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HANDBOOK of RADIOACTIVE NUCLIDES

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Handbook of Radioactive Nuclides

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PREFACE

In the preparation of this reference volume, the aim has been to provide a convenient single source for basic information on radioactive nuclides, instrumentation, dosimetry, and applications, as well as on general radiation protection. Most of the information is in tabular or graphical form, but narrative presentation and explanation are also included. For convenient reference, the Handbook has been divided into several sections, many of which cover special applications of radionuclides.

A considerable proportion of the material herein has been compiled especially for this book from current scientific journals and from various authoritative collections of basic radionuclide data and applications. The editors are grateful for permissions to reprint these materials and have made every effort to designate the original sources and to give references to further information available on each subject.

Although the editors have tried to include in condensed form the information most frequently used and needed in the fields of radionuclide application, there is always a question of what to include in a one-volume desk-reference book. Suggestions from readers for additions or modifications in future editions are invited.

We would like to take this opportunity to express our deep gratitude to our contributors and to the members of the editorial board as well as to others who have assisted us in the compilation of this volume. The information on radionuclides is so voluminous that the completion of the book would not have been possible without their effort and assistance.

YEN WANG

June 1969

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DETERMINATION OF FACILITIES, EQUIPMENT, AND PROCEDURES REQUIRED FOR VARIOUS TYPES OF OPERATIONS

Allen Brodsky, Sc.D., C.H.P.

There are already many good references on general safety procedures and proper design considerations for laboratories or facilities using radioactive material or radiation sources.[1-5] This chapter will summarize only some of the general considerations in selecting appropriate facilities, equipment and procedures, including Table 41, which arranges the radionuclides according to intrinsic radiotoxicity along with the respective radioactivity levels above which various safeguards or combinations of several safeguards should be considered.[6]

A check list of considerations involved in determining the types of facilities, equipment, and procedures that might be required for handling radioactive materials in quantities large enough to be of some potential hazard to personnel is given below, presented in a format such as one might find in a hazard summary report prepared for a licensing review.

INFORMATION TO BE INCLUDED IN A HAZARD SUMMARY REPORT*

I. A Description of Operations or Applications Involving Radioactive Materials.

Include (as applicable to operations with radioactive material) a description of any chemical, physical, metallurgical, or nuclear processes to be carried out. The description should be detailed enough to permit evaluation of the radiation hazards involved. The forms and amounts of radioactivity to be handled in the proposed processes and any thermal energy likely to be generated should be given.

II. A Description of Facilities and Equipment.

Describe the design criteria for the facility as a whole and for those parts that are essential to the safe operation of the facility. The description should contain enough detail to allow an evaluation of the various methods proposed to minimize any chances of exposing persons on or off site to excessive amounts of radiation or radioactive materials. The description should also cover any activities (in addition to those involving radioactive material) that will be carried on in the building that will house the facility and on the balance of the site. The description should include, but not necessarily be limited to, such items as: shielding to be provided, including types of material, densities, dimensions, and attenuations expected; detailed descriptions of radiation monitoring systems and alarms and their sensitivities; features of the air ventilation and filtration systems that will prevent contamination of unrestricted areas or nearby farms and com-

* The items indicated are intended to serve as a relatively exhaustive check list; however, for individual installations many of these items may not be applicable or may require only brief answers. In some cases, items not indicated in this list may deserve mention.

Table 41.
RADIOTOXICITY VERSUS LEVELS ABOVE WHICH VARIOUS SAFEGUARDS MAY BE REQUIRED[6]

(See footnotes at end of table.)

Radionuclides	Physical Properties			Relative Radiotoxicity	
	Physical Half-Life, days	Specific Activity, Ci/g	External Gamma Dose Rate, r/hr at 1 meter per curie	Single Inhalation, in curies, to Give 15 rem to Critical Organ, Ci/15 rem	Single Inhalation, in curies, to Give 15 rem to Lung,[a] Ci/15 rem
Group I					
^{3}H	4.5×10^{3}	9.78×10^{3}	<0.0002	6.15×10^{-2}	—
^{14}C	2.0×10^{6}	4.61	<0.01	2.88×10^{-2}	—
Group II					
^{82}Br	1.5	1.06×10^{6}		7.47×10^{-3}	—
^{51}Cr	27.8	9.20×10^{4}		8.84×10^{-2}	5.30×10^{-3}
^{55}Fe	1.1×10^{3}	2.51×10^{3}		2.17×10^{-3}	2.30×10^{-3}
Group III					
^{35}S	87.1	4.28×10^{4}	<0.01	7.23×10^{-4}	6.90×10^{-4}
^{198}Au	2.7	2.44×10^{5}	0.25	7.25×10^{-4}	5.30×10^{-4}
^{47}Ca	4.9	5.90×10^{5}		2.59×10^{-4}	4.60×10^{-4}
^{132}I	0.097	1.05×10^{7}		4.50×10^{-4}	—
^{141}Ce	32	2.80×10^{4}		7.06×10^{-4}	4.20×10^{-4}
Mixed Fission* Products	*	$<4.00 \times 10^{11}$*		1.40×10^{-4}	*
^{85}Sr	65	2.37×10^{4}		2.00×10^{-3}	2.70×10^{-4}
^{140}La	1.68	5.61×10^{5}	0.95	4.20×10^{-4}	2.60×10^{-4}
^{95}Nb	35	3.93×10^{4}		3.60×10^{-3}	2.30×10^{-4}
^{65}Zn	245	8.20×10^{3}		2.60×10^{-4}	1.50×10^{-4}
^{58}Co	72	3.13×10^{4}		8.40×10^{-3}	1.30×10^{-4}
^{59}Fe	45.1	4.92×10^{4}	0.65	3.00×10^{-4}	1.30×10^{-4}
Group IV					
^{181}Hf	46	1.62×10^{4}		9.94×10^{-5}	1.92×10^{-4}
^{147}Pm	920	9.25×10^{2}	<0.01	8.90×10^{-5}	2.30×10^{-4}
^{32}P	14.3	2.85×10^{5}	<0.01	8.70×10^{-5}	2.10×10^{-4}
^{140}Ba	12.8	7.30×10^{4}	1.54	1.40×10^{-4}	8.60×10^{-5}
^{234}Th	24.1	2.32×10^{4}		8.50×10^{-5}	7.30×10^{-5}
^{85}Kr	3.9×10^{3}	39.6	0.0019	6.90×10^{-2}	5.80×10^{-5}
^{192}Ir	74.5	9.16×10^{3}	0.51	3.20×10^{-4}	6.90×10^{-5}
^{36}Cl	1.2×10^{8}	3.21×10^{-2}		2.70×10^{-3}	5.30×10^{-5}
^{91}Y	58	2.50×10^{4}		5.00×10^{-5}	7.30×10^{-5}
^{182}Ta	112	6.20×10^{3}		1.10×10^{-4}	5.00×10^{-5}
^{45}Ca	164	1.77×10^{4}	<0.01	4.30×10^{-5}	2.60×10^{-4}
^{89}Sr	50.5	2.77×10^{4}		4.00×10^{-5}	8.50×10^{-5}
^{137}Cs	1.1×10^{4}	98.5	0.36	2.60×10^{-4}	3.00×10^{-5}
^{60}Co	1.9×10^{3}	1.14×10^{3}	1.32	2.60×10^{-3}	2.20×10^{-5}
^{144}Ce	290	3.18×10^{3}	0.20	1.40×10^{-5}	1.50×10^{-5}
^{126}I	13.3	7.80×10^{4}		1.40×10^{-5}	7.30×10^{-4}

Table 41. (*Continued*)
RADIOTOXICITY VERSUS LEVELS ABOVE WHICH VARIOUS SAFEGUARDS MAY BE REQUIRED[6]

(See footnotes at end of table.)

Radionuclides	Physical Properties			Relative Radiotoxicity	
	Physical Half-Life, days	Specific Activity, Ci/g	External Gamma Dose Rate, r/hr at 1 meter per curie	Single Inhalation, in curies, to Give 15 rem to Critical Organ, Ci/15 rem	Single Inhalation, in curies, to Give 15 rem to Lung,[a] Ci/15 rem
Group IV *(cont.)*					
^{154}Eu	5.8×10^{3}	1.45×10^{2}		1.30×10^{-5}	1.60×10^{-5}
^{131}I	8	1.24×10^{5}	0.25	1.20×10^{-5}	7.30×10^{-4}
^{170}Tm	127	6.08×10^{3}	0.004	3.80×10^{-5}	7.50×10^{-5}
Group V					
^{129}I	6.3×10^{9}	1.62×10^{-4}		2.30×10^{-6}	1.60×10^{-4}
^{99}Tc		1.71×10^{-2}		9.10×10^{-6}	
Group VI					
^{223}Ra	11.7	5.00×10^{4}		3.90×10^{-6}	5.30×10^{-7}
^{210}Po	138.4	4.50×10^{3}	<0.00005	1.30×10^{-6}	5.00×10^{-7}
^{227}Th	18.4	3.17×10^{4}		5.50×10^{-7}	4.60×10^{-7}
^{90}Sr	1.0×10^{4}	1.44×10^{2}	<0.01	3.90×10^{-7}	1.30×10^{-5}
^{210}Pb	7.1×10^{3}	88		3.20×10^{-7}	5.30×10^{-7}
^{242}Cm	162.5	3.34×10^{3}	<0.01	3.00×10^{-7}	4.60×10^{-7}
^{233}U	5.9×10^{7}	0.01 (with 80 ppm ^{232}U)	0.0002 (with 20 ppm ^{232}U)	7.00×10^{-7}	2.70×10^{-7}
^{235}U (+1% ^{234}U)	2.6×10^{11}	2.15×10^{-6}	<0.002	1.10×10^{-6}	2.60×10^{-7}
^{238}U+ ^{Natural}U	1.6×10^{12}	3.34×10^{-7}	<0.002	1.90×10^{-7}	3.00×10^{-7}
^{232}Th+ ^{Natural}Th	5.1×10^{12}	1.11×10^{-7}	<0.0002	2.25×10^{-9}	2.60×10^{-8}
Group VII					
^{147}Sm	4.8×10^{13}	1.95×10^{-8}		7.70×10^{-8}	6.90×10^{-7}
^{144}Nd	7.3×10^{17}	4.97×10^{-13}		7.70×10^{-8}	7.30×10^{-7}
^{226}Ra	5.9×10^{5}	1.00	0.826	4.90×10^{-8}	1.50×10^{-8}
^{244}Cm	6.7×10^{3}	82		1.10×10^{-8}	2.30×10^{-7}
Group VIII					
^{243}Am	2.9×10^{6}	1.85×10^{-1}		7.60×10^{-9}	2.70×10^{-7}
^{241}Am	1.7×10^{5}	3.21	0.039	6.60×10^{-9}	2.70×10^{-7}
^{237}Np	8.0×10^{8}	6.90×10^{-4}		5.20×10^{-9}	2.70×10^{-7}
^{227}Ac	8.0×10^{3}	72		3.00×10^{-9}	6.90×10^{-8}
^{230}Th	2.9×10^{7}	1.97×10^{-2}	0.009	2.80×10^{-9}	2.30×10^{-8}
^{242}Pu	1.4×10^{8}	3.90×10^{-3}		2.50×10^{-9}	8.50×10^{-8}
^{238}Pu	3.3×10^{4}	16.8	<0.02	2.20×10^{-9}	7.30×10^{-8}
^{240}Pu	2.4×10^{6}	0.227	<0.001	2.00×10^{-9}	8.50×10^{-8}
^{239}Pu	8.9×10^{6}	0.0617	<0.00001	2.00×10^{-9}	8.50×10^{-8}

Table 41. RADIOTOXICITY VERSUS LEVELS ABOVE WHICH VARIOUS SAFEGUARDS MAY BE REQUIRED[6] (*Continued*)

Radionuclides	Facilities and Equipment								Site
	Chemical Hood Required	Glove Box Required	Glove Box Inside Hot Cell or Cave[b]	1 Absolute Filter[c]	2 Absolute Filters in Series[d]	Continuous General Air Sampler with Alarm[e]	Continuous Exhaust Stack Monitor and Alarm[f]	Building Containment or Controlled Leak Rate[f]	Radius[g] of Low-Population Zone (X), meters
Group I									
^{3}H	1 Ci	10 Ci		10 Ci	10^4 Ci	10^4 Ci	10^5 Ci	10^6 Ci	0.47 $Q^{2/3}$
^{14}C	1 Ci	10 Ci		10 Ci	10^4 Ci	10^4 Ci	10^5 Ci	10^6 Ci	0.47 $Q^{2/3}$
Group II									
^{82}Br	0.1 Ci	1 Ci		1 Ci	10^3 Ci	10^3 Ci	10^4 Ci	10^5 Ci	2.2 $Q^{2/3}$
^{51}Cr	0.1 Ci	1 Ci		1 Ci	10^3 Ci	10^3 Ci	10^4 Ci	10^5 Ci	2.2 $Q^{2/3}$
^{55}Fe	0.1 Ci	1 Ci		1 Ci	10^3 Ci	10^3 Ci	10^4 Ci	10^5 Ci	2.2 $Q^{2/3}$
Group III									
^{35}S	10^{-2} Ci	0.1 Ci		0.1 Ci	10^2 Ci	10^2 Ci	10^3	10^4 Ci	10 $Q^{2/3}$
^{198}Au	↑	↑	4 Ci	↑	↑	↑	↑	↑	↑
^{47}Ca									
^{132}I									
^{141}Ce									
Mixed Fission* Products			1 Ci						
^{85}Sr									
^{140}La			1 Ci						
^{95}Nb									
^{65}Zn									
^{58}Co	↓	↓		↓	↓	↓	↓	↓	↓
^{59}Fe	10^{-2} Ci	0.1 Ci	2 Ci	0.1 Ci	10^2 Ci	10^2 Ci	10^3	10^4 Ci	10 $Q^{2/3}$

Table 41. RADIOTOXICITY VERSUS LEVELS ABOVE WHICH VARIOUS SAFEGUARDS MAY BE REQUIRED[6] (*Continued*)

Radionuclides	Facilities and Equipment								Site
	Chemical Hood Required	Glove Box Required	Glove Box Inside Hot Cell or Cave[b]	1 Absolute Filter[c]	2 Absolute Filters in Series[d]	Continuous General Air Sampler with Alarm[e]	Continuous Exhaust Stack Monitor and Alarm[f]	Building Containment or Controlled Leak Rate[f]	Radius[g] of Low-Population Zone (X), meters
Group IV									
^{181}Hf	10^{-3} Ci	10^{-2} Ci		10^{-2} Ci	10 Ci	10 Ci	10^2 Ci	10^3 Ci	47 $Q^{2/3}$
^{147}Pm			100 Ci						
^{32}P			100 Ci						
^{140}Ba			0.5 Ci						
^{234}Th									
^{85}Kr			500 Ci						
^{192}Ir			2 Ci						
^{36}Cl									
^{91}Y									
^{182}Ta									
^{45}Ca			100 Ci						
^{89}Sr									
^{137}Cs									
^{60}Co			3 Ci						
^{144}Ce			1 Ci						
^{126}I			5 Ci						
^{154}Eu									
^{131}I			4 Ci						
^{170}Tm	10^{-3} Ci	10^{-2} Ci	250 Ci	10^{-2} Ci	10 Ci	10 Ci	10^2 Ci	10^3 Ci	47 $Q^{2/3}$
Group V									
^{129}I	10^{-4} Ci	10^{-3} Ci		10^{-3} Ci	1 Ci	1 Ci	10 Ci	10^2 Ci	220 $Q^{2/3}$
^{99}Tc	10^{-4} Ci	10^{-3} Ci		10^{-3} Ci	1 Ci	1 Ci	10 Ci	10^2 Ci	220 $Q^{2/3}$

Table 41. RADIOTOXICITY VERSUS LEVELS ABOVE WHICH VARIOUS SAFEGUARDS MAY BE REQUIRED[6] (*Continued*)

