placard
Transporting vehicle must be placarded on all sides of vehicle or the cargo-carrying body, if any quantity of packages bearing the RADIOACTIVE-YELLOW III labels is 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 G.4. NBC Contamination marking signs [10]

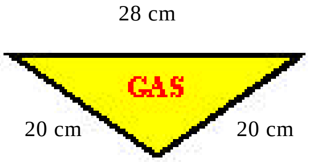
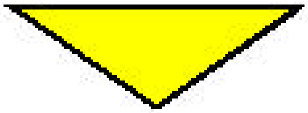
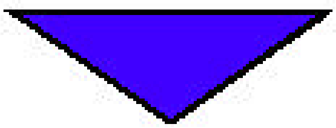
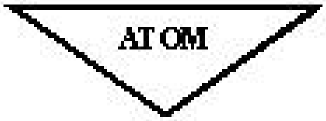
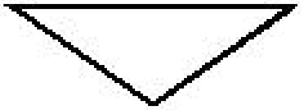
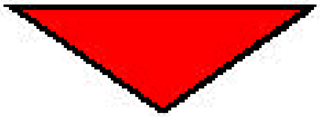
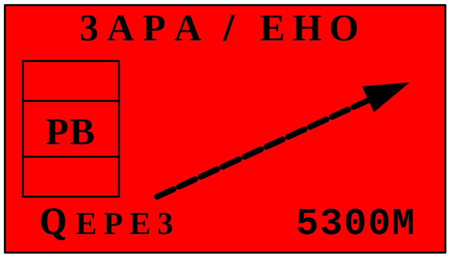
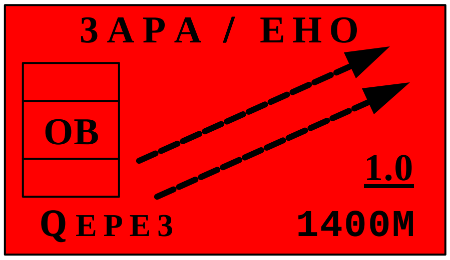
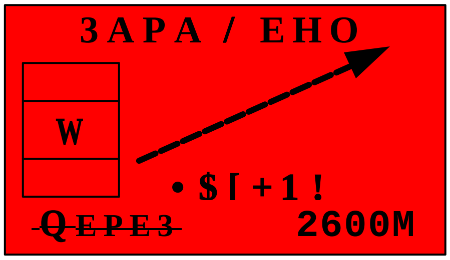
NBC Sign	Front	Back
CHEMICAL YELLOW background with RED lettering	 Name of Agent (if known) Date and Time of Detection	
BIOLOGICAL Blue background with RED lettering	 Name of Agent (if known) Date and Time of Detection	
RADIOLOGICAL WHITE background with BLACK lettering	 Dose Rate Date and Time of Reading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

Table G.5. Threat markers (former Warsaw Pact) [10]

Symbol	Description
Former Warsaw-Pact Markers	
	Background = Red Lettering = Black Rectangle on the left side contains contamination symbol PB = Nuclear W = Biological OB = Chemical
	An arrow (dotted line on sign) indicates direction of contaminated area. A set of lines indicates a decontaminated path through the area. A number to the right of the lines indicates the width of this path.
	At the bottom of the sign, **QEPE3** means across, over, or through. If followed by a number, it indicates the distance across the contaminated area. If **QEPE3** is crossed and replaced by **•$[+1!** (detour), the area cannot be decontaminated.
Soviet Contamination Markers	
	Contamination Flag Cloth Flag Color: Red or Yellow Pocket in flag is for contamination data.
	Radiological Contamination Flag Cloth Flag Background Colors: Yellow - 1 cGy/hr Red - 5 cGy/hr Multicolor - > 100 cGy/hr

Figures G.1 and G.2 are an illustration 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 is detailed in chapter 3 of FM 21-60 [49].

Figure G.1. Typical radiation symbols

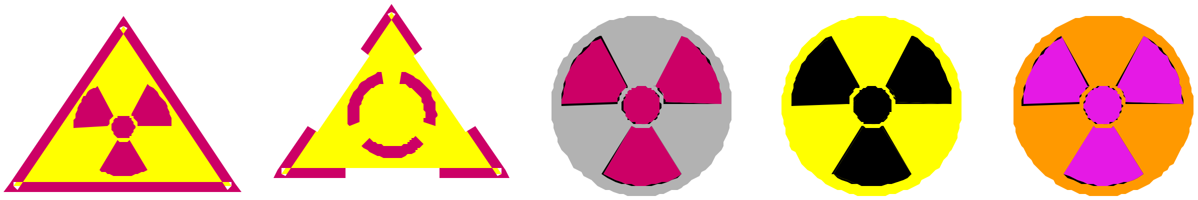


Figure G.2. Signal Flags Representing: NUCLEAR, BIOLOGICAL, CHEMICAL HAZARD PRESENT [49]

Appendix H. Example Computations

Once radiological sources have been identified and exposure or contamination is suspected, responsible NBC personnel will perform a dose assessment. The scenarios that are described below illustrate the use of tabulated parameters to obtain preliminary estimates of doses to exposed personnel.

H.1. Scenario 1 - Weapons Grade Uranium

As an example of a dose estimate from an inhalation of average weapons grade uranium, assume an inhalation of 1 μg of material. To evaluate the internal exposure for a mixture of radionuclides, we need to calculate the activity of each radionuclide present in the material inhaled. Also, we need to make an assumption about the particle size of the inhaled material. All of the conversion factors presented here for inhalation are based on the assumption that the particles of radioactivity have an activity median aerodynamic diameter (AMAD) of 1 μm and are class Y[45]. The AMAD is a measure of the effective particle size of the inhaled material. The class of the material refers to how quickly the material is cleared from the lung. Once the activity of each radionuclide inhaled is known, to estimate the internal dose equivalents multiply the intakes by the appropriate conversion factors. For class Y uranium, the committed effective dose equivalent, $H_{E,50}$, is the limiting value; therefore, only the $H_{E,50}$ is considered.
The following parameters are given:

Amount of HEU inhaled:	1 μg;
AMAD:	1 μm; and,
Class of the inhaled material:	Y.

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[45] Biological clearance classes can be class D (radionuclide dissolves in days), W (radionuclide dissolves in weeks), or Y (radionuclide dissolves in years).

