EPR-D-VALUES 2006

EMERGENCY PREPAREDNESS AND RESPONSE

Dangerous quantities of radioactive material (D-values)

PUBLICATION DATE: AUGUST 2006

IAEA
International Atomic Energy Agency

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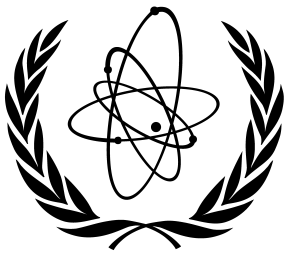

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DANGEROUS QUANTITIES OF RADIOACTIVE MATERIAL (D-VALUES)
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FOREWORD

Radioactive material is widely used in industry, medicine, education and agriculture. In addition, it occurs naturally. The health risk posed by these materials vary widely depending on many factors, the most important of which are the amount of the material involved and its physical and chemical form. Therefore, there is a need to identify the quantity and type of radioactive material for which emergency preparedness and other arrangements (e.g. security) are warrant due to the health risk they pose.

The aim of this publication is to provide practical guidance for Member States on that quantity of radioactive material that may be considered dangerous. A dangerous quantity is that, which if uncontrolled, could be involved in a reasonable scenario resulting in the death of an exposed individual or a permanent injury, which decreases that person's quality of life.

This publication is published as part of the IAEA Emergency Preparedness and Response Series. It supports several publications including: the IAEA Safety Requirements "Preparedness and Response for a Nuclear or Radiological Emergency", IAEA Safety Standards Series No. GS-R-2. IAEA, Vienna (2002); IAEA Safety Guide "Categorization of Radioactive Sources", IAEA Safety Standards Series No RS-G-1.9, IAEA, Vienna (2005) and IAEA Safety Guide "Arrangements for Preparedness for a Nuclear or Radiological Emergency" IAEA Safety Standards Series No. GS-G-2.1, IAEA, Vienna (2006).

The procedures and data in this publication have been prepared with due attention to accuracy. However, as part of the review process, they undergo ongoing quality assurance checks. Comments are welcome and, following a period that will allow for a more extensive review, the IAEA may revise this publication as part of the process of continuous improvement.

The publication uses a number of exposure scenarios, risk models and dosimetric data, which could be used during the response to nuclear or radiological emergency or other purposes. However, this should be done only after careful review and adaptation of the material.

The IAEA is grateful for the contribution made by various experts from Member States that took part in the development of this publication. The IAEA is particularly grateful to V. Kutkov (Kurchatov Institute, Russian Federation) for his development of the risk approach; to K. Eckerman (Oak Ridge National Laboratory, United States of America) for his calculation of the external dose conversion factors described in Appendix IV and to B. Dodd (United States of America) for his review and comments. The IAEA officer responsible for this publication was T. McKenna of the Division of Radiation, Transport and Waste Safety.

EDITORIAL NOTE

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CONTENTS

1. INTRODUCTION

In March 2002, the IAEA's Board of Governors approved a Safety Requirements publication entitled "Preparedness and Response for a Nuclear or Radiological Emergency" [1]. This was jointly sponsored by seven international organizations and it established the requirements for an adequate level of preparedness and response for a nuclear or radiological emergency in any Member State. Amongst other things, the publication specifies requirements for emergencies involving a dangerous source. The Requirements define a dangerous source as one "that could, if not under control, give rise to exposure sufficient to cause severe deterministic effects". The Requirements then go on to define a severe deterministic effect as one that "is fatal or life threatening or results in a permanent injury that decreases the quality of life".

In order to be able to apply the Requirements [1], an operational definition of a dangerous source was needed. This operational definition of a dangerous source is known as the D-value. The D-value is that quantity of radioactive material, which, if uncontrolled, could result in the death of an exposed individual or a permanent injury that decreases that person's quality of life. Refs. [2] and [3] provide D-values for about 65 radionuclides; however, the basis for these D-values was not fully described in those publications. In addition, D-values were not developed for all of the radionuclides that may become of concern. Since there was a need for a categorization of radioactive sources that was based upon the potential for sources to cause deterministic health effects, D-values were also used as normalizing factors in generating the numerical relative ranking of sources and practices. Thus, the D-values in Ref. [2] were also used as the basis for the IAEA's system for categorization of radioactive sources [4], parts of which became included in the Code of Conduct on the Safety and Security of Radioactive Sources [5].

1.1. BACKGROUND

In determining D-values a variety of defined exposure scenarios are used. Allowances are made for the fact that sources may be more hazardous with time (later in life) due to the in-growth of progeny; however, D-values are expressed in terms of the activity of the parent radionuclides before decay, i.e. at the time of manufacture.

Using D-values that are overly conservative may result in unjustified actions and unjustified use of resources and may give decision makers and the public an unrealistic perception of the risks. Consequently, D-values were calculated based on realistic (not overly conservative) assessments of the risk posed by the radioactive material if it becomes uncontrolled.

It should be noted that there is the potential for amounts of material less than the D values given in this report to be dangerous. This could be the case in the event of intentional ingestion of radioactive material or intentionally exposing oneself to a radioactive source. A plain language explanation of the risk associated with different multiples of the D-values is provided in refs [2 and 4].

1.2. OBJECTIVE

The objectives of this publication are to describe, in detail, the basis for the D-values given in Refs [2, 3 and 4] and to provide an expanded set of D-values that includes other radionuclides that may be important in the event of a nuclear or radiological emergency.

1.3. SCOPE

D-values are provided for non-dispersed (D_1-values) and for dispersed (D_2-values) radionuclides that may be important in the event of a nuclear or radiological emergency. This list includes the radionuclides addressed by the transport regulations [6], but has been expanded to include important fission products and possible fissionable materials. External exposure (distant and adjacent) is

considered for non-dispersed material. For dispersed radioactive material, the hazards from intake by inadvertent ingestion, by drinking contaminated water and by inhalation are considered, as well as the hazards from contamination of the skin. For noble gases, only external exposure from immersion is considered.

1.4. STRUCTURE

Section 2 contains the list of the recommended D-values. Sections 3, 4 and 5 contain a summary of their basis to include the health effects, scenarios and characteristics of the radioactive material that were considered. Section 6 describes the approaches used to calculate the D-values.

The appendices provide information and the technical basis for deriving the D-values. Reference and threshold levels for the onset of the deterministic effects used are described in Appendix I. The scenarios used for establishing the D-values are described in Appendix II. Appendix III contains a detailed description of the approaches used to establish the D-values. The dose conversion factors for external and internal exposure and their bases are discussed in Appendices IV, V and VI. Appendix VII contains an evaluation of the D-values. This evaluation includes a comparison of the recommended D-values and the activity of radioactive sources that have been involved in radiological emergencies. Basic nuclear characteristics of the radionuclides considered are given in Appendix VIII. This Appendix also contains a description of the approach used to consider radioactive decay and in-growth of progeny.

Annex I and Annex II provide a guide to the notation used in the report.

2. RECOMMENDED D-VALUES

For the purposes of determining D-values, the exposure scenarios that were used fall into two groups; one for material has not been dispersed and one for which the material that has been dispersed. Different numerical values are provided for each of these groups:

(a) The D_1-value is the activity[1] of a radionuclide in a source that if uncontrolled, but not dispersed (i.e. it remains encapsulated), might result in an emergency that could reasonably be expected to cause severe deterministic health effects;
(b) The D_2-value is the activity[1] of a radionuclide in a source that if uncontrolled and dispersed might result in an emergency that could reasonably be expected to cause severe deterministic health effects;
(c) The D-value is the lowest-value of the D_1- and D_2-values for a radionuclide.

The recommended D_1-, D_2- and D-values are provide in Table 1.

TABLE 1. RECOMMENDED D-VALUES.

Radionuclide [a]	D-value (TBq)	D_1-value (TBq)	D_2-value (TBq)
H-3	2.E+03	UL[b]	2.E+03[c]
Be-7	1.E+00	1.E+00	1.E+03
Be-10	3.E+01	3.E+02	3.E+01
C-11	6.E-02	6.E-02	4.E+02
C-14	5.E+01	2.E+05	5.E+01
N-13	6.E-02	6.E-02	UL
F-18	6.E-02	6.E-02	3.E+01
Na-22	3.E-02	3.E-02	2.E+01
Na-24	2.E-02	2.E-02	2.E+01
Mg-28	2.E-02	2.E-02	1.E+01
Al-26	3.E-02	3.E-02	5.E+00
Si-31	1.E+01	1.E+01	2.E+01
Si-32+	7.E+00	1.E+01	7.E+00
P-32	1.E+01	1.E+01	2.E+01
P-33	2.E+02	7.E+03	2.E+02
S-35	6.E+01	4.E+04	6.E+01
Cl-36	2.E+01[d]	3.E+02	2.E+01[d]
Cl-38	5.E-02	5.E-02	1.E+01
Ar-37	UL [e]	UL	UL [e]
Ar-39	3.E+02	3.E+02	3.E+04
Ar-41	5.E-02	5.E-02	3.E+00[d]
K-40	UL [e]	UL	UL [e]
K-42	2.E-01	2.E-01	1.E+01

[1] Allowances are made for the fact that sources may be more hazardous later in life (up to 10 years) due to the in-growth of progeny; however, D-values are expressed in terms of the activity of the parent radionuclides before decay, i.e. at the time of manufacture as described in Appendix VIII.