Radionuclides	Facilities and Equipment								Site
	Chemical Hood Required	Glove Box Required	Glove Box Inside Hot Cell or Cave[b]	1 Absolute Filter[c]	2 Absolute Filters in Series[d]	Continuous General Air Sampler with Alarm[e]	Continuous Exhaust Stack Monitor and Alarm[f]	Building Containment or Controlled Leak Rate[f]	Radius[g] of Low-Population Zone (X), meters
Group VI									
^{223}Ra	10^{-5} Ci	10^{-4} Ci		10^{-4} Ci	0.1 Ci	0.1 Ci	1 Ci	10 Ci	1,000 $Q^{2/3}$
^{210}Po			20,000 Ci						
^{227}Th									
^{90}Sr			100 Ci						
^{210}Pb									
^{242}Cm			100 Ci						
^{233}U			5,000 Ci (500 kg)						
^{235}U (+1% ^{234}U)									
^{238}U + $^{Natural}U$									
^{232}Th + $^{Natural}Th$	10^{-6} Ci	10^{-4} Ci		10^{-5} Ci	0.1 Ci	0.1 Ci	1 Ci	10 Ci	1,000 $Q^{2/3}$
Group VII									
^{147}Sm	10^{-6} Ci	10^{-5} Ci		10^{-5} Ci	10^{-2} Ci	10^{-2} Ci	0.1 Ci	1 Ci	4,700 $Q^{2/3}$
^{144}Nd									
^{226}Ra									
^{244}Cm	10^{-6} Ci	10^{-5} Ci		10^{-5} Ci	10^{-2} Ci	10^{-2} Ci	0.1 Ci	1 Ci	4,700 $Q^{2/3}$

Table 41. RADIOTOXICITY VERSUS LEVELS ABOVE WHICH VARIOUS SAFEGUARDS MAY BE REQUIRED[6] (*Continued*)

Radionuclides	Facilities and Equipment								Site
	Chemical Hood Required	Glove Box Required	Glove Box Inside Hot Cell or Cave[b]	1 Absolute Filter[c]	2 Absolute Filters in Series[d]	Continuous General Air Sampler with Alarm[e]	Continuous Exhaust Stack Monitor and Alarm[f]	Building Containment or Controlled Leak Rate[f]	Radius[g] of Low-Population Zone (X), meters
Group VIII									
^{243}Am	10^{-7} Ci	10^{-6} Ci		10^{-6} Ci	10^{-3} Ci	10^{-3} Ci	10^{-2} Ci	0.1 Ci	22,000 $Q^{2/3}$
^{241}Am	↑	↑	25 Ci	↑	↑	↑	↑	↑	↑
^{237}Np									
^{227}Ac									
^{230}Th			100 Ci						
^{242}Pu									
^{238}Pu			50 Ci						
^{240}Pu	↓	↓		↓	↓	↓	↓	↓	↓
^{239}Pu	10^{-7} Ci	10^{-6} Ci	1,000 Ci†	10^{-6} Ci	10^{-3} Ci	10^{-3} Ci	10^{-2} Ci	0.1 Ci	22,000 $Q^{2/3}$

Table 41. RADIOTOXICITY VERSUS LEVELS ABOVE WHICH VARIOUS SAFEGUARDS MAY BE REQUIRED[6] (*Continued*)

Radionuclides	Procedures							
	Personnel Monitoring and/or Appropriate Shielding vs. External Gamma Radiation	Occasional Excretion Radioassay Spot Checks of Operating Personnel	Routine Excretion Assay of All Operating Personnel	Emergency Dosimeters Worn to Measure High External Doses	Routine Environmental Monitoring of Site and Community	Preplanned Written Emergency Procedures and Drills	Written Routine Operating Procedures	Written Preoperational Analysis of Maximum Credible Accidents
Group I								
^{3}H		10 Ci	10^{2} Ci		10^{3} Ci	10^{4} Ci	10^{6} Ci	10 Ci
^{14}C		10 Ci	10^{2} Ci		10^{3} Ci	10^{4} Ci	10^{6} Ci	10 Ci

Table 41. RADIOTOXICITY VERSUS LEVELS ABOVE WHICH VARIOUS SAFEGUARDS MAY BE REQUIRED[6] (*Continued*)

Radionuclides	Procedures							
	Personnel Monitoring and/or Appropriate Shielding vs. External Gamma Radiation	Occasional Excretion Radioassay Spot Checks of Operating Personnel	Routine Excretion Assay of All Operating Personnel	Emergency Dosimeters Worn to Measure High External Doses	Routine Environmental Monitoring of Site and Community	Preplanned Written Emergency Procedures and Drills	Written Routine Operating Procedures	Written Preoperational Analysis of Maximum Credible Accidents
Group II								
^{82}Br		1 Ci	10 Ci		10^2 Ci	10^3	10^5 Ci	1 Ci
^{51}Cr	0.50 Ci	1 Ci	10 Ci	50 Ci	10^2 Ci	10^3	10^5 Ci	1 Ci
^{55}Fe		1 Ci	10 Ci		10^2 Ci	10^3	10^5 Ci	1 Ci
Group III								
^{35}S		0.1 Ci	1 Ci		10 Ci	10^2 Ci	10^4 Ci	0.1 Ci
^{198}Au	0.40 Ci	↑	↑	40 Ci	↑	↑	↑	↑
^{47}Ca								
^{132}I								
^{141}Ce								
Mixed Fission* Products	0.10 Ci			10 Ci				
^{85}Sr								
^{140}La								
^{95}Nb								
^{65}Zn								
^{58}Co		↓	↓		↓	↓	↓	↓
^{59}Fe	0.20 Ci	0.1 Ci	1 Ci	20 Ci	10 Ci	10^2 Ci	10^4 Ci	0.1 Ci

Table 41. RADIOTOXICITY VERSUS LEVELS ABOVE WHICH VARIOUS SAFEGUARDS MAY BE REQUIRED[6] *(Continued)*

Radionuclides	Procedures							
	Personnel Monitoring and/or Appropriate Shielding vs. External Gamma Radiation	Occasional Excretion Radioassay Spot Checks of Operating Personnel	Routine Excretion Assay of All Operating Personnel	Emergency Dosimeters Worn to Measure High External Doses	Routine Environmental Monitoring of Site and Community	Preplanned Written Emergency Procedures and Drills	Written Routine Operating Procedures	Written Preoperational Analysis of Maximum Credible Accidents
Group IV								
^{181}Hf		10^{-2} Ci	0.1 Ci		1 Ci	10 Ci	10^{3} Ci	10^{-2} Ci
^{147}Pm	10.00 Ci	↑	↑	1,000 Ci	↑	↑	↑	↑
^{32}P	10.00 Ci			1,000 Ci				
^{140}Ba	0.05 Ci			5 Ci				
^{234}Th								
^{85}Kr	50.00 Ci			5,000 Ci				
^{192}Ir	0.02 Ci			20 Ci				
^{36}Cl								
^{91}Y								
^{182}Ta								
^{45}Ca	10.00 Ci			1,000 Ci				
^{89}Sr								
^{137}Cs				30 Ci				
^{60}Co	0.30 Ci			10 Ci				
^{144}Ce	0.10 Ci			5 Ci				
^{126}I	0.05 Ci							
^{154}Eu								
^{131}I	0.40 Ci	↓	↓	40 Ci	↓	↓	↓	↓
^{170}Tm	25.00 Ci	10^{-2} Ci	0.1 Ci	2,500 Ci	1 Ci	10 Ci	10^{3} Ci	10^{-2} Ci
Group V								
^{129}I	100.00 Ci	10^{-3} Ci	10^{-2} Ci	10,000 Ci	0.1 Ci	1 Ci	10^{2} Ci	10^{-3} Ci
^{99}Tc		10^{-3} Ci	10^{-2} Ci		0.1 Ci	1 Ci	10^{2} Ci	10^{-3} Ci

Table 41. RADIOTOXICITY VERSUS LEVELS ABOVE WHICH VARIOUS SAFEGUARDS MAY BE REQUIRED[6] (*Continued*)

Radionuclides	Procedures							
	Personnel Monitoring and/or Appropriate Shielding vs. External Gamma Radiation	Occasional Excretion Radioassay Spot Checks of Operating Personnel	Routine Excretion Assay of All Operating Personnel	Emergency Dosimeters Worn to Measure High External Doses	Routine Environmental Monitoring of Site and Community	Preplanned Written Emergency Procedures and Drills	Written Routine Operating Procedures	Written Preoperational Analysis of Maximum Credible Accidents
Group VI								
^{223}Ra		10^{-4} Ci	10^{-3} Ci		10^{-2} Ci	0.1 Ci	10 Ci	10^{-4} Ci
^{210}Po	10.00 Ci			1,000 Ci				
^{227}Th		↕	↕		↕	↕	↕	↕
^{90}Sr	10.00 Ci			1,000 Ci				
^{210}Pb								
^{242}Cm	1.00 Ci			100 Ci				
^{233}U	50.00 Ci			5,000 Ci				
^{235}U (+1% ^{234}U)								
^{238}U+								
^{Natural}U								
^{232}Th+								
^{Natural}Th		10^{-4} Ci	10^{-3} Ci		10^{-2} Ci	0.1 Ci	10 Ci	10^{-4} Ci
Group VII								
^{147}Sm		10^{-5} Ci	10^{-4} Ci		10^{-3} Ci	10^{-2} Ci	1 Ci	10^{-5} Ci
^{144}Nd		↕	↕		↕	↕	↕	↕
^{226}Ra								
^{244}Cm		10^{-5} Ci	10^{-4} Ci		10^{-3} Ci	10^{-3} Ci	1 Ci	10^{-5} Ci

Table 41. RADIOTOXICITY VERSUS LEVELS ABOVE WHICH VARIOUS SAFEGUARDS MAY BE REQUIRED[6] (*Continued*)

Radionuclides	Procedures							
	Personnel Monitoring and/or Appropriate Shielding vs. External Gamma Radiation	Occasional Excretion Radioassay Spot Checks of Operating Personnel	Routine Excretion Assay of All Operating Personnel	Emergency Dosimeters Worn to Measure High External Doses	Routine Environmental Monitoring of Site and Community	Preplanned Written Emergency Procedures and Drills	Written Routine Operating Procedures	Written Preoperational Analysis of Maximum Credible Accidents
Group VIII								
^{243}Am		10^{-6} Ci	10^{-5} Ci		10^{-4} Ci	10^{-3} Ci	0.1 Ci	10^{-6} Ci
^{241}Am	0.25 Ci	↑	↑	25 Ci	↑	↑	↑	↑
^{237}Np								
^{227}Ac								
^{230}Th	1.00 Ci			100 Ci				
^{242}Pu								
^{238}Pu	0.50 Ci			50 Ci				
^{240}Pu	10.00 Ci†	↓	↓	1,000 Ci†	↓	↓	↓	↓
^{239}Pu		10^{-6} Ci	10^{-5} Ci		10^{-4} Ci	10^{-3} Ci	0.1 Ci	10^{-6} Ci

Note: The curie levels for protection against inhalation and contamination are intended for dry, dusty materials that may be easily dispersed in concentrated form. For liquids, or where active material will be diluted by other materials, the above safeguard levels may be raised by factors of 10 or more. For simple storage of stock solutions, or where operations are conducted only with materials of specific activity much less than 0.1 microcurie per milligram, multiply by 100 or more, depending on the nature of the material and the particular combination of safeguards selected (see text).

* For mixed gross fission products of 0-to-4-year operation, the overall relative hazard per curie changes relatively slowly with decay time for decay times shorter than 30 days, although for very short decay times (<1 day) the thyroid dose predominates (see Brodsky, A., Criteria for Acute Exposure to Mixed Fission-Product Aerosols, *Health Phys.*, 11: 1017–1032, 1965).

† Based on criticality.

[a] Insoluble materials.

[b] Based on gamma dose rates.

[c] In the exhaust from active atmosphere.

[d] In the active exhaust.

[e] In work areas.

[f] To protect public.

[g] Distance beyond which cloud dose is less than 15 rem for Q curies released, where Q = fc for C curies in process.

From: Brodsky, A., Determining Industrial Hygiene Requirements for Installations Using Radioactive Materials. *Amer. Ind. Hyg. Ass. J.*, 26: 294–310, 1965.

munities either during routine or accident conditions; hood or glove box construction details; doors and interlocks for preventing inadvertent entry into high-radiation areas; remote-handling equipment; storage facilities; and decontamination and waste disposal facilities in relation to expected levels of waste, including a description of instrumentation for monitoring all waste effluents.

III. A Description of the Site.

Include: a map of the area showing the location of the site and indicating the use to which the surrounding land is put (e.g., industrial, commercial, agricultural, residential); location of sources of potable or industrial water supply, watershed areas, and public utilities; and a scale plot plan of the site showing the proposed location of the facility in which the radioactive materials will be stored or used. Exclusion area boundaries should be well defined, and means of controlling access to the exclusion area should be specified. Meteorological, hydrological, geological, seismological, and population data needed to evaluate any possible radioactivity hazards to the public should also be included.

IV. A Description of the Organization and Qualifications of Personnel.

This should include: a chart showing the organizational relationships between managers, supervisors, operators, and radiation-safety personnel concerned with operations involving radioactive materials; the composition of cognizant committees and their responsibilities, authority, frequency of meetings, and extent of review of uses and users; operations for which detailed operating procedures will be written, and operating procedures themselves where appropriate; control of procurement, inventory, and records; and the qualifications of radiation-safety personnel and operating personnel.

V. A Description of Standard Procedures Affecting Radiation Safety.

This should include, but not necessarily be limited to: procedures for preoperational checking of all facilities and equipment important to radiation safety; procedures for initiating dry runs on any new processes to be carried out; procedures for routine maintenance and calibration of radiation instruments, alarms, and emergency devices in relation to their required sensitivities or responses; programs for personnel training in radiation safety; procedures for preventing and controlling fires or explosions; procedures—such as locked controls or doors, check lists, and close supervision—for minimizing operational mishaps; and plans for investigating unusual or unexpected incidents. The planned radiation-safety program should be described, including any procedures for: environmental surveys of air, water, soil, and vegetation in the vicinity of the facility, both before and periodically after radioactive material is received; receiving and unloading material; storing radioactive materials; labeling and restricting radiation areas in accordance with 10 CFR, Part 20, or other applicable federal, state, or local regulations; monitoring radiation levels and concentrations of radioactive materials in air and water, both in controlled and uncontrolled areas; monitoring and recording cumulative amounts of radioactive materials in air and liquid effluents; external and internal dosimetry of personnel; decontamination of facilities and personnel; leak-testing of sources; packaging and shipping radioactive materials; traffic control of materials and personnel to and from contaminated areas; and disposing of radioactive wastes.

VI. A Description of Emergency Plans for Handling Radiation Incidents.

Plans to be carried out in the event of possible unexpected incidents should be presented in detail. These plans should be related to plausible incidents that could occur as a result of operational mistakes or equipment failures in the proposed operations, or as a result of fire, electric-power failure, flood, earthquake, storm, strike, riot, or air raid, as applicable to the proposed facility and site. The emergency plans should include, but not necessarily be limited to: procedures for detecting an incident and activating emergency plans; emergency organization and command responsibilities; coordination and communication between various emergency teams, such as fire, medical, health physics, and rescue; coordination with local civil authorities; procedures for evacuating personnel and processing them at a decontamination and first-aid center; procedures or facilities for preventing the dispersal of radioactivity to farms or communities in the vicinity; dosimetry and follow-up procedures on personnel exposed to high radiation doses or high concentrations of radioactivity; means for detecting and removing wound contamination; procedures for reentry and recovery of facilities; and instruction and drill of personnel in emergency procedures.

VII. An Analysis of Credible Accidents and Their Effects.

The possible effects of postulated extreme and unexpected accidents within the possibilities and limitations of the proposed operations should be analyzed in detail. This includes calculations of estimated doses received and numbers of persons affected, both in the facility and in the surrounding community. Alternate accidents should be described where they are possible and where the effects are not delimited by those of accidents already described. After each description of the effects of an incident, the procedures or facilities that will serve to prevent or minimize these effects should be indicated.

In most facilities, some of the considerations listed above would not be pertinent. Furthermore, for quantities of radionuclides below the respective amounts shown in Table 41 for various facilities, equipment, and procedures, the individual safeguards indicated in this table would probably not be required, even if the radionuclide were to be handled in its most hazardous, dispersible form. Appropriate multiplication factors are suggested in the footnote of Table 41 and in Reference 2 for multiplying the quantities in the table in cases where the radioactive material is in liquid form, or in more diluted forms where the possibility of inhaling hazardous quantities is reduced even in the event of an accident involving total release of the material.