H.1.1. Estimating the Activities of the Nuclides Present

The amount of activity of each isotope of uranium in HEU is found by multiplying the weight fraction of each isotope present by the specific activity. These values are found in Tables 7.6 and 7.7.

$$\text{A in Bq} = \text{Weight Fraction x Specific Activity x } 10^{12}\ \text{Bq TBq}^{-1} \text{ x } 10^{-6}\ \text{g}\ \mu\text{g}^{-1}.$$

For ^{234}U we have:

$A_{U234} = 0.0175 \text{ x } (2.34 \text{ x } 10^{-4}\ \text{TBq g}^{-1}) \text{ x } 10^{12}\ \text{Bq TBq}^{-1} \text{ x } 10^{-6}\ \text{g}\ \mu\text{g}^{-1}.$

$A_{U234} = 4.10\ \text{Bq}\ \mu\text{g}^{-1}.$

For ^{235}U we have:

$A_{U235} = 0.935 \text{ x } (8.00 \text{ x } 10^{-8}\ \text{TBq g}^{-1}) \text{ x } 10^{12}\ \text{Bq TBq}^{-1} \text{ x } 10^{-6}\ \text{g}\ \mu\text{g}^{-1}.$

$A_{U235} = 7.48 \text{ x } 10^{-2}\ \text{Bq}\ \mu\text{g}^{-1}.$

For ^{238}U we have:

$A_{U238} = 0.0475 \text{ x } (1.24 \text{ x } 10^{-8}\ \text{TBq g}^{-1}) \text{ x } 10^{12}\ \text{Bq TBq}^{-1} \text{ x } 10^{-6}\ \text{g}\ \mu\text{g}^{-1}.$

$A_{U238} = 5.89 \text{ x } 10^{-4}\ \text{Bq}\ \mu\text{g}^{-1}.$

H.1.2. Calculating the Activity Inhaled - Inhalation Intake

The activity inhaled is simply the activity concentration of each isotope times the mass of material inhaled.

$$\text{I} = \text{Specific Activity x Mass of Material.}$$

For ^{234}U:

$I_{U234} = 4.10\ \text{Bq}\ \mu\text{g}^{-1} \text{ x } 1\ \mu\text{g}.$

$I_{U234} = 4.10\ \text{Bq}.$

For ^{235}U:

$I_{U235} = 7.48 \text{ x } 10^{-2}\ \text{Bq}\ \mu\text{g}^{-1} \text{ x } 1\ \mu\text{g}.$

$I_{U235} = 7.48 \text{ x } 10^{-2}\ \text{Bq}.$

For ^{238}U:

$I_{U238} = 5.89 \text{ x } 10^{-4}\ \text{Bq}\ \mu\text{g}^{-1} \text{ x } 1\ \mu\text{g}.$

$I_{U238} = 5.89 \text{ x } 10^{-4}\ \text{Bq}.$

H.1.3. Estimating the Committed Effective Dose Equivalent

The committed effective dose equivalent, $H_{E,50}$, for a mixture can be estimated by summing the committed effective dose equivalents for each nuclide present. The $H_{E,50}$ for each nuclide is the product of the intake and the committed effective dose equivalent factors, h_E (Table 7.17).

$$H_{E,50} \approx \left(\sum (h_E \text{ x Intake})\right); \text{ so,}$$

$$H_{E,50} = \left(h_E^{U234} \text{ x } I_{U234} + h_E^{U235} \text{ x } I_{U235} + h_E^{U238} \text{ x } I_{U238}\right).$$

$H_{E,50}$ = (3.58 x 10^{-5} Sv Bq^{-1} x 4.10 Bq) + (3.32 x 10^{-5} Sv Bq^{-1} x 7.48 x 10^{-2} Bq) + (3.20 x 10^{-5} Sv Bq^{-1} x 5.89 x 10^{-4} Bq).

$H_{E,50}$ = 1.49 x 10^{-4} Sv.

These steps are summarized in the table below.

Table H.1. Steps in estimating internal exposure to HEU

Step	Procedure	Example
1	Estimate the activity (A) the isotopes present. Multiply the weight percentage (w%) by the specific activity, S, and by appropriate conversion factors, k. A = w% x S x k	^{234}U: A_{234} = 0.0175 x 2.34 x 10^{-4} TBq g^{-1} x 10^{12} Bq TBq^{-1} x 10^{-6} g μg^{-1} A_{234} = 4.10 Bq μg^{-1} of ^{234}U ^{235}U: A_{235} = 0.935 x 8.00 x 10^{-8} TBq g^{-1} x 10^{12} Bq TBq^{-1} x 10^{-6} g μg^{-1} A_{235} = 7.48 x 10^{-2} Bq μg^{-1} of ^{235}U ^{238}U: A_{238} = 0.0475 x 1.24 x 10^{-8} TBq g^{-1} x 10^{12} Bq TBq^{-1} x 10^{-6} g μg^{-1} A_{238} = 5.89 x 10^{-4} Bq μg^{-1} of ^{238}U
2	Estimate the activity inhaled by multiplying the specific activity above by the mass of material inhaled. In this example, the mass is 1 μg.	I = A x mass I_{U234} = 4.10 Bq μg^{-1} x 1 μg = 4.10 Bq I_{U235} = 7.48 x 10^{-2} Bq μg^{-1} x 1 μg = 0.00748 Bq I_{U238} = 5.89 x 10^{-4} Bq μg^{-1} x 1 μg I_{U238} = 5.89 x 10^{-4} Bq
3	Estimate the committed effective dose equivalent (CEDE) by adding the CEDE's for all the nuclides inhaled.	$H_E \approx \left(\sum (h_E \text{ x Intake})\right)$; so, $H_E = \left(h_E^{U234} \text{ x } I_{U234} + h_E^{U235} \text{ x } I_{U235} + h_E^{U238} \text{ x } I_{U238}\right)$. $H_E = \begin{pmatrix} (3.58\text{x}10^{-5}\ \text{Sv Bq}^{-1})\ \text{x}\ 4.10\ \text{Bq} + \\ (3.32\text{x}10^{-5}\ \text{Sv Bq}^{-1})\ \text{x}\ 7.48\text{x}10^{-2}\ \text{Bq} + \\ (3.20\text{x}10^{-5}\ \text{SvBq}^{-1})\ \text{x}\ 5.89\text{x}10^{-4}\ \text{Bq} \end{pmatrix}$. H_E = 1.49 x 10^{-4} Sv (14.9 mrem)

H.1.4. Significance of the Exposure

This is about 15 mrem committed effective dose equivalent with almost all of the dose equivalent coming from the ^{234}U. By similar means, the committed effective dose equivalent for an inhalation of 1 μg of 1 μm AMAD depleted uranium can be estimated as 0.04 mrem.