Radionuclide [a]	D-value	D_1-value	D_2-value
	(TBq)	(TBq)	(TBq)
K-43	7.E-02	7.E-02	3.E+01
Ca-41	UL [e]	UL	UL [e]
Ca-45	1.E+02	6.E+03	1.E+02
Ca-47+	6.E-02	6.E-02	1.E+01
Sc-44	3.E-02	3.E-02	1.E+01
Sc-46	3.E-02	3.E-02	4.E+01
Sc-47	7.E-01	7.E-01	8.E+01
Sc-48	2.E-02	2.E-02	3.E+01
Ti-44+	3.E-02	3.E-02	9.E+00
V-48	2.E-02	2.E-02	3.E+01
V-49	2.E+03	UL	2.E+03
Cr-51	2.E+00	2.E+00	5.E+03
Mn-52	2.E-02	2.E-02	2.E+01
Mn-53	UL [e]	UL	UL [e]
Mn-54	8.E-02	8.E-02	4.E+01
Mn-56	4.E-02	4.E-02	2.E+01
Fe-52+	2.E-02	2.E-02	9.E+00
Fe-55	8.E+02	UL	8.E+02
Fe-59	6.E-02	6.E-02	1.E+01
Fe-60+	6.E-02	6.E-02	1.E+01 [d]
Co-55+	3.E-02	3.E-02	2.E+02
Co-56	2.E-02	2.E-02	2.E+01
Co-57	7.E-01	7.E-01	4.E+02
Co-58	7.E-02	7.E-02	7.E+01
Co-58m+	7.E-02	7.E-02	2.E+02
Co-60	3.E-02	3.E-02	3.E+01
Ni-59	1.E+03 [d]	UL	1.E+03 [d]
Ni-63	6.E+01	UL	6.E+01
Ni-65	1.E-01	1.E-01	2.E+01
Cu-64	3.E-01	3.E-01	4.E+01
Cu-67	7.E-01	7.E-01	3.E+02
Zn-65	1.E-01	1.E-01	3.E+02
Zn-69	3.E+01	8.E+01	3.E+01
Zn-69m+	2.E-01	2.E-01	2.E+01
Ga-67	5.E-01	5.E-01	4.E+02
Ga-68	7.E-02	7.E-02	1.E+01
Ga-72	3.E-02	3.E-02	2.E+01
Ge-68+	7.E-02	7.E-02	2.E+01
Ge-71	1.E+03	6.E+05	1.E+03
Ge-77+	6.E-02	6.E-02	1.E+01
As-72	4.E-02	4.E-02	9.E+01
As-73	4.E+01	4.E+01	1.E+02

Radionuclide [a]	D-value	D_1-value	D_2-value
	(TBq)	(TBq)	(TBq)
As-74	9.E-02	9.E-02	3.E+01
As-76	2.E-01	2.E-01	1.E+01
As-77	8.E+00	8.E+00	4.E+01
Se-75	2.E-01	2.E-01	2.E+02
Se-79	2.E+02	UL	2.E+02
Br-76	3.E-02	3.E-02	2.E+02
Br-77	2.E-01	2.E-01	7.E+02
Br-82	3.E-02	3.E-02	7.E+01
Kr-81	3.E+01	3.E+01	7.E+02
Kr-85	3.E+01	3.E+01	2.E+03
Kr-85m	5.E-01	5.E-01	3.E+01
Kr-87	9.E-02	9.E-02	4.E+00
Rb-81	1.E-01	1.E-01	2.E+03
Rb-83	1.E-01	1.E-01	5.E+01
Rb-84	7.E-02	7.E-02	2.E+01
Rb-86	7.E-01	7.E-01	2.E+01
Rb-87	UL [e]	UL	UL [e]
Sr-82	6.E-02	6.E-02	5.E+00
Sr-85	1.E-01	1.E-01	7.E+01
Sr-85m+	1.E-01	1.E-01	3.E+02
Sr-87m	2.E-01	2.E-01	9.E+01
Sr-89	2.E+01	2.E+01	2.E+01
Sr-90+	1.E+00	4.E+00	1.E+00
Sr-91+	6.E-02	6.E-02	2.E+01
Sr-92+	4.E-02	4.E-02	1.E+01
Y-87+	9.E-02	9.E-02	2.E+02
Y-88	3.E-02	3.E-02	2.E+01
Y-90	5.E+00	5.E+00	1.E+01
Y-91	8.E+00	8.E+00	2.E+01
Y-91m+	1.E-01	1.E-01	2.E+02
Y-92	2.E-01	2.E-01	1.E+01
Y-93	6.E-01	6.E-01	1.E+01
Zr-88+	2.E-02	2.E-02	3.E+01
Zr-93+	UL [e]	UL	UL [e]
Zr-95+	4.E-02	4.E-02	1.E+01
Zr-97+	4.E-02	4.E-02	9.E+00
Nb-93m	3.E+02	2.E+03	3.E+02
Nb-94	4.E-02	4.E-02	3.E+01 [d]
Nb-95	9.E-02	9.E-02	6.E+01
Nb-97	1.E-01	1.E-01	2.E+01
Mo-93+	3.E+02 [d]	2.E+03	3.E+02 [d]
Mo-99+	3.E-01	3.E-01	2.E+01

Radionuclide [a]	D-value	D_1-value	D_2-value
	(TBq)	(TBq)	(TBq)
Tc-95m	1.E-01	1.E-01	6.E+01
Tc-96	3.E-02	3.E-02	3.E+01
Tc-96m+	3.E-02	3.E-02	2.E+02
Tc-97	UL [e]	UL	UL [e]
Tc-97m	4.E+01	2.E+02	4.E+01
Tc-98	5.E-02	5.E-02	1.E+01 [d]
Tc-99	3.E+01	UL	3.E+01
Tc-99m	7.E-01	7.E-01	7.E+02
Ru-97	3.E-01	3.E-01	5.E+02
Ru-103+	1.E-01	1.E-01	3.E+01
Ru-105+	8.E-02	8.E-02	2.E+01
Ru-106+	3.E-01	3.E-01	1.E+01
Rh-99	1.E-01	1.E-01	1.E+02
Rh-101	3.E-01	3.E-01	1.E+02
Rh-102	3.E-02	3.E-02	3.E+01
Rh-102m	1.E-01	1.E-01	4.E+01
Rh-103m	9.E+02	9.E+02	1.E+04
Rh-105	9.E-01	9.E-01	8.E+01
Pd-103+	9.E+01	9.E+01	1.E+02
Pd-107	UL [e]	UL	UL [e]
Pd-109	2.E+01	2.E+01	2.E+01
Ag-105	1.E-01	1.E-01	1.E+02
Ag-108m	4.E-02	4.E-02	2.E+01
Ag-110m	2.E-02	2.E-02	2.E+01
Ag-111	2.E+00	2.E+00	3.E+01
Cd-109	2.E+01	2.E+01	3.E+01
Cd-113m	4.E+01	4.E+02	4.E+01
Cd-115+	2.E-01	2.E-01	2.E+01
Cd-115m	3.E+00	3.E+00	2.E+01
In-111	2.E-01	2.E-01	1.E+02
In-113m	3.E-01	3.E-01	5.E+01
In-114m	8.E-01	8.E-01	1.E+00
In-115m	4.E-01	4.E-01	3.E+01
Sn-113+	3.E-01	3.E-01	5.E+01
Sn-117m	5.E-01	5.E-01	4.E+01
Sn-119m	7.E+01	7.E+01	1.E+02
Sn-121m+	7.E+01	1.E+02	7.E+01
Sn-123	7.E+00	7.E+00	2.E+01
Sn-125	1.E-01	1.E-01	8.E+00
Sn-126+	3.E-02	3.E-02	7.E+00[d]
Sb-122	1.E-01	1.E-01	2.E+01
Sb-124	4.E-02	4.E-02	1.E+01