It should be noted that the radionuclide groups covered in Table 41 range over about eight orders of magnitude of radiotoxicity,[6] rather than the four groups often recommended previously,[2] since it has been found that the order of the radionuclides in terms of maximum dose per microcurie inhaled, or in terms of MPC_{air}, ranges over about eight orders of magnitude in the same fashion.[6] For most of these radionuclides the specific activities of the pure radionuclide are so high that, in practice, the maximum dose per microcurie inhaled is indexed as the only fundamental way of ranking these nuclides without the addition of extrinsic considerations of the specific chemical forms and processes unique to each facility. Such an order automatically takes into account a certain amount of ingestion, as described earlier in the presentation of the ICRP lung models.[7,8]

The rationale behind the selection of the various levels of radioactivity above which the various safeguards might be required is outlined in Reference 6; it is based on a quantitative consideration of measurements of typical amounts of radioactivity resuspended from contaminated surfaces as well as on experience with the safety factors provided by various safeguards and meteorological dispersion. Thus, although some professional experience would be necessary in designing suitable facilities combining the various safeguards that may be required, the table may be used as a guide to help avoid expensive over-design as well as the possibility of overlooking needed safeguards for work with higher levels of potentially radiotoxic materials. Basically, the table serves as a starting point or baseline from which hazard evaluation and facility design and operations may be planned in a consistent and safe manner, even though the radionuclides vary widely in their fundamental radiotoxicity. Considerations of probability of intake, systematic absorption, and retention in critical organs may then be taken into account in order to reduce the requirements according to specific knowledge of operations to be conducted in the facility.[6]

The design of open hoods for handling radioactive materials is carried out according to the same principles of capturing contaminated air as that already developed for other industrial-hygiene purposes.[9,10] Generally, a face velocity of air at the opening of an ordinary laboratory hood would be about 150 feet per minute, to guard against backdrafts resulting from movement of materials within the hood. Face velocities should be checked regularly with a velometer. However, when materials are in a state of high radionuclide purity or specific activity, and when processes have a high potential for dispersing the material (e.g., dry, loose powder under mechanical agitation or pulverization, or experimental chemical procedures with a potential for volatilization or large energy release), completely enclosed operations within a "dry-box" or glove box have often been required for quantities in process above those given in the glove-box column of Table 41. Failure to provide complete containment when operating with loose radioactive materials above the levels indicated has on specific occasions resulted in significant personnel exposures. Limited experience with radiation-accident cases lends some validation to the semi-empirical methods of derivation of Table 41.[6]

A typical radioisotope hood is shown in Figure 14, and a sealed glove box with exhaust fan and an absolute filter in the intake is shown in Figure 15. For work with extremely hazardous quantities of radionuclides in loose form, an additional filter may also be placed in the dry-box exhaust preceding the blower. Also, provisions for filling the dry-box with a suitable inert gas are made when handling pyrophoric or potentially combustible materials. Special procedures are required when replacing the gloves of a glove box, or when "bagging" materials or wastes in or out of the box through the double airlock.[11,12]

The arrangement of hoods, dry-boxes, and other laboratory furnishings required in a radiochemical laboratory needs special planning, preferably with the assistance of an engineer experienced in operations with radioactive materials. Figure 16 shows the layout of a simple radiochemical laboratory, such as one might use, for example, for mixed-fission-product-separations chemistry below about 10 millicuries, or for plutonium chemistry with less than 1 microcurie in process;[6] it illustrates how the general air flow in the laboratory should be directed towards the hood, where higher amounts of radioactive contamination are likely to be found, and away from the areas that are to be kept free of radioactivity. Storage areas for radioactivity are shown, as well as waste containers for both radioactive and nonradioactive materials.

In selecting furniture for such a laboratory, consideration should be given to using surfaces that may be easily decontaminated when necessary.[13] Paints forming coatings that may be stripped from surfaces as necessary are commercially available. Floors should generally be covered with a paint or plastic coating free of cracks and may be covered with wax to simplify decontamination procedures.

Although federal and state regulations allow only very small amounts of radioactivity to be disposed of through sanitary sewers, plumbing should be planned to insure that there are no connections between radioactive waste lines and drinking water supplies. For production facilities where larger amounts of radioactive material may need to be washed down drains after an accident, or where storage of larger quantities of radioactive waste may be required, special waste-treatment facilities and waste-storage tanks must be designed.[14] Generally, sanitary engineers who have specialized in radioactive-waste treatment should be consulted in the design of chemical processes and equipment for handling larger amounts of wastes. Smaller amounts of waste may be stored in drums for collection by AEC-licensed commercial waste-disposal firms.

There are various items of special equipment for use in handling radioactive materials at a distance, even for the smaller laboratories, when the quantities of material in process emit sufficient beta or gamma radiation to require tongs, manipulators, or shields, to reduce external radiation exposures. Most of the items available for ordinary radiochemical laboratories are commercially available and may be found advertised in the journals servicing the nuclear professions.

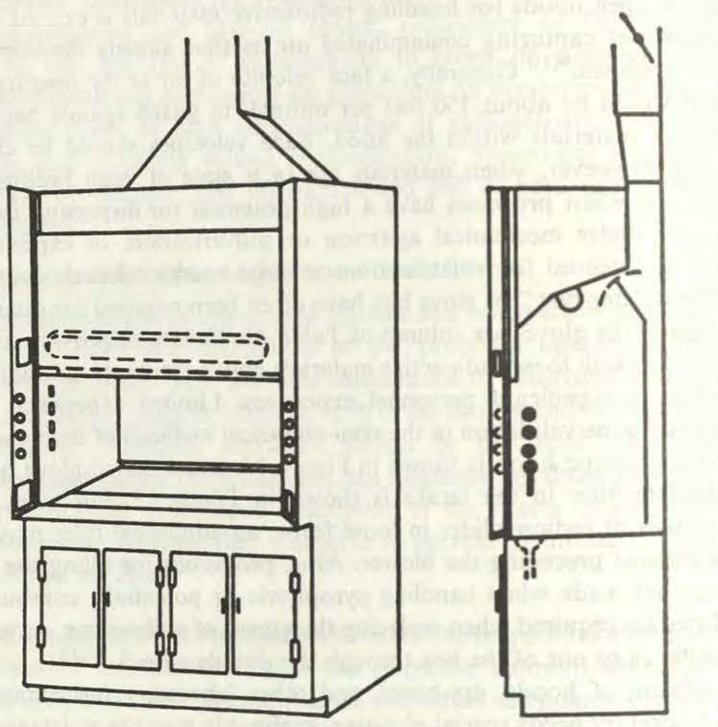

FIGURE 14. Radioisotope Hood.
(From: Blatz, H., ed., *Radiation Hygiene Handbook*, p. 9-5. McGraw-Hill, New York, 1959.)

When the amounts of radioactive material emit bremsstrahlung or gamma radiation in such intensities that massive shielding would be required between the operator and the material in process, operations may be carried out inside a "hot cell" or "cave". In this case the operator would handle the materials and equipment through special mechanical manipulator arms that provide a sense of touch directly to the operator;[15] glove boxes may also be utilized within these hot cells, to avoid excessive contamination of the hot cell by personnel entering it from time to time in the event that processes must be changed. In some cases disposable dry-boxes may be utilized for economy in disposing of the contaminated wastes when the operations are completed.[16]

The provision of appropriate radiation shielding for facilities where large radiation levels are produced is a subject that has received intensive investigation by specialists. For shielding such complex radiation fields as those originating from a nuclear reactor, nuclear engineers must draw on complex theoretical considerations of radiation scattering and absorption, as

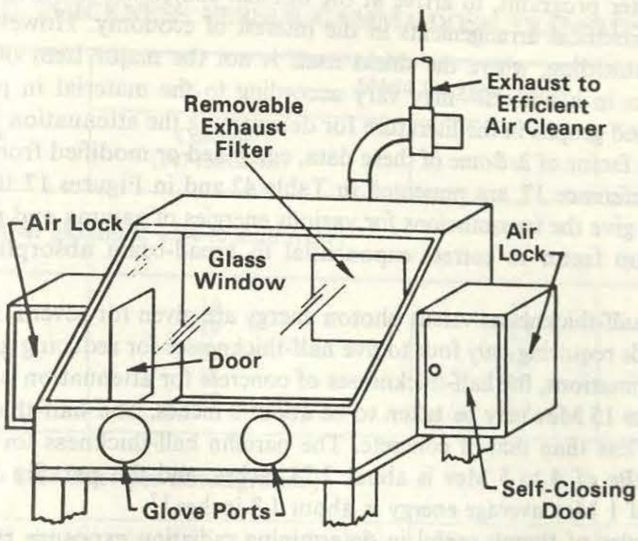

FIGURE 15.
Typical Glove-Box Design for Handling of Alpha and Beta Materials.
(From: Blatz, H., ed., *Radiation Hygiene Handbook*, p. 9-9. McGraw-Hill, New York, 1959.)

Air flow = 50 cfm/sq. ft. of open-door area, entry loss = 0.25 VP plus dirty-filter resistance, duct velocity = 3,500 fpm. Filters: 1) inlet dust filters in doors, 2) prefilter at exhaust connection to hood, and 3) after cleaner for final air cleaning. All facilities totally enclosed in hood; exterior controls may be advisable. Arm-length rubber gloves are sealed to glove port rings; strippable plastic on interior and air cleaner on exhaust may be used, to facilitate decontamination of the system. Filter units may be installed in the doors, to allow the air flow necessary for burners, etc. (American Conference of Governmental Hygienists, *Industrial Ventilation Manual*.)

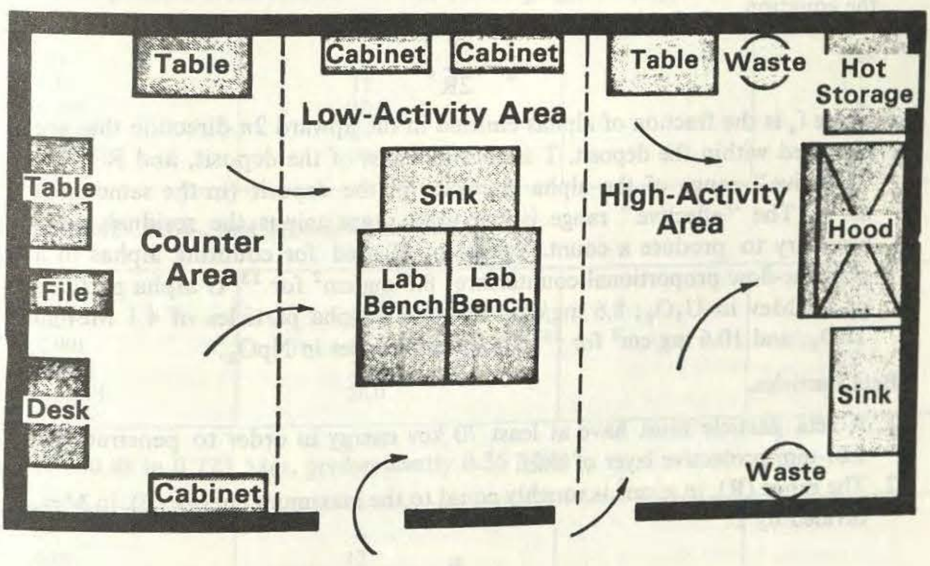

FIGURE 16.
Simple Radiochemical Laboratory.
(From: Blatz, H., ed., *Radiation Hygiene Handbook*, p. 9-9. McGraw-Hill, New York, 1959.)

well as on computer programs, to arrive at the optimal combination of materials and thicknesses and of geometrical arrangements in the interest of economy. However, for designing most laboratory shielding, where the shield itself is not the major item of expense and its functions—such as in a hot cell—may vary according to the material in process, there are abundant tables and graphs in the literature for determining the attenuation of most shielding materials within a factor of 2. Some of these data, combined or modified from various sources in literature in Reference 17, are presented in Table 42 and in Figures 17 through 20. These tables and figures give the transmissions for various energies of gamma and neutron radiation where the build-up factor to correct exponential to broad-beam absorption is taken into account.

In Table 43 half-thicknesses versus photon energy are given for several materials, for use in designing shields requiring only four to five half-thicknesses for reducing gamma dose rates. For crude approximations, the half-thicknesses of concrete for attenuation of pile neutrons or fast neutrons up to 15 Mev may be taken to be about 3 inches. The half-thickness of water is about 10 percent less than that of concrete. The paraffin half-thickness for neutrons spectra from PuBe or RaBe of 4 to 5 Mev is about 2.73 inches, and the paraffin half-thickness for fission neutrons of 1 Mev average energy is about 1.3 inches.[17]

Additional rules of thumb useful in determining radiation exposure rates and required shielding protection are given below.

RULES OF THUMB

Alpha Particles.

1. An alpha particle of 7.5 Mev just penetrates the 0.07-mm minimum protective layer of skin.
2. Plutonium has an alpha activity of about 140,000 alphas per minute per microgram; natural-uranium activity is 1.5 alphas per minute per microgram; ^{238}U emits about 0.741 alpha per minute per microgram; ^{232}Th emits 0.247 alpha per minute per microgram; and ^{237}Np emits 1,519 alphas per minute per microgram.
3. Self-absorption of a thin layer of alpha-emitting deposit may be estimated by the equation

$$f_a = \frac{T}{2R},$$

where f_a is the fraction of alphas emitted in the upward 2π direction that are absorbed within the deposit, T is the thickness of the deposit, and R is the "effective" range of the alpha particles in the deposit (in the same units as T). The "effective" range is the total range minus the residual range necessary to produce a count. Values of R used for counting alphas in a methane-flow proportional counter are: 8.6 mg/cm^2 for ^{238}U alpha particles of 4.2 Mev in U_3O_8; 8.6 mg/cm^2 for ^{232}Th alpha particles of 4.1 Mev in ThO_2; and 10.6 mg/cm^2 for ^{237}Np alpha particles in NpO_2.

Beta Particles.

1. A beta particle must have at least 70 kev energy in order to penetrate the 0.07-mm protective layer of skin.
2. The range (R), in g/cm^2 is roughly equal to the maximum energy (E), in Mev, divided by 2:

$$=R\frac{E}{2}.$$

3. The range of beta particles in air is about 12 feet per Mev.

Table 42.
SHIELD THICKNESS VERSUS GAMMA-DOSE TRANSMISSION[17]

Broad-Beam Transmission	Shield Thickness, inches		
	Concrete* (147 lbs/cu. ft.)	Iron	Lead
Radium (11 principal gammas, 0.24 to 2.20 Mev)			
0.1	10	3.1	1.6
0.01	19	6.2	3.5
0.001	28	9.1	5.5
0.0001	38	12.0	7.8
0.00001	47	15.3	10.2
Cobalt-60 (1.33 + 1.17 Mev per disintegration)			
0.1	11	3.2	1.7
0.01	19	6.0	3.3
0.001	27	8.8	4.8
0.0001	35	11.4	6.5
0.00001	43	14.6	8.1
Cesium-137 (0.66 Mev)			
0.1	8.5	2.6	0.85
0.01	15	4.7	1.7
0.001	22	6.8	2.5
0.001	28	8.9	3.4
0.00001	34	11.0	4.2
Iridium-192 (gammas from 0.13 to 0.87 Mev, averaging 0.3 Mev)			
0.1	7		0.48
0.01	13		1.1
0.001	18.3		1.9
0.0001	24		2.6
0.00001	30		3.5
Gold-198 (0.41-, 0.68-, and 1.1-Mev gammas)			
0.1	6.6		0.35
0.01	12.0		0.83
0.001	17.4		1.7
0.0001	22.6		2.8
0.00001	28.0		4.3
Iodine-131 (0.08 to 0.723 Mev, predominantly 0.36 Mev)			
0.1	6		
0.01	12		
0.001	18		

* After several mean free paths, each ten inches of concrete reduce the radiation by another factor of 10.

Table 42. (*Continued*)
SHIELD THICKNESS VERSUS GAMMA-DOSE TRANSMISSION[17]

Barium-140 + Lanthanum-140 (0.030 to 2.5 Mev, averaging about 1.6 Mev)

Broad-Beam Transmission	Water	Aluminum	Iron	Lead	Uranium
0.1	25	9.8	3.4	1.6	0.87
0.01	44	18	6.4	3.4	2.0
0.001	64	27	9.2	5.2	3.0
0.0001	81	35	11.8	7.1	4.1
0.00001	104	44	14.8	9.0	5.2
0.000001		51			6.3

From: Brodsky, A. and Beard. G. V., *A Compendium of Information for Use in Controlling Radiation Emergencies, TID-8206* (Rev.). By permission of the U.S. Atomic Energy Commission, Washington, D.C.

Table 43.
HALF-THICKNESS VERSUS PHOTON ENERGY FOR SEVERAL MATERIALS[17]

Photon Energy, Mev	Half-Thickness, inches			
	Water	Concrete	Iron	Lead
0.2	2.0	0.8	0.28	0.06
0.5	3.0	1.1	0.45	0.17
1.0	4.1	1.7	0.63	0.35
1.5	4.7	2.0	0.70	0.46
2.0	5.7	2.3	0.82	0.53
2.5	6.8	2.7	0.88	0.57
3.0	7.7	3.0	0.92	0.59
4.0	8.4	3.3	1.02	0.59
5.0	9.2	3.7	1.10	0.58

From: Brodsky, A. and Beard, G. V., *A Compendium of Information for Use in Controlling Radiation Emergencies, TID-8206* (*Rev.*). By permission of the U.S. Atomic Energy Commission, Washington, D.C.