H.2. Scenario 2 - External Exposure to ^{238}U

As an example, we will calculate the external exposure rate at 80 cm from a 1 mCi point source of ^{238}U in equilibrium with its short lived progeny. The external gamma dose equivalent rate can be estimated by using the point source gamma constants in Table 7.8 and the inverse square law.

Because the short- lived progeny are beta emitters, the contribution of these beta particles must be considered as well. To estimate the beta dose from a point source, we use the tabulated conversion factors in Table 7.11.

H.2.1. Estimating the External Gamma Dose Equivalent Rate

The external gamma dose equivalent is estimated by multiplying the sum of the gamma constant (Γ) of ^{238}U and short lived progeny by the source activity and dividing by the distance from the source squared.

$$H_G = \frac{\text{Gamma Constant x Activity}}{(\text{Source distance})^2}$$

$H_G = 0.166 \text{ mrem h}^{-1} \text{ mCi}^{-1} \text{ m}^2 \text{ x 1 mCi x } (0.8 \text{ m})^{-2}$.

$H_G = 0.259 \text{ mrem h}^{-1}$.

H.2.2. Estimating the External Beta Dose Equivalent Rate

The beta dose equivalent is estimated from tabulated data because the rules that apply to gamma dose equivalent rates do not apply. The conversion factors for beta dose rates are in Table 7.9. The value at 80 cm is multiplied by 3.7×10^3 to obtain 50.47 mrem h^{-1} mCi^{-1}.

$$H_B = \text{Conversion Factor x Activity}$$

$H_B = 50.47 \text{ mrem h}^{-1} \text{ mCi}^{-1} \text{ x 1 mCi}$

$H_B = 50.47$ mrem

These steps are presented in the table below.

Table H.2. Steps in estimating external exposure to DU

Step	Procedure	Example at 0.8 m distance
1	Estimate the gamma exposure rate using the gamma constant, and inverse square law. Note that the gamma constant shown here does not include the contribution from ^{234}U.	$H_G = \frac{\text{Gamma Constant x Activity}}{(\text{Source distance})^2}$ $H_G = 0.166$ mrem h^{-1} mCi^{-1} m^2 x 1 mCi x $(0.8\ m)^{-2}$ $H_G = 0.259$ mrem h^{-1}
2	Estimate the beta dose rate for a point source. Note that the constant here has been multiplied by 3700 to convert that tabulated value to conventional units.	H_B = Conversion Factor x Activity $H_B = 50.47$ mrem h^{-1} mCi^{-1} x 1 mCi $H_B = 50.47$ mrem h^{-1}

H.2.3. The Significance of the Exposure Rates

The total is about 50.8 mrem h^{-1} with the vast majority caused by beta particles. Because the majority of the radiation hazard from ^{238}U is from beta particles, the external exposure can be controlled with moderate shielding. Also, because of the low specific activity, it takes a relatively large mass of ^{238}U to cause appreciable exposures.

H.3. Scenario 3 – Weapons Grade Plutonium

In an attempt to block passage through an industrial complex, a terrorist group uses conventional explosives to disperse 1 kilogram (2.3 TBq (62 Ci) see Table 7.19 of specific activities) of ^{239}Pu. As a reasonable estimate about 20% of the Pu is dispersed as aerosols of respirable size [50]. This aerosol is disbursed through a cubic volume of air 100 meters on a side. The remaining Pu is uniformly distributed over a square area of ground 100 meters on a side.

If a person could sprint this 100 meters at a rate of 4 m s^{-1}, it would take 25 seconds to cross the contaminated zone. For this example, we assume that the Pu concentration in the air is constant and that the ground concentration is unaffected by movement. Furthermore, because of the exertion involved the breathing rate can be assumed to be about 40 L min^{-1} (6.7×10^{-4} m^3 s^{-1}), twice the normal breathing rate.

First, we will estimate the internal dose equivalent for our hypothetical soldier. The estimation requires three steps: first, estimate the airborne concentration of Pu; second, estimate the intake; and, third estimate the dose equivalent based on the appropriate conversion factors.
The following parameters are given:

Amount of plutonium: 1 kilogram = 2.3 TBq;

Fraction converted to a respirable aerosol: 0.20;

Geometry of air volume: A cube 100 meters on a side;

Geometry of ground contamination: A square 100 meters on a side;

Sprinting speed: 4 m s^{-1};

Distance to sprint: 100 meters;

Breathing rate: 40 liters min^{-1} (6.7×10^{-4} m^3 s^{-1}).

H.3.1. Internal Dose Estimation: Estimating the Airborne Concentration

The airborne concentration (U_{Pu}) is calculated by multiplying the total amount of Pu in the explosion by the fraction that is converted into respirable particles and dividing that product by the volume of air throughout which the Pu is dispersed.

$$(2.3 \text{ TBq} \times 0.20) \times (100 \text{ m})^{-3} = 4.6 \times 10^{5} \text{ Bq m}^{-3}.$$

H.3.2. Internal Dose Estimation: Estimating the Intake

We can estimate the intake by multiplying the concentration by the total volume of contaminated air inhaled. The volume of inhaled air is simply the breathing rate multiplied by the duration of the exposure (100 m divided by 4 m s^{-1}).

$$(4.6 \times 10^{5} \text{ Bq m}^{-3}) \times (6.7 \times 10^{-4} \text{ m}^{3} \text{ s}^{-1}) \times 25 \text{ s} = 7700 \text{ Bq}.$$

H.3.3. Internal Dose Estimation: Estimating the Internal Dose Equivalent

Once the intake is found the committed effective dose equivalent (H_E) can be estimated by multiplying the intake by the appropriate conversion factor, h_E, found in Table 7.27.

$$H_E = 7700 \text{ Bq} \times 8.33 \times 10^{-5} \text{ Sv Bq}^{-1} = 0.64 \text{ Sv (64 rem)}.$$

Similarly, the effective dose equivalent to the bone surfaces can be estimated by multiplying the intake by h_{BS}.

$$H_{BS} = 7700 \text{ Bq} \times 8.21 \times 10^{-4} \text{ Sv Bq}^{-1} = 6.3 \text{ Sv (630 rem)}.$$

These steps and example calculations are repeated below. Neglected in these estimates are intakes caused by inhaling material kicked up by activities in the area (resuspension).