Radionuclide [a]	D-value	D_1-value	D_2-value
	(TBq)	(TBq)	(TBq)
Sb-125+	2.E-01	2.E-01	3.E+01
Sb-126	2.E-02	2.E-02	2.E+01
Te-121	1.E-01	1.E-01	3.E+01
Te-121m+	1.E-01	1.E-01	8.E+00
Te-123m	6.E-01	6.E-01	9.E+00
Te-125m	1.E+01	2.E+01	1.E+01
Te-127	1.E+01	1.E+01	4.E+01
Te-127m+	3.E+00	1.E+01	3.E+00
Te-129	1.E+00	1.E+00	2.E+01
Te-129m+	1.E+00	1.E+00	2.E+00
Te-131m+	4.E-02	4.E-02	2.E-01
Te-132+	3.E-02	3.E-02	8.E-01
I-123	5.E-01	5.E-01	3.E+01
I-124	6.E-02	6.E-02	4.E-01
I-125	2.E-01	1.E+01	2.E-01
I-126	1.E-01	1.E-01	2.E-01
I-129	UL [e]	UL	UL [e]
I-131	2.E-01	2.E-01	2.E-01
I-132	3.E-02	3.E-02	6.E+00
I-133	1.E-01	1.E-01	3.E-01
I-134	3.E-02	3.E-02	2.E+01
I-135	4.E-02	4.E-02	2.E+00
Xe-122	6.E-02	6.E-02	4.E+00
Xe-123+	9.E-02	9.E-02	5.E+00
Xe-127	3.E-01	3.E-01	2.E+01
Xe-131m	1.E+01	1.E+01	7.E+02
Xe-133	3.E+00	3.E+00	2.E+02
Xe-135	3.E-01	3.E-01	2.E+01
Cs-129	3.E-01	3.E-01	1.E+03
Cs-131	2.E+01	2.E+01	2.E+03
Cs-132	1.E-01	1.E-01	1.E+02
Cs-134	4.E-02	4.E-02	3.E+01
Cs-134m+	4.E-02	4.E-02	1.E+04
Cs-135	UL [e]	UL	UL [e]
Cs-136	3.E-02	3.E-02	2.E+01
Cs-137+	1.E-01	1.E-01	2.E+01
Ba-131+	2.E-01	2.E-01	1.E+02
Ba-133	2.E-01	2.E-01	7.E+01
Ba-133m	3.E-01	3.E-01	2.E+02
Ba-140+	3.E-02	3.E-02	1.E+01
La-137	2.E+01	2.E+01	5.E+02[d]
La-140	3.E-02	3.E-02	2.E+01

Radionuclide [a]	D-value	D_1-value	D_2-value
	(TBq)	(TBq)	(TBq)
Ce-139	6.E-01	6.E-01	2.E+02
Ce-141	1.E+00	1.E+00	2.E+01
Ce-143+	3.E-01	3.E-01	1.E+01
Ce-144+	9.E-01	9.E-01	9.E+00
Pr-142	1.E+00	1.E+00	2.E+01
Pr-143	3.E+01	8.E+01	3.E+01
Nd-147+	6.E-01	6.E-01	4.E+01
Nd-149+	2.E-01	2.E-01	1.E+01
Pm-143	2.E-01	2.E-01	2.E+02
Pm-144	4.E-02	4.E-02	3.E+01
Pm-145	1.E+01	1.E+01	4.E+02
Pm-147	4.E+01	8.E+03	4.E+01
Pm-148m	3.E-02	3.E-02	3.E+01
Pm-149	6.E+00	6.E+00	2.E+01
Pm-151	2.E-01	2.E-01	3.E+01
Sm-145+	4.E+00	4.E+00	2.E+02
Sm-147	UL [e]	UL	UL [e]
Sm-151	5.E+02	UL	5.E+02
Sm-153	2.E+00	2.E+00	4.E+01
Eu-147	2.E-01	2.E-01	1.E+02
Eu-148	3.E-02	3.E-02	3.E+01
Eu-149	2.E+00	2.E+00	5.E+02
Eu-150b	2.E+00	2.E+00	3.E+01
Eu-150a	5.E-02	5.E-02	4.E+02
Eu-152	6.E-02	6.E-02	3.E+01
Eu-152m	2.E-01	2.E-01	2.E+01
Eu-154	6.E-02	6.E-02	2.E+01
Eu-155	2.E+00	2.E+00	1.E+02
Eu-156	5.E-02	5.E-02	3.E+01
Gd-146+	3.E-02	3.E-02	8.E+00
Gd-148	4.E-01	UL	4.E-01
Gd-153	1.E+00	1.E+00	8.E+01
Gd-159	2.E+00	2.E+00	3.E+01
Tb-157	1.E+02	1.E+02	1.E+03 [d]
Tb-158	9.E-02	9.E-02	5.E+01 [d]
Tb-160	6.E-02	6.E-02	3.E+01
Dy-159	6.E+00	6.E+00	5.E+02
Dy-165	3.E+00	3.E+00	2.E+01
Dy-166+	1.E+00	1.E+00	2.E+01
Ho-166	2.E+00	2.E+00	2.E+01
Ho-166m	4.E-02	4.E-02	3.E+01 [d]
Er-169	2.E+02	2.E+03	2.E+02

Radionuclide [a]	D-value	D_1-value	D_2-value
	(TBq)	(TBq)	(TBq)
Er-171	2.E-01	2.E-01	2.E+01
Tm-167	6.E-01	6.E-01	2.E+02
Tm-170	2.E+01	2.E+01	2.E+01
Tm-171	3.E+02	3.E+02	4.E+02
Yb-169	3.E-01	3.E-01	3.E+01
Yb-175	2.E+00	2.E+00	1.E+02
Lu-172	4.E-02	4.E-02	6.E+01
Lu-173	9.E-01	9.E-01	2.E+02
Lu-174	8.E-01	8.E-01	1.E+02
Lu-174m+	6.E-01	6.E-01	6.E+01
Lu-177	2.E+00	2.E+00	1.E+02
Hf-172+	4.E-02	4.E-02	6.E+00
Hf-175	2.E-01	2.E-01	3.E+01
Hf-181	1.E-01	1.E-01	1.E+01
Hf-182+	5.E-02	5.E-02	UL [e]
Ta-178a	7.E-02	7.E-02	4.E+03
Ta-179	6.E+00	6.E+00	6.E+02
Ta-182	6.E-02	6.E-02	3.E+01
W-178	9.E-01	9.E-01	6.E+02
W-181	5.E+00	5.E+00	2.E+03
W-185	1.E+02	7.E+02	1.E+02
W-187	1.E-01	1.E-01	3.E+01
W-188+	1.E+00	1.E+00	8.E+00
Re-184	8.E-02	8.E-02	3.E+01
Re-184m+	7.E-02	7.E-02	2.E+01
Re-186	4.E+00	4.E+00	1.E+01
Re-187	UL [e]	UL	UL [e]
Re-188	1.E+00	1.E+00	3.E+01
Re-189	1.E+00	1.E+00	1.E+01
Os-185	1.E-01	1.E-01	7.E+01
Os-191	2.E+00	2.E+00	9.E+01
Os-191m+	1.E+00	1.E+00	7.E+02
Os-193	1.E+00	1.E+00	3.E+01
Os-194+	7.E-01	7.E-01	9.E+00
Ir-189	1.E+00	1.E+00	2.E+02
Ir-190	5.E-02	5.E-02	6.E+01
Ir-192	8.E-02	8.E-02	2.E+01
Ir-194	7.E-01	7.E-01	2.E+01
Pt-188+	4.E-02	4.E-02	9.E+01
Pt-191	3.E-01	3.E-01	3.E+02
Pt-193	3.E+03	1.E+05	3.E+03
Pt-193m	1.E+01	1.E+01	4.E+02