4. The air dose rate at 1 foot from a beta point source is about 200 *C* rads per hour, neglecting self-absorption and air absorption, where *C* is the number of curies. Variation with energy is small for most beta emitters.
5. Readings on Geiger-Müller tube survey meters calibrated with gamma radiation in mr/hr must be multiplied by 2 to measure beta radiation in mrad/hr with the window open.
6. Beta-ray surface dose rates for several materials are given in Table 44.
7. The fallout beta dose to the skin from contact with deposited fallout within 200 days after detonation is up to 150 times the gamma dose rate in rads per hour at 3 feet above ground. (Project 37.2, Operation Teapot, May 1955.)
8. The dose to a 30-g adult thyroid from 1 microcurie of ^{131}I is about 1 rad delivered within several weeks after intake.
9. The beta activity from fission products produced in a short-criticality burst is: beta activity = $294\ t^{-1.2}$ curies per watt-second, where t is the time in seconds since the burst, ranging from 10 seconds to 100 days. For a weapon in the kiloton-TNT range, this becomes: beta activity = $1.17 \times 10^{13}\ t^{-1.2}$ curies/kiloton TNT.

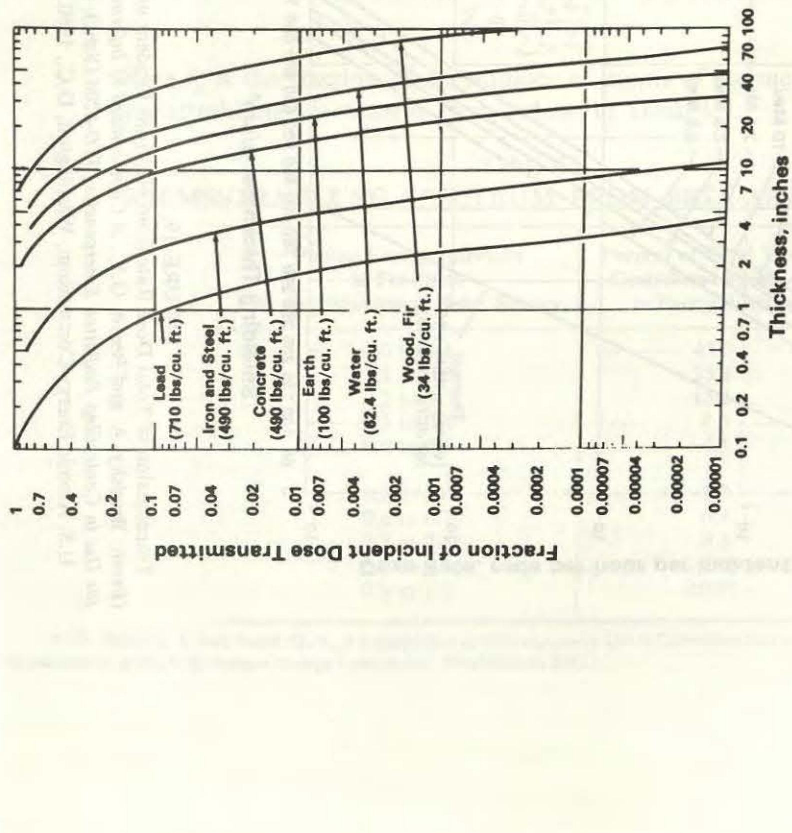

FIGURE 17.

Transmission of Fission Product Gamma Radiation in Several Shield Materials.

(From: Brodsky, A. and Beard, G. V., *A Compendium of Information for Use in Controlling Radiation Emergencies, TID-8206* (Rev.), p. 80. U.S. Atomic Energy Commission, Washington, D.C., 1960.)

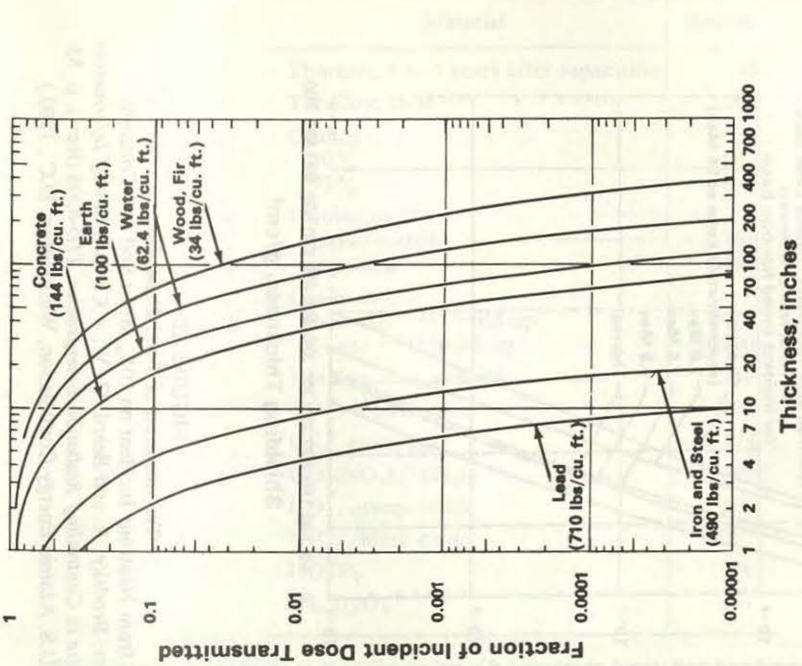

FIGURE 18.

Transmission of Prompt Gamma Radiation in Several Shield Materials.

(From: Brodsky, A. and Beard, G. V., *A Compendium of Information for Use in Controlling Radiation Emergencies, TID-8206* (Rev.), p. 81. U.S. Atomic Energy Commission, Washington, D.C., 1960.)

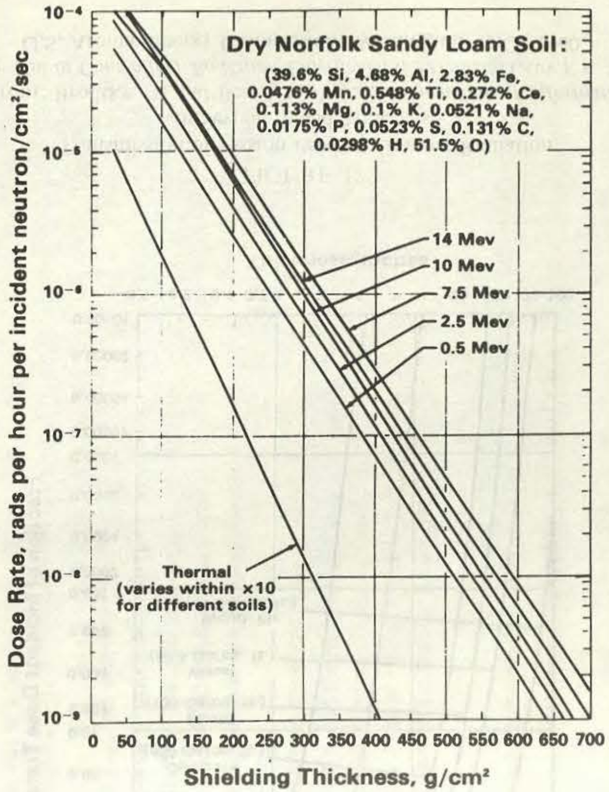

FIGURE 19.
Transmission of Total Dose Rate from Neutrons Incident on Soil.
(From: Brodsky, A. and Beard, G.V., *A Compendium of Information for Use in Controlling Radiation Emergencies, TID-8206* (Rev.), p. 82. U.S. Atomic Energy Commission, Washington, D.C., 1960.)

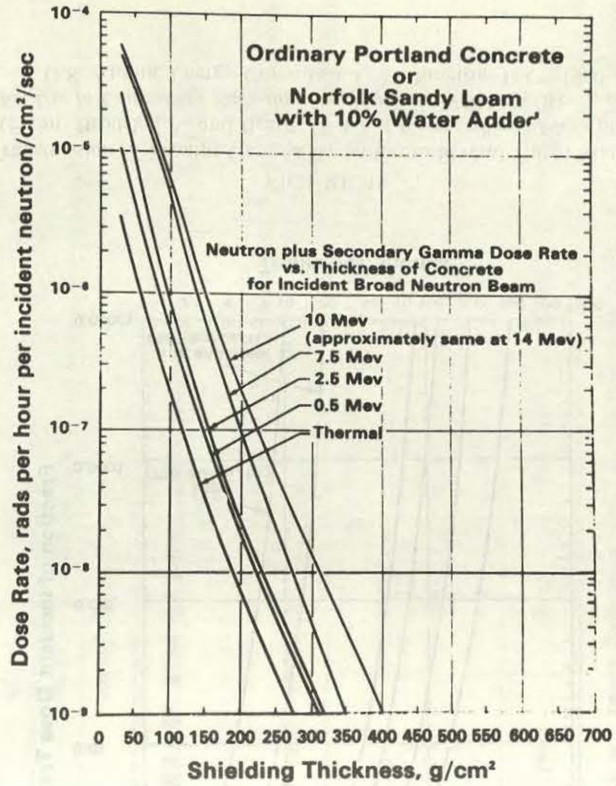

FIGURE 20.
Transmission of Total Dose Rate from Neutrons Incident on 10% Moist Soil and Concrete.
(From: Brodsky, A. and Beard, G. V., *A Compendium of Information for Use in Controlling Radiation Emergencies, TID-8206* (Rev.), p. 83. U.S. Atomic Energy Commission, Washington, D.C., 1960.)

Table 44. BETA-RAY SURFACE DOSE RATES[17]

Material	mrad/hr
Thorium, 4 to 5 years after separation	40
Tuballoy, D-38	200
Oralloy	
40%	180
93%	140
Plutonium-239	
nickel coated	360
uncoated	440
Uranium-233	
1-month ^{232}U build-up	7,000
1-year ^{232}U build-up	58,000
Uranium slug, natural	233
UO_2, brown oxide	207
UF_4, green salt	179
$UO_2(NO_3)_2 \cdot 6H_2O$	111
UO_3, orange oxide	204
U_3O_8, black oxide	203
UO_2F_2	176
$Na_2U_2O_7$	167

From: Brodsky, A. and Beard, G. V., *A Compendium of Information for Use in Controlling Radiation Emergencies, TID-8206* (Rev.). By permission of the U.S. Atomic Energy Commission, Washington, D.C.

Bremsstrahlung.

1. The energy radiated as radiation per beta ray absorbed is:

$$B = 1.23 \times 10^{-4}(\bar{Z} + 3)E^2 \text{ Mev/beta},$$

where E is the maximum beta energy, in Mev, and $\bar{Z}$ is the effective atomic number given by

$$\bar{Z} = \frac{\sum f_a Z_a^2}{\sum f_a Z_a},$$

where f_a is the fraction of the number of atoms of atomic number Z_a. The bremsstrahlung spectrum is given below, in Table 45.

Table 45. BREMSSTRAHLUNG SPECTRUM FROM BETA ABSORPTION[17]

Photon Energy Intervals in Fractions of the Maximum Beta Energy	Percent of Total Intensity Contributed by Photons in Energy Intervals
0.0 to 0.1	43.5
0.1 to 0.2	25.8
0.2 to 0.3	15.2
0.3 to 0.4	8.3
0.4 to 0.5	4.3
0.5 to 0.6	2.0
0.6 to 0.7	0.7
0.7 to 0.8	0.2
0.8 to 0.9	0.03
0.9 to 1.0	<0.01

From: Brodsky, A. and Beard, G. V., *A Compendium of Information for Use in Controlling Radiation Emergencies. TID-8206* (Rev.). By permission of the U.S. Atomic Energy Commission, Washington, D.C.

2. When beta particles from a 1-curie source of ^{90}Sr-^{90}Y are absorbed in aluminum, the bremsstrahlung intensity is approximately equal to the gamma intensity from 12 mg of radium. The average bremsstrahlung energy is about 300 kev (Haybittle, *Phys. Med. Biol.*, 1(3): 270, 1956).
3. The bremsstrahlung from a 1-curie ^{32}P aqueous solution in a glass bottle is about 3 mr/hr at 1 meter.

Gamma Radiation.

1. The gamma-ray dose rates from various radiosotopes are given in Table 37 in the preceding chapter.
2. As a rule of thumb, accurate to ± 12 percent from 0.07 to 2.0 Mev, the dose rate at 1 foot from a point source of gamma radiation is: r/hr at 1 foot = 5.64 CE, where C is the number of curies of the parent nuclide, and E is the total gamma energy, in Mev, emitted per disintegration of the parent. Rounding off, the dose rate to within ± 20 percent from 0.07 to 4 Mev is: r/hr at 1 foot = 6 CE.
3. The dose rate versus distance from a 100-curie ^{60}Co source, taking into account inverse-square attenuation, air absorption, and build-up factor for air at normal temperature and pressure, is given in Table 46.

Table 46.
DOSE RATE VERSUS DISTANCE FROM 100 CURIES ^{60}Co[17]

Distance, feet	Dose Rate, r/hr
1	1,500
10	15
50	0.6
100	0.15
400	0.0075
800	0.0012
1,000	0.0006

From: Brodsky, A. and Beard, G. V. *A Compendium of Information for Use in Controllling Radiation Emergencies, TID-8206* (Rev.). By permission of the U.S. Atomic Energy Commission, Washington, D. C.

4. The gamma activity of fission products produced in a nuclear burst may be expressed in equivalent curies according to the equation

$$\text{gamma activity} = 1.82\ t^{-1.2} \text{ curies per watt-second,}$$

where t is the time in seconds since the burst. This equation holds approximately between 10 seconds and 100 days following the burst. For kiloton-TNT-size bursts, this equation becomes

$$\text{gamma activity} = 7.3 \times 10^{12}\ t^{-1.2} \text{ curies/kiloton TNT.}$$

5. A deposition of 1 microcurie per square meter of ^{131}I on grass gives a gamma radiation level of about 0.003 mr/hr near ground level and results in about 0.1 microcurie per liter of milk from cows grazing in the area. A deposition of 1 megacurie of fission products per square mile gives a gamma dose rate of about 4 r/hr at 3 feet above ground. A deposition of 1 microcurie of fission products per square meter gives 10.6 μr/hr at 3 feet above ground.
6. The dose rate in a foxhole due to air-scattered radiation from a fallout field is 2 percent of the open-field dose rate per steradian of the sky viewed from the foxhole.
7. The backscattered intensity of ^{60}Co gamma radiation from a thick wall per square meter of the wall visible at both source and detector may be approximated by the equation

$$mr/hr/m^2 \text{ for } 1 \text{ kCi } ^{60}Co = \frac{4 \times 10^3}{D^2 d^2},$$

where D is the distance (in meters) of the source from the wall, and d is the distance (in meters) at which the backscattered dose rate is being measured. It is assumed that D and d are large compared to the dimensions of the irradiated area of the wall and that the gamma rays are scattered at angles greater than about 140°. For example, if a 10-kilocurie ^{60}Co source in a well-shielded collimator 10 meters from a thick concrete wall irradiated the wall with a beam area measuring 4 square meters at the wall, the dose rate at a point beside the collimator would be about 16 mr/hr from radiation scattered back from the wall.

Shelter Shielding.

The added shielding against fallout radiation to give an additional factor of 5 to a nominal basement shelter factor of 20, or a total factor of 100, is given in Table 47. The dose rate in a foxhole due to air-scattered radiation from a fallout field is 2 percent of the open-field dose rate per steradian of sky viewed from the foxhole.

Table 47.
SHELTER SHIELDING MATERIALS FOR ONE-FIFTH REDUCTION[17]

Material	Density, lbs/ft³	Thickness, inches
Wood (birch, oak, maple, etc.)	40	17.5
Earth, loose	75	9.3
Sand, dry	100	7.0
Brick, common	110	6.4
Concrete block, solid	140	5.0

From: Brodsky, A. and Beard, G. V., *A Compendium of Information for Use in Controlling Radiation Emergencies, TID-8206* (Rev.). By permission of the U.S. Atomic Energy Commission, Washington, D.C.

In operations requiring dry-boxes, usually one or more absolute filters will be required in the exhaust ventilation in order to insure a high degree of removal of radioactivity in exhaust air before its release to the environment. There are stringent federal and state regulations that require average concentrations in exhaust air to be lower than those specified in the table of regulatory maximum permissible concentrations for occupational exposure, presented earlier. These filters are generally designed to retain more than 99.97 percent of particulates of particle size greater than 0.3 microns and may be fairly fragile. Requirements for inspection, storage, handling, and installation have been proposed by the U.S. Atomic Energy Commission.[18] Figure 21 shows a filter damaged by moisture and by shipment.