Table H.3. Steps in estimating internal exposure to Pu

Step	Procedure	Example
1	Estimate the Pu concentration in air, U_{Pu}.	$U_{Pu} = \frac{\text{Amount of Pu x Fraction Aerosolized}}{\text{Volume of Distribution}}$ $U_{Pu} = \frac{2.3\text{ TBq x } 0.2}{(100\text{ m})^3} = 4.6 \text{ x } 10^5 \text{ Bq m}^{-3}$
2	Estimate the intake (I) from the exposure scenario.	I = U_{Pu} x Breathing Rate x Exposure Duration I = 4.6 x 10^5 Bq m^{-3} x 6.7 x 10^{-4} m^3 s^{-1} x 25 s I = 7700 Bq
3	Estimate the committed effective dose equivalent and committed dose equivalent to the bone surfaces. The conversion factors (h_X) are found in Table 7.27.	H_X = Intake x h_X H_{BS} = 7700 Bq x 8.21 x 10^{-4} Sv Bq^{-1} = 6.3 Sv H_E = 7700 Bq x 8.33 10^{-5} Sv Bq^{-1} = 0.64 Sv
4	Convert SI to conventional U.S. units, if needed.	1 Sv = 100 rem H_{BS} = 6.3 Sv = 630 rem H_E = 0.64 Sv = 64 rem

Because the radiation emitted from Pu is mainly alpha and beta, we expect the external dose equivalents to be small. Remember that the soldiers will be exposed to external radiation from both the cloud of suspended material and the material deposited on the ground. The steps involved in estimating the external exposure are very similar to estimating internal exposure. First, we need the airborne concentration (4.6 x 10^5 Bq m^{-3}), which was calculated above, and we also need the surface contamination on the ground.

H.3.4. External Dose Estimation: Estimating the Surface Contamination

The surface contamination, S_A, is estimated by multiplying the total amount of Pu by the fraction that was not converted into respirable particles and dividing that number by the surface area that is contaminated. The fraction not converted is simply one minus the aerosolized fraction.

$$S_A = 2.3 \text{ TBq x } (1 - 0.2) \text{ x } (100 \text{ m})^{-2} = 1.84 \text{ x } 10^8 \text{ Bq m}^{-2}.$$

$$U_{Pu} = 4.6 \text{ x } 10^5 \text{ Bq m}^{-3} \text{ (from the internal exposure section).}$$

H.3.5. External Dose Estimation: Estimating the Dose Equivalents

Once these concentrations are found, all that remains is to multiply them by the appropriate conversion factors and the exposure duration. For the contaminated ground, we use the conversion factor for an infinite surface (Table 7.22).

$$H_{Surface} = S_A \text{ x } h_{Surface} \text{ x Exposure Duration.}$$

$H_{Surface} = 1.84 \text{ x } 10^8 \text{ Bq m}^2 \text{ x } 3.67 \text{ x } 10^{-19} \text{ Sv s}^{-1} \text{ Bq}^{-1} \text{ m}^2 \text{ x 25s.}$

$H_{Surface} = 1.7 \text{ x } 10^{-9} \text{ Sv} = 1.7 \text{ x } 10^{-4} \text{ mrem.}$

In addition, an estimate of the dose to exposed skin must be estimated from submersion in a cloud of Pu.

$$H_{Cloud} = U_{Pu} \text{ x } h_{Cloud} \text{ x Exposure Duration.}$$

$H_{Cloud} = 4.6 \text{ x } 10^5 \text{ Bq m}^3 \text{ x } 4.24 \text{ x } 10^{-18} \text{ Sv s}^{-1} \text{ Bq}^{-1} \text{ m}^3 \text{ x 25 s}$

$H_{Cloud} = 4.9 \text{ x } 10^{-11} \text{ Sv} = 4.9 \text{ x } 10^{-6} \text{ mrem.}$

The dose equivalent to the skin is estimated as follows.

$$H_{Skin} = U_{Pu} \text{ x } h_{Skin} \text{ x Exposure Duration}$$

$H_{Skin} = 4.6 \text{ x } 10^5 \text{ Bq m}^3 \text{ x } 1.86 \text{ x } 10^{-17} \text{ Sv s}^{-1} \text{ Bq}^{-1} \text{ m}^3 \text{ x 25 s}$

$H_{Skin} = 2.1 \text{ x } 10^{-10} \text{ Sv} = 2.1 \text{ x } 10^{-5} \text{ mrem.}$

The steps used to estimate the external dose equivalents are summarized in the table below.

Table H.4. Steps in estimating external exposure to Pu

Step	Procedure	Example
1	Estimate the Pu concentration in air, U_{Pu}. The same way as for estimating internal exposures.	$U_{Pu} = \frac{\text{Amount of Pu x Fraction Aerosolized}}{\text{Volume of Distribution}}$ $U_{Pu} = \frac{2.3\,\text{TBq x 0.2}}{(100\text{ m})^3} = 4.6 \text{ x } 10^5 \text{ Bq m}^{-3}$
2	Estimate the surface contamination, S_A.	$S_A = \frac{\text{Amount of Pu x Fraction not Aerosolized}}{\text{Surface Area}}$ $S_A = \frac{2.3\text{ TBq x 0.8}}{(100\text{ m})^2} = 1.84 \text{ x } 10^8 \text{ Bq m}^2$
3	Estimate the effective dose equivalent from external radiation from the ground surface. The conversion factors ($h_{Surface}$) are found in Table 7.22.	$H_{Surface} = S_A$ x $h_{Surface}$ x Exposure Duration $H_{Surface} = 1.84 \text{ x } 10^8 \text{ Bq m}^2 \text{ x } 3.67 \text{ x } 10^{-19} \text{ Sv s}^{-1} \text{ Bq}^{-1} \text{ m}^2 \text{ x 25 s}$ $H_{Surface} = 1.7 \text{ x } 10^{-9} \text{ Sv}$
4	Estimate the effective dose equivalent from external radiation from submersion in a cloud. The conversion factors (h_{Cloud}) are found in Table 7.22.	$H_{Cloud} = U_{Pu}$ x h_{Cloud} x Exposure Duration $H_{Cloud} = 4.6 \text{ x } 10^5 \text{ Bq m}^3 \text{ x } 4.24 \text{ x } 10^{-18} \text{ Sv s}^{-1} \text{ Bq}^{-1} \text{ m}^3 \text{ x 25 s}$ $H_{Cloud} = 4.9 \text{ x } 10^{-11} \text{ Sv}$
5	Estimate the dose equivalent to the skin from the submersion. The conversion factors (h_{Skin}) are found in Table 7.23.	$H_{Skin} = U_{Pu}$ x h_{Skin} x Exposure Duration $H_{Skin} = 4.6 \text{ x } 10^5 \text{ Bq m}^3 \text{ x } 1.86 \text{ x } 10^{-17} \text{ Sv s}^{-1} \text{ Bq}^{-1} \text{ m}^3 \text{ x 25 s}$ $H_{Skin} = 2.1 \text{ x } 10^{-10} \text{ Sv}$
6	This step is estimating the external skin dose from surface contamination.	This dose equivalent is about one tenth of the dose equivalent from submersion and is neglected here.