Radionuclide [a]	D-value	D_1-value	D_2-value
	(TBq)	(TBq)	(TBq)
Pt-195m	2.E+00	2.E+00	3.E+02
Pt-197	4.E+00	4.E+00	5.E+01
Pt-197m+	9.E-01	9.E-01	2.E+01
Au-193	6.E-01	6.E-01	1.E+03
Au-194	7.E-02	7.E-02	4.E+02
Au-195	2.E+00	2.E+00	1.E+02
Au-198	2.E-01	2.E-01	3.E+01
Au-199	9.E-01	9.E-01	3.E+02
Hg-194+	7.E-02	7.E-02	9.E+00
Hg-195m+	2.E-01	2.E-01	1.E+01
Hg-197	2.E+00	2.E+00	3.E+01
Hg-197m+	7.E-01	7.E-01	2.E+01
Hg-203	3.E-01	3.E-01	2.E+00
Tl-200	5.E-02	5.E-02	2.E+02
Tl-201	1.E+00	1.E+00	1.E+03
Tl-202	2.E-01	2.E-01	2.E+02
Tl-204	2.E+01	7.E+01	2.E+01
Pb-201+	9.E-02	9.E-02	8.E+02
Pb-202+	2.E-01	2.E-01	6.E+01 [d]
Pb-203	2.E-01	2.E-01	2.E+02
Pb-205	UL [e]	UL	UL [e]
Pb-210+	3.E-01	4.E+01	3.E-01
Pb-212+	5.E-02	5.E-02	9.E+00
Bi-205	4.E-02	4.E-02	7.E+01
Bi-206	2.E-02	2.E-02	5.E+01
Bi-207	5.E-02	5.E-02	4.E+01
Bi-210+	8.E+00	5.E+01	8.E+00
Bi-210m	3.E-01	6.E-01	3.E-01
Bi-212+	5.E-02	5.E-02	1.E+01
Po-210	6.E-02	8.E+03	6.E-02
At-211	5.E-01	5.E-01	1.E+01
Rn-222	4.E-02	4.E-02	9.E+04 [f]
Ra-223+	1.E-01	2.E-01	1.E-01
Ra-224+	5.E-02	5.E-02	3.E-01
Ra-225+	1.E-01	3.E-01	1.E-01
Ra-226+	4.E-02	4.E-02	7.E-02
Ra-228+	3.E-02	3.E-02	4.E-02
Ac-225	9.E-02	3.E-01	9.E-02
Ac-227+	4.E-02	2.E-01	4.E-02
Ac-228	3.E-02	3.E-02	1.E+02
Th-227+	8.E-02	2.E-01	8.E-02
Th-228+	4.E-02	5.E-02	4.E-02

Radionuclide [a]	D-value (TBq)	D_1-value (TBq)	D_2-value (TBq)
Th-229+	1.E-02	2.E-01	1.E-02
Th-230+	7.E-02 [d]	9.E+02	7.E-02 [d]
Th-231	1.E+01	1.E+01	3.E+02
Th-232+	UL [e]	UL	UL [e]
Th-234+	2.E+00	2.E+00	2.E+00
Pa-230+	1.E-01	1.E-01	9.E-01
Pa-231+	6.E-02	8.E-01	6.E-02
Pa-233	4.E-01	4.E-01	8.E+00
U-230+	4.E-02	4.E+00	4.E-02
U-232+	6.E-02 [d]	7.E-02	6.E-02 [d]
U-233	7.E-02 [f]	7.E-02 [f]	7.E-02 [d,f]
U-234+	1.E-01 [f]	1.E-01 [f]	1.E-01 [d,f]
U-235+	8.E-05 [f]	8.E-05 [f]	8.E-05 [f]
U-236	2.E-01 [d]	UL	2.E-01 [d]
U-238+	UL [e]	UL	UL [e]
U Natural	UL [e]	UL	UL [e]
U Depleted	UL [e]	UL	UL [e]
U Enriched 10-20%	8E-04 [f]	8E-04 [f]	8E-04 [f]
U Enriched >20 %	8E-05 [f]	8E-05 [f]	8E-05 [f]
Np-235	1.E+02	1.E+02	2.E+02
Np-236b+	7.E-03	7.E-03 [f]	7.E-03 [f]
Np-236a	8.E-01	8.E-01	7.E+00
Np-237+	7.E-02	3.E-01 [f]	7.E-02 [d]
Np-239	5.E-01	5.E-01	6.E+01
Pu-236	1.E-01	1.E+00	1.E-01
Pu-237	2.E+00	2.E+00	6.E+01
Pu-238	6.E-02	3.E+02 [f]	6.E-02
Pu-239	6.E-02	1.E+00 [f]	6.E-02
Pu-240	6.E-02	4.E+00 [f]	6.E-02
Pu-241+	3.E+00	2.E+03 [f]	3.E+00
Pu-242	7.E-02 [d, f]	7.E-02 [d, f]	7.E-02 [d, f]
Pu-244+	3.E-04 [d, f]	3.E-04 [f]	3.E-04 [d, f]
Am-241	6.E-02	8.E+00	6.E-02
Am-242m+	3.E-01	1.E+00 [f]	3.E-01
Am-243+	2.E-01	4.E-01	2.E-01
Am-244	9.E-02	9.E-02	9.E+01
Cm-240	3.E-01	1.E+00	3.E-01
Cm-241+	1.E-01	1.E-01	7.E+00
Cm-242	4.E-02	2.E+03	4.E-02
Cm-243	2.E-01	6.E-01	2.E-01
Cm-244	5.E-02	1.E+04 [f]	5.E-02
Cm-245	9.E-02 [f]	9.E-02 [f]	9.E-02 [f]

Radionuclide [a]	D-value	D_1-value	D_2-value
	(TBq)	(TBq)	(TBq)
Cm-246	2.E-01	6.E+00 [f]	2.E-01
Cm-247	1.E-03 [f]	1.E-03 [f]	1.E-03 [f]
Cm-248	5.E-03	5.E-03	7.E-02 [d]
Bk-247	8.E-02	8.E-02 [f]	8.E-02 [f]
Bk-249	1.E+01	1.E+01	4.E+01
Cf-248+	1.E-01	1.E+02 [f]	1.E-01
Cf-249	1.E-01	2.E-01	1.E-01
Cf-250	1.E-01	4.E-01	1.E-01
Cf-251	1.E-01	7.E-01	1.E-01
Cf-252	2.E-02	2.E-02	1.E-01
Cf-253	4.E-01	1.E+01	4.E-01
Cf-254	3.E-04	3.E-04	2.E-03
^{239}Pu/^{9}Be	6.E-02 [g]	1.E+00 [f, g]	6.E-02 [g]
^{241}Am/^{9}Be	6.E-02 [g]	1.E+00 [g]	6.E-02 [g]

a. In growth of radioactive progeny was taken into account when calculating the D values for all the radionuclides as described in Appendix VIII. An "+" indicates the radionuclides for which the progeny were significant sources of dose for the scenarios considered.

b. "UL" - Unlimited quantity as defined in Appendix II.

c. The intake fraction for ^{3}H was doubled to account for skin absorption of dispersed material. This was a conservative assumption based on ICRP Publication 71 [7] data suggesting that in atmospheric contamination by HTO, absorption through the skin contributes about 1/3 of the inhalation intake.

d. Emergencies involving these amounts of radionuclides may result in airborne concentrations exceeding the level assumed to be an immediate danger to life or health (IDLH). For more details see Appendix VIII.

e. Emergencies involving bulk amounts of these radionuclides may result in airborne concentrations exceeding the level assumed to be an immediate danger to life or health (IDLH). For more details see Appendix VIII.

f. D-value is based on consideration of the criticality limit. For more details see Appendix VIII.

g. The activity given is that of the alpha-emitting radionuclide, e.g. ^{239}Pu or ^{241}Am.

3. HEALTH EFFECTS CONSIDERED

The D-value is that quantity of radioactive material that, if uncontrolled, could result in the death of an exposed individual or a permanent injury that decreases that person's quality of life. Such health effects are referred to as severe deterministic health effects. Severe deterministic effects usually occur soon after exposure. Their severity is greater for higher doses received, and there is an effective threshold of dose below which they do not occur at all.

Two types of severe deterministic health effects were considered in calculating the D-values, namely fatal and non-fatal:

(a) Fatal effects are those that, if developed, lead to death. Experience [8,9] and research show that deaths from radiation exposure are ultimately the result of multi-organ failure. However, the organs and tissues considered here were selected because damage to them is considered critical for all radiological or nuclear emergencies. In other words, keeping the exposure dose below the threshold dose for these organs should prevent the death of the exposed person.
(b) Non-fatal effects are those that reduce the quality of life and are organ or tissue specific.

The threshold or reference values of dose used to indicate when severe deterministic effects could be expected to occur and the dosimetric methods used to calculate the dose for various exposure scenarios are described in Appendix I.

3.1 FATAL DETERMINISTIC HEALTH EFFECTS

Red marrow and colon. Exposure of the red marrow (haematopoietic system) or colon (gastrointestinal tract) can result in effects that are life threatening or fatal. This can result from exposure of the whole body from an external source or from an internal exposure following ingestion or inhalation. For external exposure, red marrow effects will be the critical ones. Following intake, either radiation induced effects to the red marrow or the colon may be critical, depending upon the radionuclide and its physical form.

Lung regions. Exposure of the lung is critical following inhalation for most radionuclides but this may depend on the physical form (e.g. solubility) of the material inhaled. Exposure to the lung can result in a lethal effect (pneumonitis) as well as effects that reduce the quality of life (pulmonary fibrosis). Here it was assumed that the development of pulmonary fibrosis would ultimately be fatal.

Skin regions. Clinical manifestations of deterministic effects from skin exposure start from erythema, and can be followed by epilation, dry and moist desquamation, blister formation, ulceration and necrosis depending on the dose received. Erythema is not considered a severe deterministic health effect. Moist desquamation and subsequent more severe stages of skin damage are considered severe deterministic health effects. The severity of the injury depends not only on the dose and on the type of radiation, but also on the location and size of the area exposed. Moist desquamation to a large area (over 100 cm^2) of the surface of the skin is considered to be potentially fatal especially if combined with other injures or exposures as occurred to the fire fighters during the Chernobyl accident.