The quantities of radionuclides requiring glove-box operations, absolute filters in the exhaust, and other special protective equipment and procedures are given in Table 41 for most of the radionuclides of concern. However, the values listed for mixed fission products pertain to a fuel irradiation time of 180 days and decay times of less than 30 days. Other quantities of fission products may be pertinent for longer operating times and longer decay times, where the radioactivity in curies represents longer half-lives and more radiotoxic fission, products. Estimates of requirements for the various fission product mixtures may be obtained with the assistance of Tables 22, 23, 24, and 25, and from Figure 11.[19]

In addition to absolute filters, larger chemical-processing installations or larger nuclear reactors may require continuous air samples, continuous exhaust-stack monitors, and even building containment or controlled leak rates, to protect the public and prevent a nuclear disaster in the event of an accident (see Table 41). Generally, a team of engineers, health physicists and industrial hygienists who have specialized in the design of such facilities must be consulted in order to deal appropriately with these problems. General recommendations may be found in more detail in the literature and in handbooks already available.[1] In some cases, a special site location may be required in the event of a release of radioactive material.

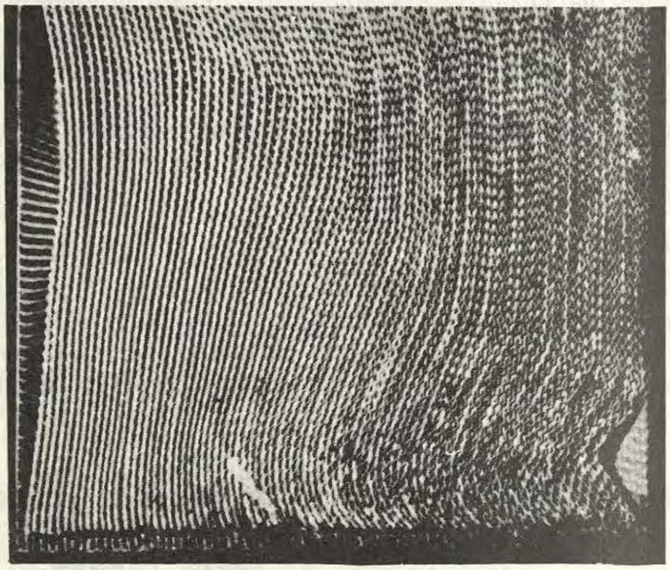

FIGURE 21.
Separators in Filter Units Absorbed Moisture;
Damage Aggravated by Shipment.
(From: Gilbert, H. and Palmer, G. H., *High-Efficiency Air Filter Units.* U.S. Atomic Energy Commission, Washington, D.C., 1961.)

Table 41 gives formulae for calculating the site radius for the release of Q curies of mixed fission products in order to give no more than 15 rem to any body organ, even under adverse meteorological conditions. These formulae have been calculated for a release at ground level, using the diffusion equations from Reference 20. The use of proper containment, filtration, or other safeguards may diminish the site radius required, depending on considerations of population density in the vicinity and of the maximum quantity and type of radioactivity that could be released accidentally. The appropriate regulatory agency should be consulted in regard to its policies on these matters when planning high-level operations. For assistance in estimating upper limits to the hazards of releasing various radionuclides, curves are presented in Figures 22 and 23, from Reference 6, for determining, under adverse conditions and for a ground release, the maximum number of curies inhaled versus distance per curie released and the maximum ground contamination at distance x. These curves are based on conservative dispersion parameters and a wind speed of only 1 meter per second. The ground deposition in curies per square meter per curie released at various distances from the point of release and along the center trajectory in the wind direction assumes an average particle deposition velocity of about 2×10^{-3} meters per second. Figures 22 and 23, together with previously given data on external dose rates of fission products per curie per square meter, allow upper-limit estimates of the probable land contamination problems and exposure rates following a nuclear incident.

The general levels of activity at which personnel monitoring and/or shielding is necessary in order to meet regulatory requirements as well as recommendations of various committees are also presented in Table 41. These quantities were taken as those that could produce a dose rate of about 10 mr/hr at one meter. Suitable protection at lower or higher levels than this may be more appropriate in special circumstances, depending on the experience of operating

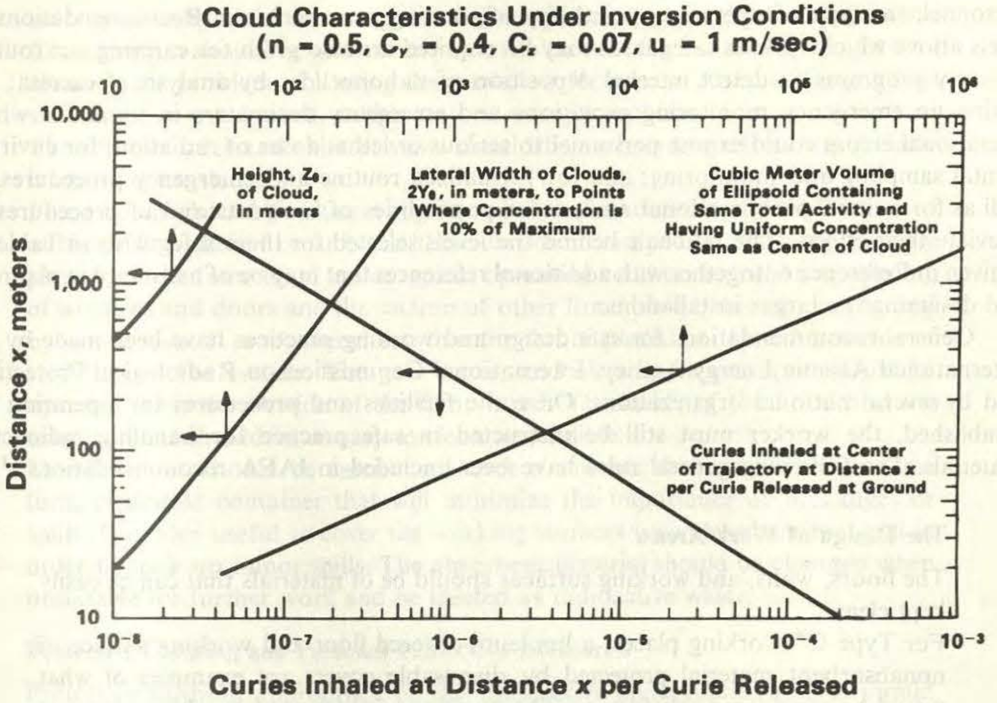

FIGURE 22.
Cloud Characteristics Under Inversion Conditions.
(From: Brodsky, A., Determining Industrial Hygiene Requirements for Installations Using Radioactive Materials. *Amer. Ind. Hyg. Ass. J.*, 26: 300, 1965.)

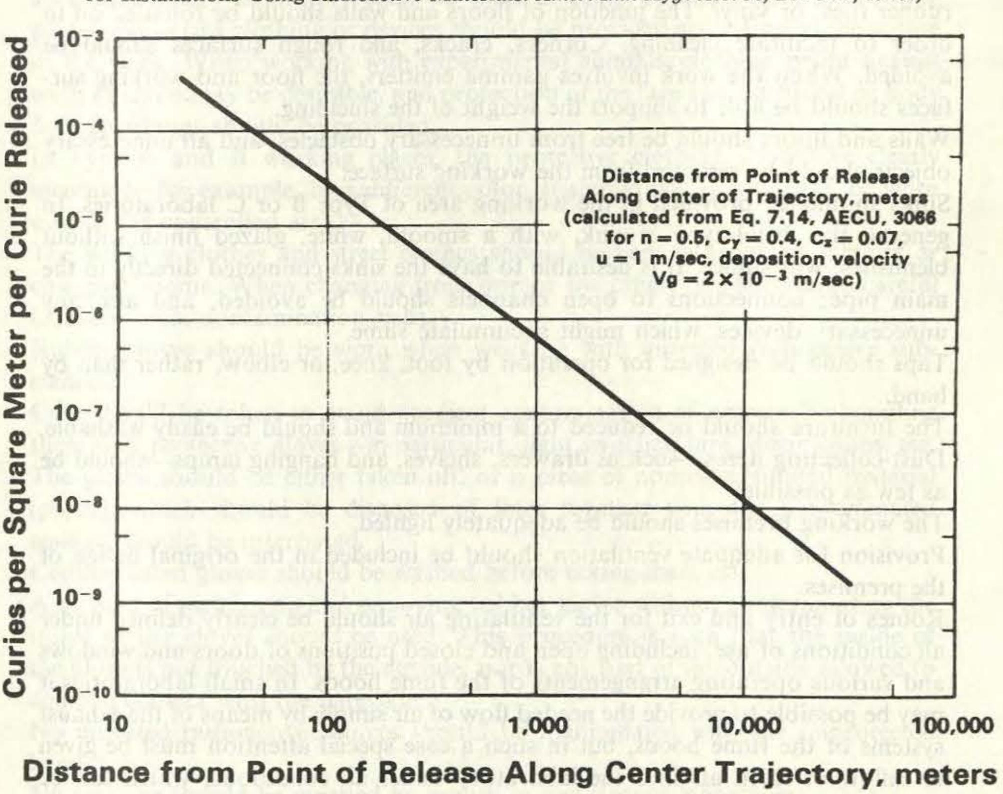

FIGURE 23.
Typical Deposition of Cloud Activity Plotted vs. Distance.
(From: Brodsky, A., Determining Industrial Hygiene Requirements for Installations Using Radioactive Materials. *Amer. Ind. Hyg. Ass. J.*, 26: 300, 1965.)

personnel, the type of operation, possibility of rotating personnel, etc. Recommendations of levels above which various safeguards may be required are also given for carrying out routine bioassay programs to detect internal deposition of radionuclides by analysis of excreta; for setting up emergency monitoring provisions and emergency dosimeters in situations where operational errors could expose personnel to serious or lethal doses of radiation; for environmental sampling and monitoring; and for formalized routine and emergency procedures, as well as for written preoperational analysis of possibilities of incidents and of procedures to alleviate their effects. The rationale behind the levels selected for these safeguards in Table 41 is given in Reference 6, together with additional references that may be of assistance in planning and designing the larger installations.

General recommendations for safe design and working practices have been made by the International Atomic Energy Agency, International Commission on Radiological Protection, and by several national organizations. Once the facilities and procedures for operation are established, the worker must still be instructed in safe practice for handling radioactive materials. The following general rules have been included in IAEA recommendations.[21,22]

The Design of Work Areas.

The floors, walls, and working surfaces should be of materials that can be easily kept clean.

For Type C* working places, a linoleum-covered floor and working surface of nonabsorbent material protected by disposable covers are examples of what would be considered satisfactory. The working surfaces must be able to support the weight of the necessary shielding against gamma radiation.

For Type B* working places, the walls and the ceilings should be covered with a washable, hard, nonporous paint, and the floor with such materials as linoleum, rubber tiles, or vinyl. The junction of floors and walls should be rounded off in order to facilitate cleaning. Corners, cracks, and rough surfaces should be avoided. When the work involves gamma emitters, the floor and working surfaces should be able to support the weight of the shielding.

Walls and floors should be free from unnecessary obstacles, and all unnecessary objects should be removed from the working surface.

Sinks should be provided in the working area of Type B or C laboratories. In general, the usual type of sink, with a smooth, white, glazed finish without blemishes, will suffice. It is desirable to have the sinks connected directly to the main pipe; connections to open channels should be avoided, and also any unnecessary devices, which might accumulate slime.

Taps should be designed for operation by foot, knee, or elbow, rather than by hand.

The furniture should be reduced to a minimum and should be easily washable. Dust-collecting items—such as drawers, shelves, and hanging lamps—should be as few as possible.

The working premises should be adequately lighted.

Provision for adequate ventilation should be included in the original design of the premises.

Routes of entry and exit for the ventilating air should be clearly defined under all conditions of use, including open and closed positions of doors and windows and various operating arrangements of the fume hoods. In small laboratories it may be possible to provide the needed flow of air simply by means of the exhaust systems of the fume hoods, but in such a case special attention must be given to inflow of fresh air into the laboratory under all conditions, which can be

* Type C and Type B laboratories are defined in the IAEA publications.[21,22] However, this author would prefer defining them as laboratories that might only require a chemical hood or completely enclosed dry-box operation respectively, as indicated in Table 41.

accomplished by such means as providing adequate louvres in the doors of rooms. Consideration should be given to any need to treat or filter incoming air. In cool climates, the problem of heating the intake air for a large group of fume hoods should not be overlooked, as this may be a major problem.

The siting of inlet and exhaust vents should be such as to prevent any recirculation of exhausted air.

Fume hoods should produce a regular air flow without any eddies. The speed of the air flow should be such that there can be no escape of air into the working place from the fume hood under typical operating conditions, including opening of windows and doors and the suction of other fume hoods; this can be checked by smoke tests. It is recommended that the fan be placed on the exhaust side of any filter in the system. The gas, water, and electrical appliances should be operated from the outside of the fume hood. The inside of the hood and the exhaust ducts should be as easy to clean as possible.

Manipulations should be carried out over a suitable drip tray, or with some form of double container that will minimize the importance of breakages or spills. It is also useful to cover the working surfaces with absorbent material in order to soak up minor spills. The absorbent material should be changed when unsuitable for further work and be treated as radioactive waste.

Protective Clothing and Personal Protective Measures.

Protective clothing appropriate to the radioactive contamination risks should be worn by every person in the controlled area, even if only very small quantities of radioactive materials are manipulated.

In Type C working places, the personnel should wear simple protective clothing, such as ordinary laboratory coats or surgical coats. In Type A or B working places, protective clothing or devices should be provided according to the nature of the work. When working with experimental animals, clothing proof against teeth or claws may be desirable, and protection of the face against blood or body fluid splashings should be provided.

In Type A and B working places, the protective clothing should be clearly identified—for example, by a different color. It should not, in any case, be worn outside the controlled area.

The working clothes and street clothes should be kept in separate cubicles or changing rooms. When changing from one or the other, one should be careful to avoid cross-contamination risks.

Rubber gloves should be worn when working with unsealed radioactive substances.

Care should be taken to avoid needless contamination of objects by handling them with protective gloves—in particular, light switches, taps, door knobs, etc. The gloves should be either taken off, or a piece of noncontaminated material (paper), which should be disposed of later together with the contaminated residue, should be interposed.

Contaminated gloves should be washed before taking them off.

A method of putting on and removing rubber gloves without contaminating the inside of the gloves should be used. This procedure is such that the inside of the glove is not touched by the outside, nor is any part of the outside allowed to come in contact with the bare skin.

No unsealed radioactive sources should be manipulated with the unprotected hand.

No solution should be pipetted by mouth in any isotope laboratory.

It is recommended that special precautions be taken to avoid punctures or cuts, especially when manipulating the more dangerous isotopes.

Anyone who has an open skin wound below the wrist (whether protected by a bandage or not) should not work with radioactive isotopes without medical approval.

The use of containers, glassware, etc., with cutting edges should be avoided.

Care should be taken with contaminated animals to avoid bites or scratches.

An annual compendium of United States and international standards in the nuclear field, including radiation protection, is now available from the United States of America Standards Institute.[23]

PROTECTION IN MEDICAL PRACTICE

The basic principles of radiation protection for the patient and the physician or his assistant are the same as for those working in other facilities involving potential radiation exposure. Basically, diagnostic radiation exposure to the patient should be a minimum consistent with the best medical practice. In radiation therapy, the radiation dose to the tumor or to the pathogenic tissue should be optimized, and exposure to healthy tissues minimized. The principles of shielding the healthy tissues or minimizing the time they are exposed relative to exposure of the pathogenic tissues are utilized in the practice of beam collimation or by the use of lead aprons to shield the patient against scattered radiation, or, in rotational therapy, by reducing the exposure time of healthy tissues relative to the tumor that remains in the center of the beam.

In addition to the references previously mentioned,[24, 25] there are a number of excellent reports and texts now available.[26–29] The National Council of Radiation Protection and Measurements (NCRP) is presently preparing a revised set of recommendations on the design of medical X-ray installations, but for the present the existing recommendations are sufficiently detailed to provide design criteria.[26, 29]

For purposes of this handbook, some of the more frequently needed recommendations and data are summarized below from Reference 26.

General Guidelines in the Clinical Use of Radiation.

As a general principle, the exposure to the patient shall be kept to the practical minimum consistent with clinical objectives. To this end, the following recommendations are presented for the guidance of physicians and of others responsible for the exposure of patients.

The useful beam should be limited to the smallest area practicable and consistent with the objectives of the radiological examination or treatment.

The voltage, filtration, and source–skin distance (SSD) employed in medical radiological examinations should be as great as is practical and consistent with the diagnostic objectives for the study (for dental X-ray examinations, see NCRP Report No. 35).