H.3.6. Significance of the Exposures

The total external exposure is about 1.7 x 10^{-4} mrem and about 2 x 10^{-5} mrem to the skin. These are genuinely trivial exposures, as expected. However, the internal exposures are not trivial. The committed effective dose equivalent is 0.64 Sv (64 rem) and the committed dose equivalent to the bone surfaces is 6.3 Sv (630 rem). Under the current RES guides, the committed effective dose equivalent would be in risk category 1E, but the dose equivalent to the bone surface cannot be directly compared to the RES guides as they currently stand. The 6.3 Sv does exceed the current USNRC regulatory limit of 0.5 Sv by a factor of about 12.

This projected intake can be reduced or eliminated by respiratory protection gear, such as the MOPP gear. However, the use of respiratory protection gear and personnel protective clothing can cause a significant performance decrement. For example, under hot and humid conditions, the potential for heat exhaustion can become very significant. So, the decision to use protective gear must take into account non-radiological hazards as well.

Appendix I. Radiation Contamination Case Study

The following case study was copied entirely from the NBC-MED web page at www.nbc-med.org/csgoiania.html. Only minor formatting changes have been made.

I.1. Case Study: Accidental Leakage of Cesium-137 in Goiania, Brazil, in 1987

In September of 1987, scavengers dismantled a metal canister from a radiotherapy machine at an abandoned Cancer Clinic in Goiania, Brazil. Five days later a junkyard worker pried open the lead canister to reveal a pretty blue, glowing dust: radioactive cesium-137. In the following days, scores of Goianian citizens were exposed to the radioactive substance. In a nuclear disaster second only to Chernobyl, the city of Goiania had one of the largest radioactive leaks on its hands and for a few days, they knew nothing about it.

I.1.1. History

In the early 1980's, "three doctors had owned the private downtown [Cancer] clinic...when they left [in 1985], the doctors simply abandoned the radiotherapy machine and left the building to deteriorate without windows or doors." [i] Two years later, the canister containing cesium-137 was found by scavengers. Accounts differ as to who found the canister and how it was opened. However, once the canister was pried open releasing its radioactive contents, tragedy ensued.

I.1.2. Radiation Contamination Facts

Radiation destroys the most rapidly dividing cells of the body the cells of the skin, hair, gastrointestinal tract, and bone marrow. Because the bone marrow gives rise to the blood cells, including those of the immune system and the platelets that staunch [*sic*] bleeding, radiation victims are susceptible to infections and hemorrhaging. [ii]

I.1.3. Cesium Facts

Naturally occurring cesium is entirely the non-radioactive isotope, ^{133}Cs; 20 radioactive isotopes from ^{123}Cs to ^{144}Cs have been artificially prepared. Cesium-137 is useful in medical and industrial radiology because of its long half-life of 30 years. Cesium is the most electropositive and most alkaline element, and thus, more easily than all other elements, it loses its single valence electron and forms electrovalent bonds, with nearly all the inorganic and organic anions[iii]. When cesium comes into contact with plants and animals, it is absorbed into system[s] by replacing potassium.

I.1.4. Goiania facts

Goiania, city, capital of Goias estado (state), south-central Brazil. It is situated in the Brazilian Highlands of the Meia Ponte River valley, southwest of Brasilia, the federal capital. The city lies at an elevation of 2,493 feet (760 m) above sea level. Goiania was planned in 1933 to replace the unhealthful [*sic*] former state capital of Goias, 70 miles (110km) northwest. In 1937 the state government moved there, and in 1942 the official inauguration was held. The city has wide avenues and attractive parks. Goiania is the seat of both the Federal University of Goias (1960) and the Catholic University of Goias (1959). ...Pop (1980) 702,858. [iii]

I.1.5. Case

Sometime around September 21, 1987, a lead canister containing 1400 curies of cesium-137 was opened launching the second largest nuclear accident after Chernobyl. [ii] The cesium from within the canister was a "luminous blue powder" which both children and adults rubbed on their bodies. [i] Six year old Leide das Neves Ferreira "rubbed the powder on her body so that she glowed and sparkled." [iv]. She later ate a sandwich tainted with cesium powder from her hands; "she reportedly received five to six times the lethal dose [of radiation] for adults". [ii] The cesium was later parceled out to friends and family, spreading the contamination from the junkyard to homes around the city, although mainly contained within a localized area. The radioactive substance continued to contaminate the population for a week before Devair Ferreira finally reported to health authorities.