3.2 NON-FATAL DETERMINISTIC HEALTH EFFECTS

Soft tissue. External exposure from carrying an unshielded source in the hand or pocket can cause localized necrosis (tissue death). This is the most common cause of radiation-induced severe deterministic health effects involving uncontrolled (stolen or lost) radioactive sources. While local necrosis of soft tissue is usually not life threatening, it can cause lost of function (e.g. of the hand) or injuries requiring reconstructive surgery. Past clinical experience in treating soft tissue injures indicate that necrosis in an area of 50 to 100 cm^2 to a depth of 0.5 cm requires multiple surgical operations and therefore is considered a severe deterministic health effect. Experience also indicates that necrosis to a depth of 0.1 to 0.2 cm in the hand can result in loss of functions and therefore it is considered a severe deterministic health effect.

Thyroid. Examples of deterministic health effects after thyroid irradiation include acute radiation thyroiditis (characterized by inflammation and necrosis of the thyroid tissue) and hypothyroidism (abnormal metabolic state due to insufficient amounts of thyroid hormones for normal physiologic function). These effects are typically not fatal if properly treated. However, this treatment often requires taking hormone replacement drugs for a lifetime. Therefore radiation inducted injures to the thyroid were considered as severe deterministic health effects because they reduce the quality of life.

Lens of the eye. The lens of the eye is particular radiosensitive, with subsequent production of opacities or cataract formation within the lens. Cataracts have been identified as a late health effect in atomic bomb survivors and in many accidental exposures. They can result in blindness or at least impaired vision and are considered a severe deterministic health effect.

Reproductive organs. Examples of deterministic health effects resulting from exposure of reproductive organs include temporary and permanent sterility or suppression of ovulation and sperm production. Permanent sterility or permanent suppression of ovulation and sperm production are considered severe deterministic health effects because they would, in many cases, decrease the quality of life.

Embryo and foetus. Non fatal deterministic health effects from foetal exposure include an increase in malformation and impairment of mental development over the background incidence. Most of these effects have a threshold that is above 100 to 200 mGy. However, during the period of 8–25 weeks post

conception, a foetal dose of 100 mGy or more may result in a verifiable decrease in the intelligence quotient (IQ). The involvement of a pregnant woman during the most sensitive period of foetus development in a radiological emergency is likely to be very rare, and consideration of these effects would result in D_1-values that would be about a factor 10 more limiting than those calculated based on all other severe deterministic health effects. Use of such values would be very conservative for the vast majority of potential radiological emergencies. Therefore, it was decided not to consider non fatal effects resulting from embryo and foetal exposure in establishing D-values.

4. SCENARIOS AND EXPOSURE PATHWAYS

In determining D-values, a number of defined scenarios that could result in human exposures following loss of control over a source were considered. These scenarios and assumptions were developed taking account of past experience[2] and other relevant concerns such as malicious use of radioactive materials (e.g. use in an radiological dispersal device (RDD)). The scenarios considered are summarized in Table 2 and their details are presented in Appendix II.

TABLE 2. SCENARIOS CONSIDERED IN DETERMINING THE D VALUES

	D_1-value Non-dispersed material		D_2-value Dispersed material			
Organs or tissue	Pocket (I)	Room (II)	Inhalation (III)	Ingestion (IV)	Contamination [a] (V)	Immersion (VI)
Red marrow		●	●	●		●
Colon		●	●	●		●
Lung regions		●	●	●		●
Skin regions					●	
Soft tissue	●					
Thyroid		●	●	●		●
Len of the eye		●				●
Reproductive		●				●

a. skin contamination

In calculating the D_1-values for non-dispersed material, the following scenarios were considered:

(a) the “pocket” scenario (Scenario I), in which it was assumed that the person was carrying an unshielded source resulting in localized damage to soft tissue; and,
(b) the "room" scenario (Scenario II), in which it was assumed that a person was in the vicinity of an unshielded source for days to weeks resulting in exposure to the total body by external penetrating radiation.

In calculating the D_2-value for dispersed material, the following scenarios were considered:

(a) the “inhalation” scenario (Scenario III), in which it was assumed that there was a fire or explosion (e.g. RDD) exposing someone to airborne radioactive material;
(b) the “ingestion” scenario (Scenario IV), in which the more limiting of two scenarios was used. The first assumed that the source was leaking and was handled resulting in inadvertent ingestion of the material. In the second it was assumed that the source was

[2] See Appendix VII.

placed in a public water supply resulting in contamination of the water, which was then drunk;

(c) the "contamination" scenario (Scenario V), in which it was assumed that the skin became contaminated due to a leaking source;

(d) the "immersion" scenario (Scenario VI) for exposure to noble gases, for which it was assumed that the activity was released into a room exposing the occupants. In this case, only external exposure of red marrow was considered.

The specific assumptions used in the derivation of the radionuclide-specific D-values were established such that there is a reasonable confidence that:

(a) holding or carrying (e.g. in a pocket) less than this amount of unshielded radioactive material should not result in an injury that will reduce the quality of life;

(b) having less than this amount of unshielded radioactive material at home or in the work place should not result in an exposure that is life threatening or that can cause an injury that will reduce the quality of life;

(c) airborne dispersal resulting from a fire or explosion involving less than this amount of radioactive material should not result in injuries from inhalation that would be life threatening or reduce the quality of life;

(d) handling a ruptured container containing less than this amount of dispersible material should not result in an inadvertent ingestion or skin contamination that would be life threatening or that could cause an injury that will reduce the quality of life;

(e) a source containing less than this amount of dispersible material placed in a public water supply should not result in any severe deterministic effects due to water consumption; and,

(f) a source containing less than this amount of radioactive material cannot go critical.

5. IMPORTANT CHARACTERISTICS OF A SOURCE

This section discusses characteristics of the material in a source that are important in determining the D-value. This is addressed in more detail in Appendix VIII.

Decay and in-growth. A radioactive source has a life that starts when the source is manufactured and finishes when the source is decommissioned and conditioned as radioactive waste. The physical properties of a source change during this period. The activity of a parent radionuclide at the time of manufacture (initial activity) decreases due to decay, but there may be an increase in the activity of other radionuclides (called progeny or daughters) resulting from the decay. This increase is often called in-growth. For most radionuclides the danger decreases with the source's age due to a decrease of its total activity. However, for some radionuclide decay chains (e.g. $^{241}Pu \rightarrow {}^{241}Am$) the daughter radionuclides are more radiologically toxic, for some pathways, than the parent and therefore the hazard can increase with the age of a source. The time when a source may be involved in an emergency is unpredictable and therefore the activity of a source at the time of an emergency is similarly unpredictable. To take this into account, D-values were calculated for the most dangerous mixture of parent and progeny radionuclides any time up to 10 years. However, the D-values are expressed in terms of the "initial activity" (activity before in-growth) of the parent radionuclide in the source. The details of how this was considered are described in Appendix VIII.

Nuclear radiation and its interactions. Nuclear transformations[3] in a radionuclide can generate different ionizing radiations. Two groups of radiations are important for this report. They are those with high linear energy transfer (LET), such as alpha particles and neutrons, and those with low LET, including beta particles and photons.

[3] Also called "radioactive decay".

(a) Photon-emitting radionuclides constitute both an internal and external hazard. Photons are one of the most penetrating types of radiation, being able to pass without interaction, many metres in air and many centimetres in the human body. Scattering of photons in air (the sky shine effect) is not a significant contributor to dose from a source that is only one metre from a body. Thus, it was not taken into account in calculating the D_1-values. However, multiple scattering of photons inside the human body was considered in dosimetry calculations.

(b) Neutrons lose energy primarily by interactions with light nuclei. Therefore, they can travel metres in lead, but are effectively stopped by water or the soft tissue of the human body. Interaction of neutrons with matter usually produces recoil nuclei and secondary photons. Therefore, neutron-emitting sources constitute both an internal and an external hazard. One source of neutrons are radionuclides capable of spontaneous fission (e.g. ^{252}Cf). In addition some dense mixtures of alpha-emitting radionuclides (e.g. ^{239}Pu and ^{241}Am) and Be, C, N, O or F can be a source of neutrons by the (α, n) reaction. Sources containing ^{241}Am/^{9}Be and ^{239}Pu/^{9}Be are commonly used as neutron sources for scientific and commercial applications, and can be an important source of external exposure. However the size of particles that can be inhaled or ingested from dispersal of the material in these neutron sources would be too small for effective production of neutron emissions by the (α, n) reaction. Therefore for ^{241}Am/^{9}Be and ^{239}Pu/^{9}Be sources, the D_1-values were calculated including the external exposure from neutrons produced by the (α, n) reaction, but the D_2-values do not include any dose contribution from neutron production following intake.