Protection of the embryo or fetus during radiological examination or treatment of women known to be pregnant should be given special consideration.*

Suitable protective devices to shield the gonads of patients who are potentially procreative should be used when the examination or method of treatment may include the gonads in the useful beam, unless such devices interfere with the conditions or objectives of the examination or treatment.

Fluoroscopy should not be used as a substitute for radiography, but should be reserved for the study of dynamics or spatial relationships, or for guidance in spot-film recording of critical details.

X-ray films, intensifying screens, and other image-recording devices should be

* Ideally, abdominal radiological examination of a woman of childbearing age should be performed during the first few (approximately 10) days following the onset of menses, to minimize the possibility of irradiation of an embryo. In practice, medical needs should be the primary factors in deciding the timing of the examination.

as sensitive as is consistent with the requirements of the examination.

Film-processing materials and techniques should be those recommended by the X-ray film manufacturer, or those otherwise tested, to ensure maximum information content of the developed X-ray film; where practical, quality-control methods should be employed to ensure optimal results.

The section on design requirements for fluoroscopic equipment is quoted in the following paragraph, since it contains data that may be checked to insure the safety of equipment in use. NCRP Report No. 33 also gives performance criteria for the design of fluoroscopic and other diagnostic equipment.

FLUOROSCOPIC EQUIPMENT*

Design Recommendations.

A diagnostic-type protective tube housing shall be used (see definition in Appendix A of Reference 26).

The source–panel or source–tabletop distance shall be at least 12 inches (30 cm) and should not be less than 15 inches (38 cm). The source–skin distance of image-intensifier equipment should not be less than 15 inches (38 cm).†

The total filtration permanently in the useful beam shall be at least 2.5 millimeters aluminum equivalent. When the tabletop or panel surface is interposed between the source and the patient, its aluminum equivalent may be included as part of the total filtration (see comment under 3.2.2(a) in Reference 26).

The equipment shall be so constructed that, under conditions of normal use, the entire cross section of the useful beam is attenuated by a primary protective barrier permanently incorporated into the equipment. The exposure shall automatically terminate when the barrier is removed from the useful beam.

1. The lead equivalent of the barrier of conventional fluoroscopes shall be at least 1.5 millimeters for equipment capable of operating up to 100 kvp, at least 1.8 millimeters for equipment whose maximum operating potential is greater than 100 kvp and less than 125 kvp, and at least 2.0 millimeters for equipment whose maximum operating potential is 125 kvp or greater (see Reference 8 in Reference 26). Special attention shall be paid to the shielding of image intensifiers, so that neither the useful beam nor the scattered radiation from the intensifier itself or from the patient will produce significant radiation exposure to the operator or other personnel.
2. A collimator shall be provided to restrict the size of the useful beam to less than the area of the barrier. The X-ray tube and collimating system shall be linked with the fluorescent screen assembly, so that the useful beam at the fluorescent screen is confined within the barrier, irrespective of the panel–screen distance. For image intensifiers, the useful beam should be centered on the input phosphor, and during fluoroscopy or cine-recording it should not exceed the diameter of the input phosphor. (Ideally, for spot-film radiography with image-intensifier equipment, the shutters should automatically open to the required field size before each exposure.)
3. Collimators, adjustable diaphragms, and shutters shall provide the same degree of attenuation as is required of the tube housing.

* Including image-intensified fluoroscopic equipment.

† The greater the source–tabletop distance, the lower is the entrance dose (and, to a lesser extent, the integral dose) for a given screen luminance. Image unsharpness and image magnification are also reduced. However, other considerations place a practical upper limit on the source–tabletop distance. The heating load on the X-ray tube increases rapidly with distance, because greater tube current is required to maintain constant screen luminance. For the same reason it may be necessary to increase spot-film exposure time, resulting in greater motion unsharpness. From the standpoint of radiation safety, it appears that the source–tabletop distance is not critical within rather broad limits. For conventional fluoroscopes, a distance of 15 to 18 inches seems to be a reasonable compromise between the conflicting factors involved (see Reference 7 in Reference 26).

The fluoroscopic-exposure switch shall be of the dead-man type (see definition in Appendix A of Reference 26).

Provision shall be made to intercept the scattered X rays from the undersurface of the tabletop and other structures under the table. In most cases this may be accomplished either by a cone extending from the tube housing to the tabletop, or by a shield around the fluoroscope understructure, or both. The cone shall provide the same degree of attenuation as that required of the tube housing, with the incident angle of the useful beam taken into consideration.

A shielding device of at least 0.25 mm lead equivalent for covering the Bucky slot during fluoroscopy should be provided.

A shield of at least 0.25 mm lead equivalent—such as overlapping protective drapes, or hinged or sliding panels—should be provided to intercept scattered radiation that would otherwise reach the fluoroscopist and others near the machine.

A cumulative timing device, activated by the fluoroscope exposure switch, shall be provided. It shall indicate the passage of a predetermined period of irradiation either by an audible signal or by temporary interruption of the irradiation when the increment of exposure time exceeds a predetermined limit not exceeding five minutes.*

Devices that indicate the X-ray tube potential and current shall be provided. On image-intensified fluoroscopic equipment, such devices should be located in such a manner that the operator may monitor the tube potential and current during fluoroscopy (see footnote under *Guidelines for the Fluoroscopist*).

Image intensification shall always be provided on mobile fluoroscopic equipment. It shall be impossible to operate mobile fluoroscopic equipment unless the useful beam is intercepted by the image intensifier. Inherent provisions shall be made, so that the machine is not operated at a source–skin distance of less than 12 inches (30 cm).

Equipment to be operated in areas where explosive gases may be used should have the approval of Underwriters Laboratory for such use.†

Since the exposure rates in fluoroscopy and the exposure times may possibly be subject to considerable variation, the following guidelines are important in training fluoroscopists to minimize radiation exposure.[25]

Guidelines for the Fluoroscopist.

The exposure rate used in fluoroscopy should be as low as is consistent with the fluoroscopic requirements and shall not normally exceed 10 r/min (measured in air) at the position where the beam enters the patient. This recommendation applies to the use of image-intensifier equipment (with or without television cameras) as well as to conventional (direct-viewing) fluoroscopes (see comment under 3.1.2(a) in Reference 26).

The fluoroscopist should know the radiation characteristics of his equipment. Therefore, periodic measurements of tabletop or patient exposure rate shall be made. Patient-exposure measurements are especially necessary on apparatus employing image intensifiers in which the intensifier brightness is automatically controlled and the X-ray factors in use are not readily ascertained. ‡Such measurements necessitate the use of a phantom in the fluoroscopic beam.

* While the timer does not ensure safe operation, it is of value as a training device for physicians learning the techniques of fluoroscopy, and for the experienced fluoroscopist as a means for emphasizing the passage of time. The design should be such that the timer reset mechanism does not create a nuisance for the physician.

† Information may be obtained from Underwriters Laboratory, 207 East Ohio Street, Chicago, Illinois, 60611.

‡ Image intensifiers may significantly reduce both observation time and exposure rate when properly used, but do not inherently accomplish this reduction. In equipment with automatic brightness control, the tube potential and current may rise to high values without knowledge of the operator, particularly if the gain of the intensifier is diminished. It is important, therefore, for the operator to monitor tube current and potential on such equipment,

The smallest practical field sizes and shortest exposure times should be employed. The possibilities of reducing dose by techniques utilizing high tube potential and low current should be considered.

Fluoroscopy should not be used as a substitute for radiography, but should be reserved for the study of dynamics or spatial relationships or for guidance in spot-film recording critical details.

Medical fluoroscopy should be performed only by or under the immediate supervision of physicians properly trained in fluoroscopic procedures.

The fluoroscopist's eyes should be sufficiently dark-adapted for the visual task required, before commencing fluoroscopy.* Under no circumstances should he attempt to compensate for inadequate adaptation by increasing the exposure factors employed or by prolonging the fluoroscopic examination.

Extraneous light that interferes with the fluoroscopic examination shall be eliminated.

Special precautions, consistent with clinical needs, should be taken to minimize exposure of the gonads of potentially procreative patients and exposure of the embryo or fetus in patients known to be or suspected of being pregnant (see 2.4.3 and 2.4.4 in Reference 26).

In cineradiography, special care should be taken to limit patient exposure when —as is often the case—tube currents and potentials employed are higher than those normally used in fluoroscopy. The exposure rates to which patients are normally subjected shall be determined periodically.

Protective aprons of at least 0.25 mm lead equivalent should be worn in the fluoroscopy room by each person (except the patient) whose trunk is exposed to radiation fields of 5 mr/hr or more .†

The hand of the fluoroscopist should not be placed in the useful beam unless the beam is attenuated by the patient and a protective glove of at least 0.25 mm lead equivalent.

Only persons whose presence is needed should be in the fluoroscopy room during X-ray exposures.

Design recommendations for diagnostic X-ray machines, including appropriate filtration, diaphragms, cones, and collimators, are given in the following paragraphs.

FIXED RADIOGRAPHIC EQUIPMENT

Design Recommendations.

A diagnostic-type protective tube housing shall be used (see definition in Appendix A and Reference 6 in Reference 26).

Suitable devices (diaphragms, cones, adjustable collimators) capable of restricting the useful beam to the area of clinical interest shall be provided to define the beam and shall provide the same degree of attenuation as that required of the tube housing. Such devices shall be calibrated in terms of the size of the projected useful beam at specified source–film distances (see 3.2.2(b) in Reference 26). For chest photofluorographic equipment, the collimator shall restrict the beam to dimensions no greater than those of the fluorographic screen.

Radiographic equipment, particularly multipurpose machines, should be equipped with adjustable collimators containing light localizers that define the

* The perception of detail under conditions of scotopic vision requires retinal adaptation. The adaptation time necessary for the competent performance of a specific visual task depends upon the nature of the task itself, the preexposure luminance level and color, the conditions of adaptation, and on a number of other physiologic factors. While wearing red goggles for 10 minutes will usually satisfy adaptation requirements in fluoroscopy, no specific adaptation period can be recommended for all situations (see Reference 9 in Reference 26). Dark-adaptation normally is not necessary when using image intensifiers.

† A busy fluoroscopist is unlikely to operate a fluoroscope more than five hours per week. Therefore he would be unlikely to receive more than 1/4 the maximum permissible dose to the trunk of the body if the scattered radiation level is less than 5 mr per hour. However, the other sources of exposure also should be taken into account when deciding whether a protective apron is to be worn.

entire field. Rectangular collimators are usually preferable. Means to produce a visible indication of adequate collimation and alignment on the developed X-ray film should be provided. The field size indication on adjustable collimators shall be accurate to within one inch for a source–film distance of 72 inches. The light field shall be aligned with the X-ray field with the same degree of accuracy.
The aluminum equivalent of the total filtration in the useful beam shall not be less than that shown in the following table (see also 3.2.2(a) in Reference 26). For dental radiography, see forthcoming NCRP Report No. 35.

Operating kvp	Minimum Total Filter (inherent plus added)
Below 50 kvp	0.5 mm aluminum
50–70 kvp	1.5 mm aluminum
Above 70 kvp	2.5 mm aluminum

A device that terminates the exposure at a preset time interval or exposure shall be provided. The operator should be able to terminate the exposure at any time.
The exposure switch, except for those used in conjunction with spot-film devices in fluoroscopy, shall be so arranged that it cannot be conveniently operated outside a shielded area.
The control panel shall include a device (usually a milliammeter) to give positive indication of the production of X rays whenever the X-ray tube is energized.
The control panel shall include devices (labeled control settings and/or meters) indicating the physical factors (such as kvp, mA, exposure time, or whether timing is automatic) used for the exposure.
Machines equipped with beryllium-window X-ray tubes* shall contain keyed filter-interlock switches in the tube housing and suitable indication of the control panel of the added filter in the useful beam if the total filtration permanently in the useful beam is less than 0.5 mm aluminum equivalent. The total filtration permanently in the useful beam shall be clearly indicated on the tube housing.
Beryllium-window X-ray tubes should not be used on multipurpose radiographic equipment.
The aluminum equivalent of the tabletop when a cassette tray is used under the tabletop, or the aluminum equivalent of the front panel of the vertical cassette holder, shall not be more than 1 mm at 100 kvp.
Equipment to be operated in areas where explosive gases may be used should have the approval of Underwriters Laboratory for such use.†

The following guidelines for the use of diagnostic X-ray equipment are based on the common-sense application of the principles of minimizing radiation exposure through shielding, distance, or reducing time of exposure.[26]

Guidelines for the User. (See also 2.4 in Reference 26.)

Particular care should be taken to limit the useful beam to the smallest area consistent with the clinical requirements and to align the X-ray beam accurately with the patient and film (see also 3.2.2(b) in Reference 26).
Gonadal shielding should be used for the patient when appropriate (see 2.4.4 in Reference 26), but never as a substitute for adequate beam collimation and alignment.
When a patient must be held in position for radiography, mechanical supporting or restraining devices should be used. If the patient must be held by an individual,

* Beryllium-window X-ray tubes with no added filtration emit low-energy X rays at very high exposure rates. It is particularly important, therefore, that the operator be able to tell by a glance at the control panel how much added filter, if any, is present.
† Information may be obtained from Underwriters Laboratory, 207 East Ohio Street, Chicago, Illinois 60611.

that individual shall be protected with appropriate shielding devices such as protective gloves and apron, and he should be so positioned that no part of his body will be struck by the useful beam and that his body is as far as possible from the edge of the useful beam.

Only persons whose presence is necessary shall be in the radiographic room during exposure. All such persons shall be protected.

The radiographer shall stand behind the barrier provided for his protection during radiographic exposures.

Special care shall be taken to ensure adequate filtration in multipurpose machines.*

Particular care shall be taken to ensure adequate filtration in any machine equipped with a beryllium-window tube. Appropriate added filter is required, to provide the filtration values recommended (see 3.2.1(d), also 3.2.1(i) and (j) in Reference 26).

Other guidelines should be consulted for the design and use of mobile radiographic equipment and of X-ray therapy equipment.[26] Similar considerations of limiting the width of the beam to necessary dimensions, using appropriate filtration to reduce the soft component that would be absorbed in tissues before reaching the tissue of interest, and increasing the distance and shielding protection of medical personnel working in the vicinity of radiographic or therapy equipment are included. Particular items that may be checked most frequently by government agencies would include: the leakage radiation from the housing of therapy machines, which should not exceed 0.1 r/hr at 5 cm; the use of permanent diaphragms or cones for collimating the beam with the same degree of protection outside the beam as provided by the housing; the use of a suitable exposure-control device (e.g., an automatic timer or exposure meter) to terminate exposures after a preset time interval or preset exposure; emergency means of terminating the exposure; and various mechanical and electrical interlocks and warning lights to insure that operating personnel do not inadvertently expose themselves or the patients. NCRP Report No. 33 should be examined in detail before designing and establishing procedures for a therapy installation.[26]

Similar guidelines are given for gamma-beam therapy equipment that utilizes the radiation from radioactive materials. In addition, there are requirements for leak-testing these radioactive sources, to show that there is less than 0.005 μCi of transferable activity when surfaces of the devices are wiped clean with moistened cotton swabs or filter paper. Leak tests and the records of their results are usually made a legal requirement in the licensing of these radioactive sources and devices. Guidelines for the use of such equipment and for emergency procedures are usually incorporated in the inspection programs of regulatory agencies. Regular calibration of the quality and intensity of radiation from therapy equipment should be carried out. Annual calibrations may suffice, however, as long as spot checks are made at least once a month or after every 50 hours of operating time. A log shall be kept of all spot-check measurements.[26] Radiation protection surveys are required periodically, as well as appropriate warning signs;[26] these surveys and signs are often necessary in order to meet regulatory requirements.

In addition to safe equipment and procedures, it is necessary to have appropriate supervision of the overall radiation safety of the radiology department operations, as well as regular monitoring and recording of personnel exposures by the use of film badges or other devices worn by the medical staff and their assistants. NCRP recommendations should be consulted in detail, in addition to requirements of state and federal agencies.[26,30] Most of the state supervision of medical facilities is carried out by state health departments. The following general working conditions are recommended by NCRP and are generally considered good practice.[26]

* For soft-tissue radiography, such as mammography, operating potentials considerably below 50 kvp may be required. In performing such examinations on multipurpose machines, it is usually necessary to reduce the amount of filtration. It is important, however, that the appropriate filter be replaced before proceeding with exposures requiring normal filtration.

General.

The owner (see definition in Appendix A of Reference 26) is responsible for radiation safety. He is responsible for assuring that radiation sources under his jurisdiction are used only by persons competent to use them. He is responsible for providing the instruction of personnel in safe operating procedures and for promulgating rules for radiation safety.