On September 28, "Devair Ferreira went to the Goiania public clinic where a health care worker correctly diagnosed radiation illness and alerted authorities". [ii] When the Brazilian Nuclear Energy Commission dispatched a team equipped to handle a radiation accident, they found: 244 persons to be contaminated, 54 seriously enough to be hospitalized for further tests or treatment. Thirty-four were treated and released. The next day the ten sickest patients...were airlifted to the Navy hospital, Dias, in Rio [de Janeiro].[i]

Upon realizing the severity of the accident, the Brazilian government requested help from the International Atomic Energy Commission (IAEC) which sent a team of doctors. The medical team found the 20 most seriously irradiated victims had received doses ranging from 100 to 800 rads. Nineteen of the 20 had radiation-induced skin burns, from minor to major. And all 20 patients were internally contaminated, which meant that they were being continually irradiated from the cesium that they had inhaled or accidentally ingested. The patients themselves were radioactive. [ii]

Because the patients themselves were radioactive, the first task was to attempt to rid their bodies of cesium. For this, they administered Prussian blue, an iron compound that bonds with cesium, aiding its excretion. The problem in this case was the substantial delay-at least a week-from initial exposure to treatment. By that time much of the cesium had moved from the bloodstream into the tissues, where it is far more difficult to remove...the patients were also treated with antibiotics as needed to combat infections and with cell infusions to prevent bleeding. [ii]

Between six and eight (according to different accounts) of the most adversely affected patients were treated with an experimental drug called "GM-CSF, or granulocyte-macrophange colony-stimulating factor...one of at least five hormones that boo[s]t the production of white blood cells in the [bone] marrow". [iv] While a debate sprang [*sic*] around the experimental treatment used: ...the doctors injected GM-CSF into each patients vena cava, the central vein that leads to the heart. Within 48 to 72 hours, the white blood cell count increased in five of the six patients...within a week, four of the six patients had dies [*sic*], overwhelmed by pneumonia, blood poisoning and hemorrhaging. [iv]

Six year old, Leide Ferreira was among the four who did not make it. As the rest of the city was being decontaminated "technicians ...checked more than 34,000 people with Geiger counters at the city's soccer stadium." [i] However, the National Commission on Nuclear Energy had: ...underestimated the severity of the problem. At least 42 of its technicians did not wear protective overalls, hoods, gloves or boots while carrying out decontamination. And no one remembered for several days to decontaminate the ambulances used to take victims from Rio de Janeiro's Santos Dumont airport to the city's naval hospital- one of only two facilities for treating radiation sickness. [I]

Decontamination efforts were lackadaisical at times, despite the use [of] helicopters equipped with radiation detectors to identify hot spots and the decontamination of items such as furniture and money. [ii] The accident contaminated homes, businesses and soil. What could not be decontaminated was collected or dismantled and placed in concrete lined drums for disposal as nuclear waste.

I.1.6. Conclusion

It is clear that the city of Goiania and the country of Brazil were ill-prepared for medical treatment of a nuclear disaster, as are many nations. The lack of regulation surrounding the use of nuclear materials in Brazil, by both national and international regulation committees, as well as the abandonment of the radiotherapy machine was an accident waiting to happen. The best protection one can have against a large-scale nuclear disaster happening is two-fold: better regulation and better preparation. The lack of adequate response time and materials greatly contributed to the number of casualties and fatalities. Although it took a few days to report the radioactive leakage, the cause is also twofold. Primarily, the canister should never have been left behind. Secondly, the general public had no idea that they were handling a radioactive substance. The lack of regulation of nuclear substances, whether for medical purposes or electricity, remains a major factor in the possibility of future nuclear accidents [and accidents involving radiation producing materials or equipment].

The city of Goiania now makes money off of [*sic*] its tourism business and it will be many years before the effects of the nuclear disaster of 1987 will be fully realized. The "incubation" period for increases in radiation fallout related Leukemia [*sic*] increases is 9-10 years. It is only in 1996, that we are seeing a significant enough rise in Leukemia [*sic*] cases in areas surrounding Chernobyl, that doctors are considering the possibility of a correlation between the nuclear accident and the rise in leukemia rates. [v] Although the Goiania accident happened barely a year after the Chernobyl accident, the people of Goiania were able to benefit from decontamination and medical treatment efforts used there. Studies and the monitoring of Chernobyl victims continues to provide the most indepth information on the long-term effects of radiation exposure.

This excert was written and compiled by Alex Neifert for the Camber Corporation.

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i Dwyer, Augusta. Playing with Radiation. Macleans. 100:44; p44.
ii Sun, Marjorie. Radiation Accident Grips Goiania. Science. 238; p1028-1031.
iii Encyclopedia Britannica. Britannica Online. http://www.eb.com/.

[iv] Gorman, Christine.A Battle Against Deadly Dust: Doctors join forces to treat radiation victims in Brazil. Time. November 16, 1987; p66.

[v] Chernobyl Study raises concerns about low-level radiation (http://cnn.com/WORLD/9607/24/chernobyl.leukemia.wir/index.html). CNN Interactive (http://cnn.com). July 24, 1996.

Appendix J. Identification of Nuclides and their Symbols

The following tables identify the elements cited in this technical guide and their symbols. Table J.1 includes the name of the elements and their corresponding symbols and Figure J.1 is the periodic table of elements. This information is included to help in the identification of specific elements, throughout this document, by providing their symbols or names.