(c) High-energy beta particles can travel several metres in air but can just penetrate skin and millimetres of soft tissue. Therefore, beta-emitting radionuclides are normally only considered an internal hazard following an intake or a skin hazard following contamination of the skin. However, if high-energy beta particles interact with material that has a high atomic number (Z), a significant part of their energy may be converted into bremsstrahlung photons. Radionuclide sources containing radionuclides emitting large quantities of high-energy beta particles (e.g. ^{90}Sr) could therefore be a significant source of penetrating radiation which would then present an external exposure hazard. Therefore, the external dose from bremsstrahlung was considered in calculating the D_1-values. Bremsstrahlung production is negligible if high-energy beta particles interact with material that has a low Z, i.e.soft tissue of the human body. Therefore, this effect was not considered in calculating the D_2-values characterizing human exposure following intake.

(d) Alpha particles are the least penetrating of ionizing radiations. They can be stopped by the outer layers of skin, and are normally only a health hazard after the alpha-emitting material enters the body. In some circumstances, alpha particles can interact with light nuclei producing neutrons via the (α, n) reaction as discussed above.

Criticality limitation. There are some radionuclides that are capable of supporting a chain reaction, and this would represent both a safety and a security concern. If the mass of the activity considered dangerous, as calculated according to one of the exposure scenarios, was greater than a limit established to prevent criticality, then the activity for the criticality limit was used in establishing the D-value.

Chemical toxicity limitation. The airborne release of any substance is hazardous to human health due to chemical toxicity and other factors if the airborne concentration is sufficiently high. There are some radionuclides that, due to their low specific activity, have D-values for which the mass of an airborne release may have the potential to be hazardous for non-radiological reasons, e.g., for chemical toxicity. The assessment of the risk of exposure due to non-radiological effects is beyond the scope of this publication. However, where this potential exists for a particular radionuclide D-value, it is noted.

6. APPROACHES FOR CALCULATING THE D-VALUES

Two different approaches were used for calculating D-values. In this report these have been termed the expert and the risk approaches:

(a) The expert approach for calculating the D-values was based on readily available data, consideration of existing guidance [10, 11] and professional judgment. This was done in order to meet a pressing need for certain D-values in the near term. The expert approach was used for calculating D-values for a number of the main radionuclides [2, 3] of interest.
(b) The risk approach for calculating D-values was based on a quantitative evaluation of the risk of developing severe deterministic effects. The models used for this approach were based on life-span studies [12, 13, 14] and on a rigorous examination of the latest data and models. The full development of this approach for the purpose of emergency response is documented in Ref. [15]. This approach was used here to calculate the D-values for an expanded list of radionuclides, including those radionuclides not addressed in Refs. [2, 3, 4] and to evaluate the adequacy of the D-values calculated using the earlier expert approach.

The algorithms for calculating D-values are described in Appendix III.

As discussed in Appendix VII, the D-values that were calculated using the expert approach were found to be in good agreement with those calculated later by the risk approach. Therefore, there was no need to revise the D-values given in Ref. [2, 3, 4]. The results of these two approaches were combined into a single set of recommended D-values as presented in Table 1.

APPENDIXES

APPENDIX I
REFERENCE AND THRESHOLD LEVELS FOR THE ONSET OF DETERMINISTIC EFFECTS

In the expert approach, the dose at which it was assumed that a severe deterministic effect could occur is termed the reference level. This is because the level was based on an expert judgement of those doses which are approaching, but below the actual threshold dose. In the risk approach, the level of dose at which it was assumed that a severe deterministic effect could occur is called the threshold level. This level was calculated to be the dose at which the effect would be expected to occur in 5% of those exposed.

Table 3 presents the list of organs or tissues [15] that were considered in developing the D-values. For each tissue a reference number is specified, and this is used throughout this publication to identify the organ or tissue.

There are two different tissue reference numbers for the lung (3E and 3R), because the expert and risk approaches used different regions of the lung as the target organ. The expert approach used absorbed dose to the "lung" where the "lung dose" was the weighted sum of the absorbed dose to the different tissues of the thoracic region of the respiratory tract as recommended by ICRP-66 [16] for assessment of stochastic effects. This is called the "thoracic region of the respiratory tract". As recommended by Ref. [15], the risk approach used the dose to the alveolar-interstitial (AI) region of the respiratory tract as the target organ.

There are two different tissue reference numbers used for the skin (6E and 6R), because the expert and risk approaches used different regions of the skin as the target organ. The expert approach used the basal membrane of skin (depth of 70 μm under the surface) because dose factors for this region were readily available. ICRP and ICRU [17, 18, 19] have recommended that the dose to the derma of the skin (300-500 μm under the surface) be evaluated for the purposes of estimating severe deterministic effects such as moist desquamation. This was the method used by the risk approach where it was assumed that development of severe deterministic effects follows irradiation of more than 100 cm^2 of skin tissue [12] lying at a depth of 400 μm (40 $mg \times cm^{-2}$).

In both approaches, the "torso" is used in Ref. [15] and here to simplify the consideration of external exposure to a uniform field of strongly penetrating radiation from a distance source. The "torso" includes the lung, red marrow, small intestine, gonads, thyroid and lens of eye. Exposure of the 'torso' by an external distance source that would expose all these organs and therefore they do not need to be considered separately.

TABLE 3. ORGANS AND TISSUES CONSIDERED

Organ or tissue	Exposure pathway	Tissue reference number	
		Expert approach	Risk approach
Soft tissue	External adjacent source	1	1
Red marrow	Internal	2	2
Lung regions	Internal	3E	3R
Colon or small intestine	Internal	4	4
Thyroid	Internal	5	5
Skin regions	Skin contact	6E	6R
Torso[a]	External distant source	7	7
Red marrow	External distant source	See note b	See note b
Throid	External distant source	See note b	See note b
Lens of the eye	External distant source	See note b	See note b
Ovum in females	External distant source	See note b	See note b
Testes in males	External distant source	See note b	See note b

[a] The torso is used to simplify the consideration of the effects of external exposure from a distant source and includes the red marrow, thyroid, lens of the eye, and reproductive organs.

[b] The threshold dose for the development of severe deterministic effects from a distant external source in this organ is below the reference level or thresholds level for dose in the torso; therefore, a specific dose calculation for this organ was not conducted.

I.1. DOSIMETRIC QUANTITIES USED IN THE CHARACTERIZATION OF DETERMINISTIC EFFECTS

Biological effects of radiation are correlated with the energy absorbed by ionization and excitation per unit mass of tissue (absorbed dose of radiation). They are modified by the microscopic spatial distribution of the energy imparted, which defines the quality of the radiation. This factor depends on the linear energy transfer (LET) of the radiation. Two types of radiation are usually considered in the context of developing radiation health effects:

(a) low LET radiation; and
(b) high LET radiation.

Biological effects of radiation may be also modified by the rate of energy absorption (absorbed dose rate), the concentration of oxygen in the tissue as well as by other factors that determine the radiosensitivity of the biological tissue concerned.

The expert and risk approaches use different dosimetric quantities for evaluating the exposures that can lead to deterministic health effects in the critical organs or tissues. These quantities are listed in Table 4 and are shown in Fig. 1 together with other quantities commonly used in radiation protection.

TABLE 4. DOSIMETRIC QUANTITIES USED IN EVALUATING RADIATION HEALTH EFFECTS

Purpose and dosimetric quantity	Symbol [a]	Unit	Exposure
Evaluating deterministic effects:			
a) Expert approach			
Absorbed dose from radiation R, in an organ or tissue T [b]	D_T^R	Gy	External
Committed absorbed dose from radiation R, in an organ or tissue T [b]	$D_T^R(\Delta)$	Gy	Internal
(b) Risk approach			
RBE [c]-weighted dose in an organ or tissue T	AD_T	Gy-Eq	External
Committed RBE-weighted dose in an organ or tissue T	$AD_T(\Delta)$	Gy-Eq	Internal
Evaluating stochastic effects:			
Radiation weighted dose in an organ or tissue T	H_T	Sv	External
Committed radiation weighted dose in an organ or tissue T	$H_T(\Delta)$	Sv	Internal

[a] A description of the symbols and indices used throughout this publication can be found in Annex I and II.

[b] The indexing of radiation specific absorbed dose introduced by the ICRP [20] was slightly modified for the purposes of this report.

[c] Relative Biological Effectiveness as discussed later.