Deliberate exposure of an individual to the useful beam for training or demonstration purposes shall not be permitted unless there is also a medical (or dental) indication for the exposure and the exposure is prescribed by a physician (or dentist).

Radiation-Protection Supervisor.

A radiation-protection supervisor (who may be the user himself) shall be designated for every installation to assume the responsibilities outlined below and to advise on the establishment of safe working conditions according to the recommendations of this report and in compliance with all pertinent federal, state, and local regulations. He should be familiar with the basic principles of radiation protection in order to properly discharge his responsibilities, although for details he may consult with appropriate qualified experts for advice.

Among the specific responsibilities of the radiation-protection supervisor or his deputy are the following.

1. To establish and supervise operating procedures, and to review them periodically to assure their conformity with the recommendations of this report.
2. To instruct personnel in proper radiation-protection practices.
3. To conduct or have conducted radiation surveys and source-leak tests where indicated (see Section 6 and 4.2.2(c) in Reference 26), and to keep records of such surveys and tests, including summaries of corrective measures recommended and/or instituted.
4. To assure that personnel-monitoring devices are used where indicated (see below) and that records are kept of the results of such monitoring.
5. To assure that interlock switches and warning signals are functioning and that signs are properly located.
6. To investigate each known or suspected case of excessive or abnormal exposure in order to determine the cause, and to take steps to prevent its recurrence.

Personnel-Monitoring.

Personnel-monitoring is valuable for checking the adequacy of the radiation-safety-program. It can be useful in disclosing inadequate or improper radiation-protection practices and potentially serious radiation-exposure situations. Personnel-monitoring may be of value also in documenting occupational exposure if proper consideration is given to the limitations of the monitoring system (see Reference 12 in Reference 26). Accordingly, the following recommendations are made.

1. Personnel-monitoring shall be performed in controlled areas for each occupationally exposed individual for whom there is reasonable possibility of receiving a dose exceeding 1/4 the applicable MPD (see Table 1, Appendix B in Reference 26).
2. A qualified expert should be consulted on establishing and evaluating the personnel-monitoring system. When feasible, the system should be tested periodically.

3. All reported cases of apparently high exposures shall be investigated by the radiation-protection supervisor, and his findings and conclusions should be made a part of the personnel-monitoring record.
4. Devices worn for the monitoring of occupational exposure shall not be worn by the individual when he is exposed as a patient for medical (or dental) reasons.
5. Monitoring devices used to estimate whole-body exposure normally should be worn on the chest or abdomen. When a protective apron is worn (e.g., during fluoroscopy), particular care should be taken in choosing the location of the monitoring device and in interpreting its reading. Devices worn on the inside of the apron will normally not provide a reliable indication of the radiation environment outside of the apron. Devices worn on the outside of the apron will usually provide only an upper limit for the estimation of the exposure of parts of the body covered by the apron. Accordingly, a qualified expert should be consulted in situations where the interpretation of the reading is highly dependent upon the conditions under which the monitoring device is used. For further information on the use of personnel-monitoring devices, see the forthcoming NCRP Report on Instrumentation and Monitoring Methods for Radiation Protection.
6. Blood counts shall not be used for personnel-monitoring (see Reference 13 in Reference 26).

Medical Examination.

A preplacement medical examination is recommended, to establish baseline values for the radiation worker and to reveal any physical condition that later might otherwise be attributed to radiation exposure. It should include medical history, radiation-exposure history, physical examination, and—at the discretion of the physician in charge—a complete blood count.

Whenever it is known or suspected that a person has received a dose substantially in excess of the MPD, the individual should be referred at once to a competent medical authority.

Vacations.

Vacations shall not be used as a substitute for adequate protection against exposure to radiation.

The emergency procedures to be used in case of failure of gamma-ray beam-control equipment depends on the individual installation, as pointed out by the NCRP.[26] However, since the procedure is brief and illustrates the general sequence of removing persons from direct intense exposure, notification of appropriate supervisory and radiation-protection personnel, planned careful entry to the area by radiation-protection personnel, utilization of appropriate survey materials to measure radiation intensity while exploring the causes, and possible rectification of the equipment of procedural failure, it is presented here.

Emergency Procedure in Case Beam Control Fails.

If the light signals indicate that the beam-control mechanism has failed to terminate the exposure at the end of the preset time (for example, if the red light stays on and/or the green signal does not light up), the source may still be in the "on" position. The following steps are to be carried out in a calm manner.

For the Radiation-Therapy Technician.

1. Open the door to the treatment room.

2. If the patient is ambulatory, direct him to get off the table and leave the room.
3. If the patient is not ambulatory, enter the treatment room, but avoid exposure to the useful beam; pull the treatment table as far away from the useful beam as possible; transfer the patient to a stretcher and remove him from the room.
4. Close the door.
5. Turn off the main switch at the control panel.
6. Notify the radiation therapist and radiation-protection supervisor at once.

For the Radiation-Protection Supervisor.

1. Secure a portable survey meter; check to see that the meter is functioning properly.
2. Turn the power on and open the door a few inches.
3. Stand behind the door and insert the survey meter into the door opening to test whether in fact the source is still in the "on" position.
4. If the source is still in the "on" position, enter the room and manually turn the source off as per manufacturer's instructions; avoid intercepting the useful beam with any part of your body.
5. Adjust the limiting diaphragm to the smallest field size.
6. Close the door to the treatment room; turn off the power; lock the control panel; post a sign warning people not to enter.
7. Notify the equipment manufacturer's representative.

Some useful data for estimating radiation exposure rates and design requirements for medical installations are given in Tables 48 to 56.

Table 48.

HALF-VALUE LAYERS AS A FUNCTION OF FILTRATION AND OF THE TUBE POTENTIAL FOR DIAGNOSTIC UNITS[26]

Total Filtration, mm Al	Peak Potential, kvp									
	30	40	50	60	70	80	90	100	110	120
	Typical Half-Value Layers, mm of Al									
0.5	0.36*	0.47*	0.58	0.67	0.76	0.84	0.92	1.00	1.08	1.16
1.0	0.55	0.78	0.95	1.08	1.21	1.33	1.46	1.58	1.70	1.82
1.5	0.78	1.04	1.25*	1.42*	1.59*	1.75	1.90	2.08	2.25	2.42
2.0	0.92	1.22	1.49	1.70	1.90	2.10	2.28	2.48	2.70	2.90
2.5	1.02	1.38	1.69	1.95	2.16	2.37*†	2.58*†	2.82*†	3.06*†	3.30*†
3.0	—	1.49	1.87	2.16	2.40	2.62	2.86	3.12	3.38	3.65
3.5	—	1.58	2.00	2.34	2.60	2.86	3.12	3.40	3.68	3.95

Note: for full-wave rectified potential; derived from Reference 32 by interpolation and extrapolation.
* Recommended minimum HVL for radiographic units (see Section 3.2.2(a) in Reference 26.
† Recommended minimum HVL for fluoroscopes (see Section 3.1.2(b) in Reference 26.
From: Medical X-Ray and Gamma-Ray Protection for Energies up to 110 Mev—Equipment Design and Use. *NCRP Report No. 33.* By permission of the National Council on Radiation Protection and Measurements, Washington, D.C.

Table 49.
EFFECT OF TUBE POTENTIAL, DISTANCE, AND FILTRATION ON AIR EXPOSURE RATE AT PANEL OF FLUOROSCOPES[26]

Potential kvp	Source-to-Panel Distance		Equivalent Total Aluminum Filtration				
			1 mm	2 mm	2.5 mm	3 mm	4 mm
	cm	inches	roentgens per milliampere minute				
70	30	12	5.3	2.7	2.2*	1.8	1.3
	38	15	3.5	1.7	1.4†	1.2	0.8
	46	18	2.4	1.2	1.0	0.8	0.6
80	30	12	7.0	3.9	3.2*	2.6	2.0
	38	15	4.6	2.5	2.1†	1.7	1.3
	46	18	3.2	1.8	1.4	1.2	0.9
90	30	12	9.0	5.2	4.3*	3.6	2.8
	38	15	5.8	3.3	2.8†	2.3	1.8
	46	18	4.0	2.3	1.9	1.6	1.2
100	30	12	11.0	6.6	5.5*	4.7	3.7
	38	15	7.0	4.2	3.5†	3.0	2.3
	46	18	4.9	2.9	2.5	2.1	1.6
110	30	12	13.1	8.0	6.8*	5.9	4.6
	38	15	8.4	5.1	4.4†	3.8	3.0
	46	18	5.8	3.5	3.0	2.6	2.0
120	30	12	14.7	9.3	8.0*	7.0	5.5
	38	15	9.5	6.0	5.1†	4.5	3.6
	46	18	6.5	4.1	3.6	3.1	2.5
130	38	15	—	6.8	5.9†	5.2	4.2
	46	18	—	4.7	4.1	3.6	2.9
140	38	15	—	7.6	6.6†	5.9	4.8
	46	18	—	5.3	4.6	4.1	3.3
150	38	15	—	8.5	7.5†	6.7	5.4
	46	18	—	5.8	5.2	4.6	3.7

Note: typical exposure rates produced by equipment with medium length cables, derived from references 31 and 32 by interpolation and extraoplation. Filtration includes that of the tabletop and the X-ray tube with its inherent and added filter. As used above, panel means either panel or table top.

† See Section 3.1.2(a) in Reference 26.

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Table 50.
SCATTERED-RADIATION EXPOSURE RATE AT SIDE OF FLUOROSCOPY TABLE[26]

Distance from Source to Point of Measurement		Tube Potential						
		50 kvp	60 kvp	70 kvp	80 kvp	90 kvp	100 kvp	125 kvp
inches	cm	roentgens per 100 milliampere seconds						
12	30	1.8	2.8	4.2	5.8	8.0	9.8	15.2
18	46	0.8	1.3	1.8	2.5	3.4	4.2	6.7
24	61	0.4	0.7	1.1	1.4	1.9	2.3	3.8
39	100	0.2	0.3	0.4	0.5	0.7	0.9	1.4
54	137	0.1	0.1	0.2	0.3	0.4	0.5	0.7
72	183	0.1	0.1	0.1	0.2	0.2	0.3	0.4

Note: measured in air, with total filtration equivalent to 2.5 mm aluminum.

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Table 51.
EXPOSURE RATE THROUGH FLUOROSCOPIC SCREEN WITHOUT PATIENT[26]

X-Ray Tube Potential kvp	Source-to-Tabletop Distance		Lead Equivalent of Screen Protective Barrier*		
			1.5 mm	1.8 mm	2.0 mm
	inches	cm	Typical Exposure Rate, mr/h per r/min at tabletop		
80	12	30	10	4.5	2.5
	15	38	13	6	3.5
	18	46	15	7	4
90	12	30	12	6	3.5
	15	38	16	7.5	4.5
	18	46	19	9	5.5
100	12	30	15	7	4.5
	15	38	20	9	5.5
	18	46	23	11	7
110	12	30	19	9	5.5
	15	38	24	12	7
	18	46	29	14	8.5
120	12	30	23	11	7
	15	38	30	14	9
	18	46	35	17	10
130	15	38	35	17	10
	18	46	42	20	12
140	15	38	41	19	12
	18	46	49	23	14
150	15	38	46	20	12
	18	46	55	24	15

Total filtration: 3 mm aluminum equivalent
Tabletop-to-screen distance: 14 inches
Screen-to-chamber distance: 2 inches
Medium-length high-tension cables

Note: adapted from Reference 31 by interpolation and extrapolation; actual exposure rate values may differ from the typical values given above by ±15%, depending upon length of high-tension cables.

* See Section 3.1.1(d) and 3.1.2(c) of Reference 26.

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Table 52. PRIMARY PROTECTIVE-BARRIER REQUIREMENTS FOR 100 mr-week[21]

Tube Voltage, Constant Potential	WUT, mA-min per week	Primary Protective Barrier Requirements in mm of Lead at a Target Distance of						Primary Protective Barrier Requirements in cm of Concrete (2.35 g/cm^3) at a Target Distance of					
		TVL	1 m	2 m	3 m	5 m	10 m	TVL	1 m	2 m	3 m	5 m	10 m
	10,000		0.7	0.6	0.5	0.4	0.3		7.0	6.0	5.0	4.0	3.0
	3,000		0.6	0.5	0.4	0.3	0.2		6.0	5.0	4.0	3.0	2.0
50 kv	1,000	0.2	0.5	0.4	0.3	0.2	0.1	2	5.0	4.0	3.0	2.0	1.0
	300		0.4	0.3	0.2	0.2	0.1		4.0	3.0	2.0	2.0	1.0
	100		0.3	0.2	0.2	0.1	0.1		3.0	2.0	2.0	1.0	1.0
	10,000		1.6	1.3	1.1	0.9	0.7		14.0	12.0	10.0	8.0	6.0
	3,000		1.4	1.1	0.9	0.7	0.5		12.0	10.0	8.0	6.0	4.5
70 kv	1,000	0.5	1.1	0.9	0.7	0.5	0.4	4	10.0	8.0	6.0	4.5	3.5
	300		0.9	0.7	0.5	0.4	0.2		8.0	6.0	4.5	3.5	2.0
	100		0.7	0.5	0.4	0.3	0.1		6.0	4.5	3.5	2.5	1.0
	10,000		2.7	2.2	1.9	1.5	1.1		23.0	19.0	16.0	13.0	9.5
	3,000		2.3	1.8	1.5	1.2	0.8		19.5	15.5	13.0	11.0	7.0
85 kv	1,000	0.8	1.8	1.4	1.1	0.9	0.6	6.5	15.5	12.5	9.5	8.0	5.0
	300		1.4	1.1	0.8	0.6	0.4		12.5	9.5	7.0	5.0	3.5
	100		1.1	0.8	0.6	0.4	0.2		9.5	7.0	5.0	3.5	2.0
	10,000		3.3	2.8	2.5	2.1	1.6		26.5	22.0	20.0	17.0	13.0
	3,000		2.9	2.4	2.0	1.7	1.2		23.0	19.0	16.0	14.0	10.0
100 kv	1,000	0.85	2.5	2.0	1.6	1.3	0.8	7	20.0	16.0	13.0	10.5	6.5
	300		2.0	1.5	1.2	0.9	0.5		16.0	12.0	10.0	7.5	4.0
	100		1.6	1.1	0.8	0.6	0.3		13.0	9.0	6.5	5.0	2.5
	10,000		3.7	3.2	2.8	2.5	1.9		30.0	26.0	24.0	21.0	16.5
	3,000		3.3	2.7	2.4	2.0	1.5		27.0	23.0	20.0	17.0	13.0
125 kv	1,000	0.9	2.8	2.3	1.9	1.6	1.0	7	24.0	19.0	16.5	14.0	9.0
	300		2.4	1.8	1.5	1.1	0.7		20.0	16.0	13.0	10.0	6.0
	100		1.9	1.4	1.1	0.8	0.4		16.5	12.0	10.0	7.0	3.0

Table 52. PRIMARY PROTECTIVE-BARRIER REQUIREMENTS FOR 100 mr-week[21] (*Continued*)

Tube Voltage, Constant Potential	WUT, mA-min per week	Primary Protective Barrier Requirements in mm of Lead at a Target Distance of						Primary Protective Barrier Requirements in cm of Concrete (2.35 g/cm^3) at a Target Distance of					
		TVL	1 m	2 m	3 m	5 m	10 m	TVL	1 m	2 m	3 m	5 m	10 m
150 kv	10,000	0.9	3.9	3.4	3.1	2.7	2.1	8	33.0	29.0	26.0	23.0	18.0
	3,000		3.5	2.9	2.6	2.2	1.6		30.0	25.0	22.0	19.0	14.0
	1,000		3.0	2.5	2.2	1.7	1.2		25.5	21.0	19.0	14.5	10.5
	300		2.6	2.1	1.7	1.3	0.8		22.0	18.0	15.0	11.0	7.0
	100		2.2	1.6	1.3	0.9	0.5		19.0	14.0	12.0	8.0	4.0
200 kv	30,000	2	8.0	6.5	6.0	5.0	4.0	9	49.0	42.0	39.0	34.0	30.0
	10,000		7.0	5.5	5.0	4.2	3.3		44.0	37.0	34.0	30.0	25.0
	3,000		6.0	4.5	4.0	3.3	2.5		39.0	32.0	29.0	25.0	21.0
	1,000		5.0	3.8	3.3	2.7	1.8		34.0	27.0	25.0	22.0	16.0
	300		4.0	3.0	2.5	1.9	1.2		30.0	23.0	21.0	17.0	12.0
	100		3.3	2.4	1.9	1.3	0.9		25.0	20.0	17.0	13.0	8.0
250 kv	30,000	3	13.5	12.0	10.5	9.0	7.5	10	55.0	49.0	45.0	41.0	35.0
	10,000		12.0	10.5	9.0	7.5	6.0		50.0	45.0	40.0	35.0	30.0
	3,000		10.5	8.5	7.5	6.0	4.5		45.0	39.0	35.0	30.0	24.0
	1,000		9.0	7.0	6.0	5.0	3.5		40.0	34.0	30.0	26.0	20.0
	300		7.5	5.5	4.5	3.5	2.5		35.0	28.0	25.0	20.0	15.0
	100		6.0	4.5	3.5	2.5	1.5		30.0	25.0	20.0	15.0	10.0
300 kv	30,000	6	24.0	20.0	18.0	15.5	12.0	10	58.0	51.0	48.0	44.0	38.0
	10,000		21.0	17.0	15.0	12.5	9.5		53.0	46.0	43.0	39.0	33.0
	3,000		18.0	14.0	12.0	10.0	7.0		48.0	41.0	38.0	33.0	28.0
	1,000		15.0	11.5	10.0	7.5	5.0		43.0	36.0	33.0	29.0	23.0
	300		12.0	9.0	7.5	5.5	3.5		38.0	32.0	29.0	24.0	18.0
	100		9.5	7.0	5.5	4.0	2.5		33.0	28.0	24.0	19.0	15.0

Note: the tabulated values give the shielding required to reduce the exposure dose to 100 mr in a week, the value assumed for design purposes in controlled areas; to compute the shielding required outside controlled areas, it is necessary to add half a tenth-value layer to reduce the weekly exposure dose to about 30 mr, and one tenth-value layer to reduce it to 10 mr.