Table J.1. List of elements with their symbol and atomic number

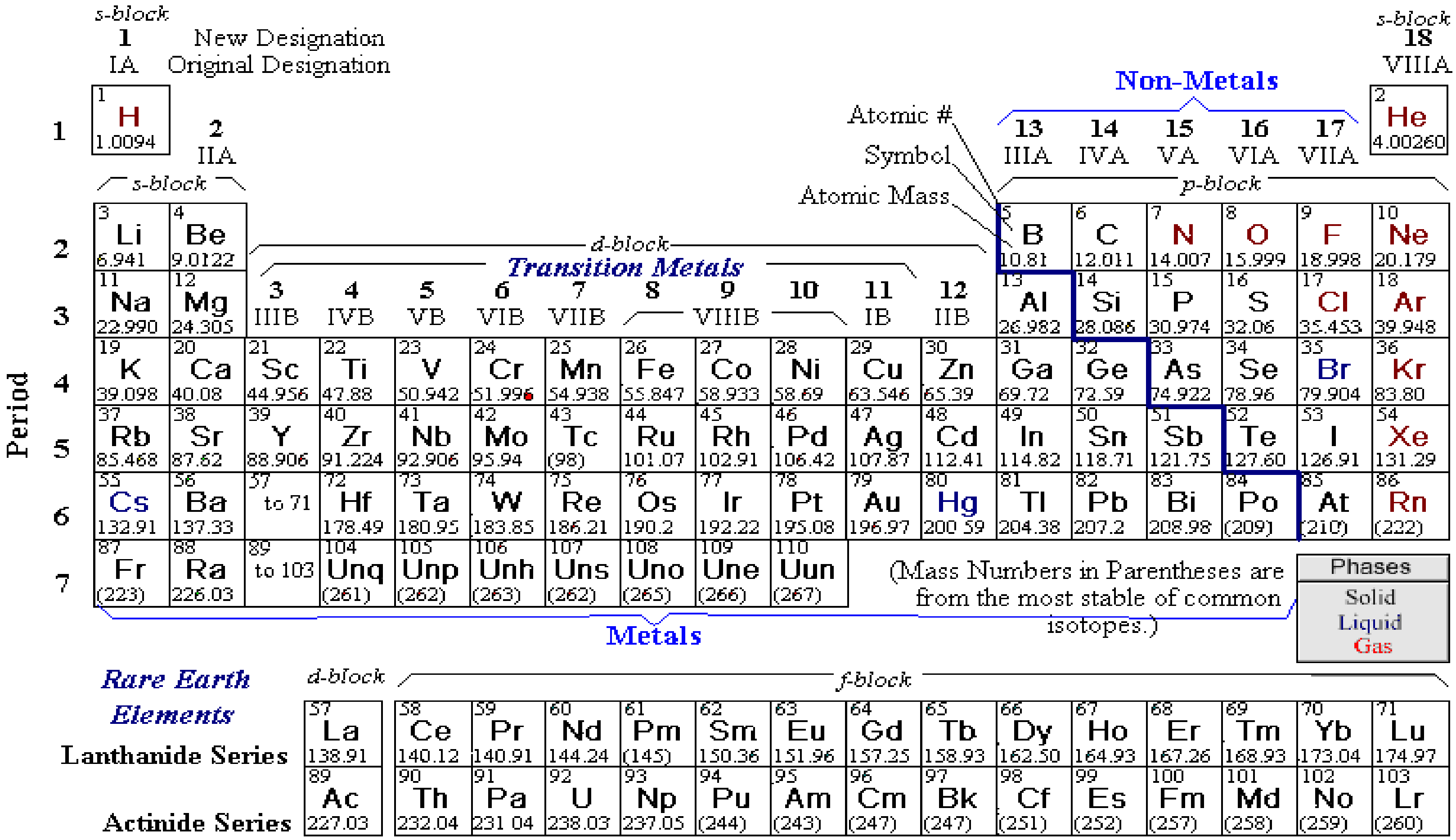
Symbol	Element	Atomic Number
Ac	Actinium	89
Al	Aluminum	13
Am	Americium	95
Sb	Antimony	51
Ar	Argon	18
As	Arsenic	33
At	Astatine	85
Ba	Barium	56
Bk	Berkelium	97
Be	Beryllium	4
Bi	Bismuth	83
B	Boron	5
Br	Bromine	35
Cd	Cadmium	48
Ca	Calcium	20
Cf	Californium	98
C	Carbon	6
Ce	Cerium	58
Cs	Cesium	55
Cl	Chlorine	24
Cr	Chromium	17
Co	Cobalt	27
Cu	Copper	29
Cm	Curium	96
Dy	Dysprosium	66
Es	Einsteinium	99
Er	Erbium	68
Eu	Europium	63
Fm	Fermium	100
F	Flourine	9
Fr	Francium	87
Gd	Gadolinium	64
Ga	Gallium	31
Ge	Germanium	32
Au	Gold	79

Symbol	Element	Atomic Number
Md	Mendelevium	101
Hg	Mercury	80
Mo	Molybdenum	42
Ns	Neilsborium	107
Nd	Neodymium	60
Ne	Neon	10
Np	Neptunium	93
Ni	Nickel	28
Nb	Niobium	41
N	Nitrogen	7
No	Nobelium	102
Os	Osmian	76
O	Oxygen	8
Pd	Palladium	46
P	Phosphorus	15
Pt	Platinum	78
Pu	Plutonium	94
Po	Polonium	84
K	Potassium	19
Pr	Praseodymium	59
Pm	Promethium	61
Pa	Protactinium	91
Ra	Radium	88
Rn	Radon	86
Re	Rhenium	75
Rh	Rhodium	45
Rb	Rubidium	37
Ru	Ruthenium	44
Rf	Rutherfordium	104
Sm	Samarium	62
Sc	Scandium	21
Sg	Seaborgium	106
Se	Selenium	34
Si	Silicon	14
Ag	Silver	47

Symbol	Element	Atomic Number
Hf	Hafnium	72
Ha	Hahnium	105
Hs	Hassium	108
Hi	Helium	2
Ho	Holmium	67
H	Hydrogen	1
In	Indium	49
I	Iodine	53
Ir	Iridium	77
Fe	Iron	26
Kr	Krypton	36
La	Lanthanum	57
Lr	Lawrencium	103
Pb	Lead	82
Li	Lithium	3
Lu	Lutetium	71
Mg	Magnesium	12
Mn	Manganese	25
Mt	Meitnerium	109

Symbol	Element	Atomic Number
Na	Sodium	11
Sr	Strontium	38
S	Sulfur	16
Ta	Tantalum	73
Tc	Technetium	43
Te	Tellurium	52
Tb	Terbium	65
Tl	Thallium	81
Th	Thorium	90
Tm	Thulium	69
Sn	Tin	50
Ti	Titanium	22
W	Tungsten	74
U	Uranium	92
V	Vanadium	23
Xi	Xenon	54
Yb	Ytterbium	70
Yb	Yttrium	39
Zn	Zinc	30
Zr	Zirconium	40

Figure J.2. The periodic table of elements



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)								

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

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)

References:

1. DA: Fixed site protection. Washington, DC: Department of the Army, 1989.

2. DA: Nuclear Accident and Incident Response and Assistance (NAIRA). Washington, DC: Department of the Army, 1988.

3. DA: NBC Protection. . Washington, DC: Department of the Army, U.S. Marine Corps, 1992.

4. DA: NBC Decontamination. Washington, DC: Department of the Army, 1993.

5. DA: Health service support in a nuclear, biological and chemical environment. Washington, DC: Department of the Army, 1993.

6. DA: Nuclear Contamination Avoidance. Washington, DC: Army, U.S. Marine Corps, 1994.

7. DOD: Nuclear Weapon Accident Response Procedures. Washington, DC: Department of Defense, 1990.

8. DA, DON, DOAF: NATO Handbook on the medical aspects of NBC defensive operations, AMedP-6(B). Washington, DC: Department of the Army, the Navy and the Air Force, 1996.