The absorbed dose in an organ or tissue is the basic dosimetric quantity. The absorbed dose, (D_T^R)[4], is equal to the energy of the ionizing radiation R, delivered to a unit mass of the organ or tissue T, and is defined as

$$D_T^R = \frac{\Delta\varepsilon_R}{m_T}, \tag{1}$$

where:

m_T is the mass of the organ or tissue, T; and

$\Delta\varepsilon_R$ is the energy of ionizing radiation R, imparted to the mass of the given organ or tissue.

The committed absorbed dose $D_T(\Delta)$, in the organ or tissue T, is defined as the time integral of the absorbed dose rate in the organ or tissue over time Δ after intake of the radioactive material and is given by:

$$D_T^R(\Delta) = \int_{t_0}^{t_0+\Delta} \dot{D}_T^R(t)dt = \sum_S I_S \times DF_{T,S}^R(\Delta), \tag{2}$$

where:

t_0 is the time of intake:

Δ is the period of integration also called the period of commitment;

[4] A complete description of the symbols and indices used throughout this publication can be found in Annex I.

$\dot{D}_T^R(t)$ is the absorbed dose rate of radiation R, in organ or tissue T, at time t after intake of a radionuclide, Gy/s;

I_S is the activity of intake of a radionuclide via a pathway determined by scenario S, (Bq); and

$DF_{T,S}^R(\Delta)$ is the dose conversion factor equal to the absorbed dose from radiation R, in organ or tissue T, committed in accordance with scenario S, for time interval Δ after intake of 1 Bq of a radionuclide, (Gy/Bq).

The unit of absorbed dose and committed absorbed dose is the gray (Gy) [20].

In evaluating the external exposure to radiation R, (low LET or high LET), the expert approach used the organ absorbed dose D_T^R. For evaluating internal exposure it used the committed absorbed dose in the organ or tissue, $D_T^R(\Delta)$. In the expert approach, the components of the absorbed dose produced by low LET and high LET radiation were treated differently depending on the exposure pathway, organ, and characteristics of the material.

In the risk approach, the components of the absorbed dose produced by low LET and high LET radiation were weighted by the relative biological effectiveness (RBE) and were considered together. In evaluating the external exposure, the risk approach used an RBE-weighted dose in an organ or tissue, AD_T [15, 21]. For evaluating internal exposure, the committed RBE-weighted dose in an organ or tissue, $AD_T(\Delta)$ was used. The RBE-weighted dose (AD_T) is defined as the product of the absorbed dose in an organ or tissue, D_T^R, and the relative biological effectiveness, RBE_T^R; and is given by:

$$AD_T = \sum_R D_T^R \times RBE_T^R \ . \qquad (3)$$

For a particular organ or tissue T, the RBE_T^R is the ratio of the absorbed dose from a reference radiation that produces a specified biological effect relative to the absorbed dose from the radiation of interest R, producing the same biological effect. The value of RBE_T^R depends on the effect in the organ or tissue concerned, the biological condition under consideration, and the quality of the radiation producing the absorbed dose. The quality of the radiation depends upon many factors, the most important being the linear energy transfer (LET), and the penetrating capability of the radiation. Due to the microdistribution of radionuclides emitting weakly penetrating radiations, the value of RBE_T^R will be different for internal and external exposure from radiation with the same value of LET.

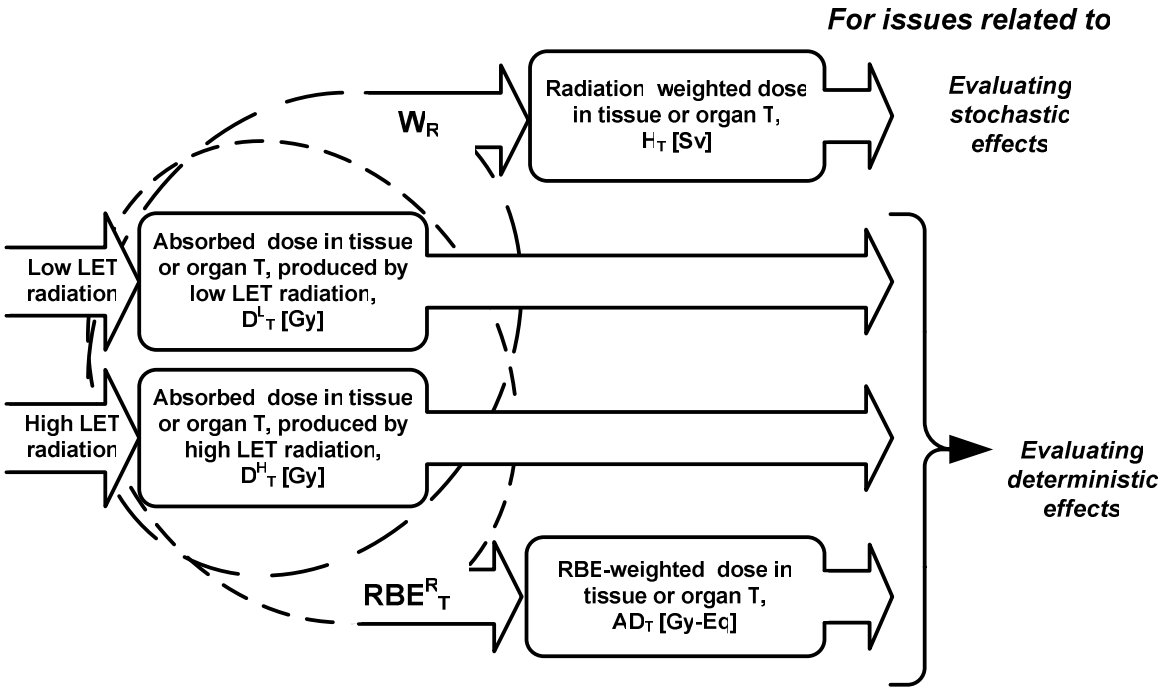

FIG. 1. Dosimetric quantities used in evaluating radiation health effects.

Committed RBE-weighted dose, $AD_T(\Delta)$, was used for evaluating the risk of developing severe deterministic health effects after the intake of a radionuclide. The committed RBE-weighted dose $AD_T(\Delta)$, in the organ or tissue T, is defined as the time integral of the RBE-weighted dose rate in the organ or tissue over time Δ after an intake of the radioactive material, and is given by:

$$AD_T(\Delta) = \int_{t_0}^{t_0+\Delta} \dot{AD}_T(t)dt = \sum_S I_S \times AF_{T,S}(\Delta), \quad (4)$$

where:

t_0 is the time of intake;

Δ is the period of integration also called the period of commitment;

$\dot{AD}_T(t)$ is the RBE-weighted dose rate in organ or tissue T, at time t after intake of a radionuclide of concern, ((Gy-Eq)/s);

I_S is the intake activity of the radionuclide via a pathway determined by scenario S, (Bq); and

$AF_{T,S}(\Delta)$ is the dose conversion factor equal to the RBE-weighted dose in organ or tissue T, committed over time Δ, in accordance with scenario S, for an intake of 1 Bq of a radionuclide, ((Gy-Eq)/Bq).

RBE-weighted dose and committed RBE-weighted dose are expressed in gray-equivalents (Gy-Eq) [15, 21, 22,].

The radiation weighted dose and committed radiation weighted dose are used in radiation protection and are not used in this report. The radiation weighted dose, H_T, is defined as the product of the absorbed dose (external and committed) in the organ or tissue and the radiation weighting factor w_R [11, 20, 23] summed over all radiation types. It is given by:

$$H_T = \sum_R D_T^R \times w_R \quad \text{and} \quad H_T(\tau) = \sum_R D_T^R(\tau) \times w_R \tag{5}$$

where:

H_T is the radiation-weighted dose to organ or tissue T, from external radiation;

$H_T(\tau)$ is the committed radiation-weighted dose to tissue T over the integration time τ and w_R is the radiation weighting factor for radiation R. When τ is not specified, it will be taken to be 50 years for adults and to age 70 years for intakes by children [11,20].

The unit of radiation-weighted dose and committed radiation-weighted dose is the sievert (Sv) [20, 23].

I.2. THE EXPERT APPROACH

The expert approach for calculating the D-values used reference levels of absorbed dose in critical organs or tissues for evaluating the onset of severe deterministic effects:

(a) For the evaluation of external exposure, reference levels are expressed in terms of organ absorbed dose, D_T^R, and are given in Table 5;
(b) For the evaluation of internal exposure, reference levels are expressed in terms of committed organ absorbed dose, $D_T^R(\Delta)$, and are given in Table 6.

The reference level of dose is that which if not exceeded, avoids the development of the effect in exposed persons.