From: Recommendations of the ICRP. *Publication No. 3, Report of Committee 3.* Copyright 1960, Pergamon Press, New York.

Table 53.
SECONDARY PROTECTIVE BARRIER REQUIREMENTS FOR 100 mr-week[21]

Tube Voltage, Constant Potential	WUT mA-min per week	Secondary Protective Barrier Requirements in mm of Lead at Target Distances of					Secondary Protective Barrier Requirements in mm of Concrete (2.35 g/cm³) at Target Distances of				
		1 m	2 m	3 m	5 m	10 m	1 m	2 m	3 m	5 m	10 m
	10,000	0.35	0.25	0.2	0.1	0	3.5	2.5	2	1	0
50 kv[1]	3,000	0.25	0.15	0.1	0.1	0	2.5	1.5	1	1	0
	1,000	0.2	0.1	0.1	0	0	2	1	1	0	0
	300	0.1	0	0	0	0	1	0	0	0	0
	100	0	0	0	0	0	0	0	0	0	0
	10,000	0.9	0.7	0.5	0.3	0.1	7	5.5	4	2.5	1
70 kv[1]	3,000	0.7	0.5	0.3	0.1	0	5.5	4	2.5	1	0
	1,000	0.5	0.3	0.1	0	0	4	2.5	1	0	0
	300	0.3	0.1	0	0	0	2.5	1	0	0	0
	100	0.1	0	0	0	0	1	0	0	0	0
	10,000	1.4	1.0	0.8	0.4	0.2	12	8	6.5	4	2
85 kv[1]	3,000	1.1	0.7	0.4	0.2	0	9	6	4	2	0
	1,000	0.8	0.4	0.2	0	0	6.5	4	2	0	0
	300	0.4	0.2	0	0	0	4	2	0	0	0
	100	0.2	0	0	0	0	2	0	0	0	0
	10,000	1.6	1.1	0.9	0.5	0.2	13	10	7	4	2
100 kv[1]	3,000	1.2	0.8	0.5	0.2	0	10	7	4	2	0
	1,000	0.9	0.4	0.2	0	0	7	4	2	0	0
	300	0.5	0.2	0	0	0	4	2	0	0	0
	100	0.2	0	0	0	0	2	0	0	0	0
	10,000	1.8	1.4	1.0	0.5	0.2	14.5	11	8	4	2
125 kv[1]	3,000	1.4	0.9	0.5	0.2	0	11	7.5	4	2	0
	1,000	1.0	0.5	0.2	0	0	7.5	4	2	0	0
	300	0.5	0.2	0	0	0	4	2	0	0	0
	100	0.2	0	0	0	0	2	0	0	0	0
	10,000	1.9	1.5	1.0	0.6	0.2	15	11	8	5	2
150 kv[1]	3,000	1.5	0.9	0.6	0.2	0	11	7.5	5	2	0
	1,000	1.0	0.6	0.2	0	0	8	5	2	0	0
	300	0.6	0.2	0	0	0	5	2	0	0	0
	100	0.2	0	0	0	0	2	0	0	0	0
	30,000	5.1	3.9	3.2	2.6	1.6	36	29	25	22	15
200 kv[2]	10,000	4.1	3.0	2.4	1.8	0.8	31	24	20	16	9
	3,000	3.2	2.2	1.6	0.9	0.3	26	19	15	10	5
	1,000	2.4	1.4	0.9	0.3	0	21	14	10	5	0
	300	1.6	0.7	0.3	0	0	15	8	5	0	0
	30,000	7.5	6.0	5.0	4.0	2.5	37	31	27	23	17
250 kv[2]	10,000	6.2	4.8	3.8	2.7	1.2	32	26	22	18	10
	3,000	5.0	3.6	2.6	1.4	0.5	27	21	17	11	5
	1,000	3.8	2.4	1.4	0.5	0	22	16	11	5	0
	300	2.5	1.0	0.5	0	0	17	9	5	0	0
	30,000	14.5	11	9.5	7.5	5	40	32	28	25	19
300 kv[2]	10,000	12	8.5	7	5	3	34	27	24	19	14
	3,000	9.5	6	5	3	1	28	22	19	14	8
	1,000	7	4	3	1	0	24	16	14	8	0
	300	5	2.5	1	0	0	19	12	8	0	0

Note: the tabulated values give the shielding required to reduce the exposure dose to 100 mr in a week, the value assumed for design purposes in controlled areas; to compute the shielding required outside controlled areas, it is necessary to add half a tenth-value layer to reduce the weekly exposure dose to about 30 mr, and one tenth-value layer to reduce it to 10 mr.

The figures in the table allow for both scattered and leakage radiation. The scattered radiation at 1 m was assumed to be 0.1 percent of the incident beam. To compute the leakage radiation, it was assumed that the maximum ratings were 180 mA-min in 1 hour and 900 mA-min in 1 hour for the diagnostic-type protective tube housing (1) and the therapeutic-type protective tube housing (2) respectively.

From: Recommendations of the ICRP. *Publication No. 3, Report of Committee 3.* Copyright 1960. Pergamon Press, New York.

Table 54.
^{60}Co SHIELDING REQUIREMENTS FOR 100 mr/week[21]

WUT*			Distance from Source to Occupied Area, meters										
80,000			1.4	2.0	2.8	4.0	5.6	8.0	11.0	16.0			
40,000				1.4	2.0	2.8	4.0	5.6	8.0	11.0	16.0		
20,000				1.0	1.4	2.0	2.8	4.0	5.6	8.0	11.0	16.0	
10,000					1.0	1.4	2.0	2.8	4.0	5.6	8.0	11.0	16.0
5,000						1.0	1.4	2.0	2.8	4.0	5.6	8.0	11.0
2,500							1.0	1.4	2.0	2.8	4.0	5.6	8.0
1,250								1.0	1.4	2.0	2.8	4.0	5.6
620									1.0	1.4	2.0	2.8	4.0
310										1.0	1.4	2.0	2.8
	Approximate		Thickness of Lead, cm										
	HVL	TVL											
Primary Barrier	1.20	4.00	22.7	21.5	20.3	19.1	17.9	16.7	15.5	14.3	13.1	11.9	10.7
Leakage† (0.1%) Barrier	1.20	4.00	10.7	9.5	8.4	7.3	6.2	4.9	3.6	2.2	0.8	0.0	0.0
Scatter‡ Barrier													
30°	1.02	3.40	12.4	11.3	10.3	9.2	8.2	7.2	6.2	5.1	4.1	3.1	2.1
45°	0.87	2.90	9.8	8.9	8.1	7.2	6.3	5.4	4.5	3.7	2.8	1.8	1.1
60°	0.75	2.50	7.8	7.0	6.3	5.6	4.8	4.1	3.3	2.6	1.8	1.1	0.4
90°	0.43	1.45	3.7	3.2	2.8	2.4	1.9	1.5	1.1	0.7	0.3	0.1	0.0
120°	0.20	0.65	1.5	1.3	1.1	0.9	0.7	0.5	0.35	0.2	0.1	0.0	0.0
150°	0.14	0.45	0.9	0.8	0.7	0.55	0.45	0.3	0.2	0.1	0.05	0.0	0.0
	Approximate		Thickness of Concrete (2.35 g/cm³), cm										
	HVL	TVL											
Primary Barrier	6.6	21.8	122	116	110	104	97	91	85	79	72	66	60
Leakage† (0.1%) Barrier	6.6	21.8	60	54	48	41	34	27	19.5	12	4.5	0.0	0.0
Scatter‡ Barrier													
30°	6.3	20.8	79	73	67	60	54	48	41	35	29	22	16
45°	6.1	20.3	70	64	58	52	46	39	33	27	21	15	9
60°	5.9	19.2	62	56	50	45	39	33	27	21	15	9	2.5
90°	4.6	15.8	44	39	35	30	25	21	16	11	6	1	0
120°	4.3	14.7	39	35	30	26	21	17	13	8.5	4	0	0
150°	3.8	12.5	32	28	25	21	17	13	10	6	2	0	0

Note: add one tenth-layer (TVL), to reduce radiation to 10 mr/week.

* W = work load in r/week at 1 m, U = use factor, T = occupancy factor.

† Refers to leakage radiation of source housing.

‡ For large field (20 cm diameter) and a source—scatterer distance of 50 cm; these values include scattering from the collimator and from the phantom.

From: Recommendations of the ICRP. *Publication No. 3 Report of Committee 3.* Copyright 1960. Pergamon Press, New York.

Table 55.
^{137}Cs SHIELDING REQUIREMENTS FOR 100 mr/week[21]

WUT*			Distance from Source to Occupied Area, meters										
24,000			1.4	2.0	2.8	4.0	5.6	8.0	11.0	16.0			
12,000			1.0	1.4	2.0	2.8	4.0	5.6	8.0	11.0	16.0		
6,000				1.0	1.4	2.0	2.8	4.0	5.6	8.0	11.0	16.0	
3,000					1.0	1.4	2.0	2.8	4.0	5.6	8.0	11.0	16.0
1,500						1.0	1.4	2.0	2.8	4.0	5.6	8.0	11.0
750							1.0	1.4	2.0	2.8	4.0	5.6	8.0
375								1.0	1.4	2.0	2.8	4.0	5.6
	Approximate		Thickness of Lead, cm										
	HVL	TVL											
Primary Barrier	0.65	2.1	10.6	10.0	9.4	8.7	8.1	7.5	6.8	6.2	5.6	4.9	4.2
Leakage† (0.1%) Barrier	0.65	2.1	4.3	3.6	3.0	2.4	1.7	1.1	0.5	0.0	0.0	0.0	0.0
Scatter‡ Barrier													
35°	0.45	1.5	5.4	5.0	4.5	4.0	3.6	3.1	2.7	2.3	1.8	1.4	0.9
56°	0.38	1.3	4.2	3.8	3.4	3.0	2.6	2.2	1.8	1.5	1.1	0.8	0.5
90°	0.22	0.7	2.1	1.9	1.7	1.4	1.2	1.0	0.8	0.6	0.5	0.3	0.2
119°	0.13	0.4	1.0	0.9	0.8	0.7	0.6	0.5	0.3	0.2	0.2	0.1	0.05
	Approximate		Thickness of Concrete (2.35 g/cm^3), cm										
	HVL	TVL											
Primary Barrier	4.9	15.8	88	83	78	73	68	63	58	53	49	44	39
Leakage† (0.1%) Barrier	4.9	15.8	39	34	29	24	19	14	6	0	0	0	0
Scatter‡ Barrier													
35°	4.6	15.5	61	56	51	47	42	38	33	28	23	19	14
56°	3.8	12.5	49	45	41	37	33	30	26	22	19	15	11
90°	3.6	12.0	42	39	35	31	28	25	21	17	14	10	6
119°	3.3	11.2	39	36	32	29	25	22	19	15	12	8	4

Note: add one tenth-value layer (TVLL), to reduce radiation to 10 mr/week.
* W = work load in r/week at 1 m, U = use factor, T = occupancy factor.
† Refers to leakage radiation of source housing.
‡ For large field (20 cm diameter) and a source—scatterer distance of 50 cm; these values include only scattering from an obliquely positioned concrete scatterer.
From: Recommendations of the ICRP. *Publication No. 3. Report of Committee 3.* Copyright 1960, Pergamon Press, New York.

Table 56.
THICKNESS OF LEAD REQUIRED TO REDUCE USEFUL BEAM TO 5 PERCENT[26]

Beam Quality		Required Lead Thickness, millimeters
Potential	Half-Value Layer, millimeters	
60 kvp	1.2 Al	0.10
100 kvp	1.0 Al	0.16
100 kvp	2.0 Al	0.25
100 kvp	3.0 Al	0.35
140 kvp	0.5 Cu	0.70
200 kvp	1.0 Cu	1.00
250 kvp	3.0 Cu	1.70
400 kvp	4.0 Cu	2.30
1000 kvp	3.2 Pb	20.50
2000 kvp	6.0 Pb	43.00
2000 kvcp	14.5 Pb	63.00
3000 kvcp	16.2 Pb	70.00
6000 kv	17.0 Pb	74.00
8000 kv	15.5 Pb	67.00
^{60}Co	10.4 Pb	47.00

Note: approximate values for broad beams. Transmission data for brass, steel, and other material for potentials up to 2,000 kvp may be found in Reference 15 of Reference 26. Measurements on 1,000 kvp and 2,000 kvp made with resonant-type therapy units. Data for 6,000 kv taken from Reference 33 for a linear accelerator. Data for 2,000 kvcp, 3,000 kvcp, and 8,000 kv derived by interpolation from graph presented in Reference 34. The third column refers to lead or to the required equivalent lead thickness of lead-containing materials (e.g. lead rubber, lead glass, etc.).

From: Medical X-Ray and Gamma-Ray Protection for Energies up to 110 Mev—Equipment Design and Use. *NCRP Report No. 33.* By permission of the National Council on Radiation Protection and Measurements, Washington, D.C.

Figure 24 presents a graph of the effective energy of an X-ray beam of given constant kilovolt potential as a function of the added g/cm² of copper filtration, illustrating the initial rapid hardening of a beam as filtration is added.[36]

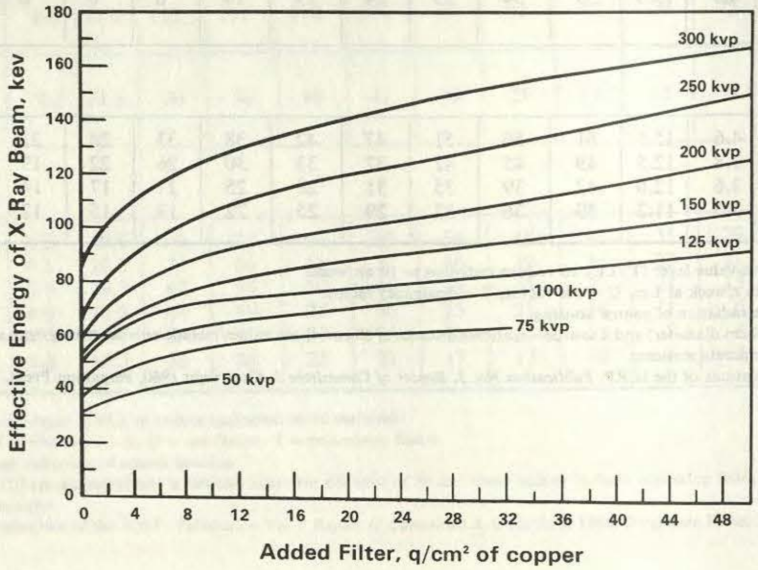

FIGURE 24.
X-Ray Beam Effective Energy vs. Thickness of Copper Filter Added for Various Applied Voltages. (From: Childers, H. M., Brodsky, A., and Nash, A. E., *A Standardized X-Ray Field Range.* Naval Research Laboratory, Washington, D.C., 1958.)

There has been considerable interest in recent years in developing further standards for medical X-ray protection.[37, 38] The increased supervision over the safety aspects of the design and manufacture of equipment, the training of medical X-ray technicians in proper radiation-safety practices, and periodic surveys and equipment calibration by certified physicists may be expected to provide adequate radiation safety in medical installations.

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