9. DA: Joint doctrine for nuclear, biological, and chemical (NBC) defense. Washington, DC: Army, Marine Corp, Navy, Air Force, 1995.

10. DA: NBC Field Handbook. Washington, DC: Department of the Army, 1994.

11. Shleien, B., Slaback, J.L.A., and Birky, B.K.*: The Health Physics and Radiological Health Handbook*, 3rd ed. Baltimore, Maryland: Williams & Wilkins, 1998. (Shleien, B., ed.)

12. DA: Soldier's Manual of Common Tasks (SMCT) Skill Level 2-4. Washington, DC: Department of the Army, 1992.

13. Wald, N.: Acute Radiation Injuries and their Medical Management. The Biological Basis or Radiation Protection Practice, Proceedings of the 1991 HPS Summer School. Baltimore, Maryland: Williams and Wilkins, 1991.

14. DA: Radioactive Material Handling Safety. Washington, DC: ACALA, 1998.

15. DA: Instructions for safe handling, maintenance, storage and disposal of radioactive items licensed by U.S. Army Armament and Chemical Acquisition and Logistics Activity. Washington, DC: AMSTA-AC-NML, 1997.

16. NATO: ACE Policy for defensive measures against low level radiological hazards during military operations. Brussels: SHAPE, Supreme Headquarters Allied Powers Europe, 1996.

17. ANS: Nuclear power plants worldwide. Nuclear News 1997 (March).

18. ANS: Nuclear News World List of Nuclear Power Plants, Operable, Under Construction, or on Order (30 MWe and Over) as of December 31, 1998. Nuclear News 1999 (March): 33-56.

19. Duderstadt, J.J. and Hamilton, L.J.: *Nuclear Reactor Analysis*. New York, New York: John Wiley & Sons, 1976.

20. Glasstone, S.,and Jordan, W.H.: Nuclear Power and its Environmental Effects. La Grange Park, Illinois: American Nuclear Society, 1980.

21. Web: URL: http://www.uilondon.org/uihome.html, 1997.

22. Graves, H.W., Jr.: *Nuclear Fuel Management*. New York: John Wiley & Sons, 1979.

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

24. Glasstone, S., *Sesonske: Nuclear Reactor Engineering*. 3rd ed. New York: Van Nostrand Reinhold Co., 1981.

25. Rust, J.H.: *Nuclear Power Plant Engineering*. Atlanta, Georgia: S.W. Holland Company, 1979.

26. Lamarsh, J.R.: *Introduction to Nuclear Engineering.* 2nd ed. Massachusetts: Addison-Wesley Publishing Company, 1983.

27. IAEA: Summary report on the post-accident review meeting on the Chernobyl accident. Vienna and Lanham, Maryland: International Atomic Energy Agency, 1986.

28. Eisenbud, M. and Gesell, R.: *Environmental Radioactivity from Natural, Industrial and Military Sources.* 4th ed. New York: Academic Press, 1997.

29. ORNL, Finney, B.C.: Correlation of Radioactive Waste Treatment Costs and the environmental Impact of Waste Effluents in the Nuclear Fuel Cycle - Nuclear Fuel Reprocessing. Oak Ridge, Tennessee: Oak Ridge National Laboratory, 1975.

30. ANSTO: Jane's Fighting Ships, 92nd and 98th ed, 1996. (Nuclear Services Section, Nuclear News, eds.

31. Simpson, J.: Nuclear Power from Underseas to Outer Space: American Nuclear Society, 1995.

32. Web: The Uranium Information Centre Ltd. Homepage. Melbourne, Australia: UIC, 1999.

33. Crick, M.J.and Lindsley, G.S.: An assessment of the radiological impact of the Windscale reactor fire, October 1957. *International Journal of Radiation Biology 1984*; 46: 479-506.

34. Arnold, L.: *Windscale 1957*. London: Macmillan, 1992.

35. NCRP: Radiation Protection Design Guidelines for 0.1-100 MeV Particle Accelerator Facitilities. Bethesda, Maryland: National Council on Radiation Protection and Measurements, 1977.
36. Shleien, B., Alexander, R.E., and Eckerman, K.F., et al.: *The Health Physics and Radiological Health Handbook*. Silver Spring, Maryland: Scinta, Inc., 1992. (Shleien, B., ed.)
37. Patterson: Accelerator Health Physics, 1973.
38. NCRP: Medical x-ray and gamma ray protection for energies up to 10 MeV. Washington, DC: National Council on Radiation Protection and Measurements, 1970.
39. Khan, F.M.: *The Physics of Radiation Therapy*.,2nd ed. Baltimore: Williams & Wilkins, 1984.
40. Karzmark, C.J., C. PN: Electron linear accelerators for radiation therapy: history, principles and contemporary developments. *Physics Medical Biology* 1973; 18(321).
41. IAEA: Lessons Learned from Accidents in Industrial Irradiation Facilities. Vienna: International Atomic Energy Agency, 1996.
42. IAEA: The Radiological Accident in San Salvador. Vienna: International Atomic Energy Agency, 1990.
43. IAEA: The Radiological Accident at the Irradiation Facility in Nesvizh. Vienna: International Atomic Energy Agency, 1996.
44. IAEA: An Electron Accelerator Accident in Hanoi, Viet Nam. Vienna: International Atomic Energy Agency, 1996.
45. NRC US: Title 10 Code of Federal Regulations, Part 20 revisions. Washington, DC: United States Nuclear Regulatory Commission, 1991.
46. DOT: Hazardous Materials Regulations. Washington, DC: Department of Transportation, Government Printing Office.
47. ICRP: Limits for Intakes of Radionuclides by Workers. : International Commission on Radiological Protection, Pergamon, Oxford, 1979.
48. EPA: Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion. Oak Ridge, Tennessee: Environmental Protection Agency, 1988.
49. DA: Visual Signals. Washington, DC: Department of the Army, 1987.

50. Sutcliffe, W.G., Condit, R.H., Mansfield, W.G., Myers, D.S., Layton. D.W., and Murphy, P.W.: A Perspective on the Dangers of Plutonium. : Lawrence Livermore National Laboratory, 1995.

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