TABLE 5. REFERENCE LEVELS USED IN THE EXPERT APPROACH FOR THE ONSET OF SEVERE DETERMINISTIC EFFECTS FROM EXTERNAL EXPOSURE

Exposure pathway	Effect	Critical organ or tissue	Reference level	
			Value (Gy)	Symbol [a]
Soft tissue exposure to adjacent source	Necrosis of soft tissue	Soft tissue [b] (Tissue 1)	25	RD_1^{L+H}
Contact exposure to surface contamination	Moist desquamation	Basal membrane of skin (Tissue 6E)	25 [d]	RD_{6E}^{L+H}
Total body exposure to a distant source or immersions	See note c	Torso (Tissue 7)	1 [c]	RD_7^{L+H}

[a] A description of the symbols and indices can be found in Annex I and II.
[b] 50-100 cm^2 and to a depth of about 0.5 cm below the body surface.
[c] The value is the minimum reference dose for developing any severe deterministic effect from uniform irradiation of the whole body. The reference level of 1 Gy was selected because it is the lower bound of the reference levels for onset of severe deterministic effects in the red bone marrow, thyroid, lens of the eye and reproductive organs as shown inTable 7.
[d] To approximately 100 cm^2 of skin. The dose is to skin structures at a depth of 7 mg/cm^2 (or 0.07 mm) under the surface, which was assumed to be the critical tissue for developing a severe deterministic effect. This is a conservative assumption as discussed in Appendix V.

TABLE 6. REFERENCE LEVELS USED IN THE EXPERT APPROACH FOR THE ONSET OF SEVERE DETERMINISTIC EFFECTS FROM INTERNAL EXPOSURE

Exposure pathway	Effect	Organ or tissue	Characteristics of the radioactive material	Reference level		
				Value (Gy)	Δ (d)	Symbol [a]
Inhalation or ingestion	Haematopoietic syndrome	Red marrow (Tissue 2)	Any radionuclide	1	2	$RD_2^{L+H}(\Delta)$
Inhalation	Pneumonitis	Thoracic region of the respiratory tract (Tissue 3E)	Type S [b] long-lived emitter of high LET radiation	25	365	$RD_{3E}^{HS}(\Delta)$
			Type S [b] long-lived emitter of ^{90}Sr (i.e. $^{90}Sr\ TiO_3$ [c])	40	365	$RD_{3E}^{LS}(\Delta)$
			Other emitters of low LET radiation	6	2	$RD_{3E}^{L}(\Delta)$
Inhalation or ingestion	Hypothyroidism	Thyroid (Tissue 5)	Thyroid seeking radionuclides [d]	5	365	$RD_5^{L}(\Delta)$

[a] A description of the symbols and indices can be found in Annex I and II.
[b] Type S denotes slow absorption from the lung [11].
[c] The special case of the insoluble compound of ^{90}Sr.
[d] Thyroid seeking radionuclides are emitters of low LET radiation.

Where appropriate, the reference levels used by the expert approach, were based on the action levels give in the international safety standards, specifically Table IV-I of Ref. [11] reproduced here in Table 7. These are the projected absorbed dose to the organ or tissue in less than 2 days, at which urgent protective action is expected to be undertaken under any circumstances in order to prevent deterministic health effects. The levels were assumed to be doses approaching those at which deterministic effects would be expected [10] from a brief exposure. Such exposure would only be expected from external sources. The reference levels of dose used in the expert approach differ from the action levels given in Ref. [11], as discussed below, primarily in order to take account of:

(a) severe deterministic health effects in skin; and soft tissue; and
(b) severe deterministic health effects developing due to longer duration exposures.

TABLE 7. ACTION LEVELS OF PROJECTED ABSORBED DOSE TO THE ORGAN OR TISSUE IN LESS THAN 2 DAYS

Target organ or tissue	Action level (Gy)
Whole body (red marrow)	1
Lung	6
Skin	3
Thyroid	5
Lens of the eye	2
Gonads	3

For whole body exposure from external source the reference level for the torso in Table 5 is the minimum dose for developing any severe deterministic effect from uniform irradiation of the whole body. The reference level of 1 Gy to the red marrow in 100 hours from a distant source was used as the reference level because it is the lower bound of the reference levels for onset of severe deterministic effects in the red bone marrow, thyroid, lens of the eye and reproductive organs as

shown Table I-3 of Ref. [15]. The longer exposure period of 100 hours was used instead of 2 days as the exposure duration because this is gives the lowest dose rates that are considered life threatening [12]. Subsequent works [15, 21] showed that a dose of 1 Gy from external exposure is also at, or below, the threshold level of dose at which severe deterministic effects would be expected in other organs (e.g. lens of the eye, gonads) or tissues as a result of whole body exposure from a distant source.

As discussed in Appendix II, the expert did not explicitly consider ingestion since the inhalation scenario should be controlling in the case of intake. Furthermore, it was recognized that [12] the threshold doses for onset of severe deterministic effects in the bone marrow and lung following inhalation would be considerably higher than those for the brief external exposure given in Table 7. However, based on an examination of studies [12] available at the time (when expert approach calculations were being done), for low LET emitters, the intake associated with the action levels for the lung given in Table 7 (6 Gy in 2 days) were found to deliver a dose rate that was a reasonable limiting case for estimating the intake that was considered life threatening. In the case of Strontium-90, the insoluble compound $^{90}SrTiO_3$[5] (lung absorption type s) was assumed. For this special case a reference level of 40 Gy, committed in 365 days to the lung thoracic region was assumed. This more conservative assumption was based on the data in Ref. [24] which was based on animal studies. These characteristics are indicated on the reference level symbol ($RD_{3E}^{LS}(\Delta)$) by the super scrip LS for low LET radiation from a compound with a type s lung absorption.

For lung exposure following inhalation of high LET emitting radionuclides the action level for the lung from Table 7 (6 Gy over 2 days) was not considered an appropriate reference level for onset of severe deterministic effects. In this case 25 Gy absorbed dose to the thoracic region, committed in 365 days, was used as the reference level for the onset of severe deterministic effects in the lung. This was based on Ref. [24] which indicates, based on animal studies, that 25 Gy delivered to the lung in 365 days is indicative of about a 5% risk of developing radiation pneumonitis following inhalation of the long lived alpha-emitter ^{239}Pu. These characteristics are indicated on the reference level symbol ($RD_{3E}^{HS}(\Delta)$)by the super scrip HS for high LET radiation from a compound with a type s lung absorption.

The action level for the skin from Table 7 (3 Gy in 2 days) was not considered appropriate because it was for erythema [10] which is not a severe deterministic health effect. Experience shows [25, 26, 27] that necrosis of the surface layer of soft tissue over an area of about 50-100 cm^2 and to a depth of about 0.5 cm is needed to result in severe deterministic effect of local external exposure. An absorbed dose of 25 Gy is the reference level for evaluating this effect [15, 25].

For internal exposure of the thyroid due to the intake of thyroid-seeking radionuclides, hypothyroidism was assumed to be a severe deterministic effect that decreases the quality of life. An absorbed dose of 5 Gy to the thyroid received in 2 days is given in Table IV-I of the Ref. [11] as an action level at which intervention is always justified to prevent hypothyroidism. However the only dose conversion factors readily available for thyroid exposure following intake were for a lifetime committed absorbed dose in the thyroid [28]. Therefore these dose factors were used. Considering the biological and physical half-life of the radionuclides that result in significant thyroid dose (isotopes of I and Te) these dose factors were in fact for a commitment period of much less than less than 365 days; however, a commitment period (Δ) of 365 days is assigned to this reference level $RD_5^L(\Delta)$ to indicate a commitment period well past several effective half lives.

[5] Compound typically used in radioisotopic thermoelectric generators (RTGs)

I.3. THE RISK APPROACH FOR EVALUATING THE ONSET OF DETERMINISTIC EFFECTS

The risk approach for calculating D-values used threshold levels of RBE-weighted dose in the critical organ or tissue for evaluating the onset of severe deterministic effects:

(a) For the evaluation of external exposure, threshold levels are expressed in terms of RBE-weighted dose, $AD_{T,05}$. They are given in Table 8; and

(b) For the evaluation of internal exposure, threshold levels are expressed in terms of committed RBE-weighted dose, $AD_{T,05}(\Delta)$. They are given in Table 9.

A threshold level of dose is that which theoretically results in the effect in 5% of exposed people.

Scott first proposed the biophysical model used in the risk approach for the evaluation of severe deterministic effects in 1980 [29, 30]. The risk model of correlating severe deterministic effects and associated parameters was developed using available data on animal experiments and an analysis of human exposures. The mathematical formulation of the model is similar to the probability function used in reliability theory and is described in NUREG/CR-4214 [12, 13, 14]. The use of this model for the risk approach is fully described in Ref. [15].

TABLE 8. THRESHOLD LEVELS OF RBE-WEIGHTED DOSE FROM EXTERNAL EXPOSURE

Exposure	Effect	Organ or tissue	Threshold level	
			Value (Gy-Eq)	Symbol [a]
Local exposure from an adjacent source	Necrosis of soft tissue	Soft tissue [b] (Tissue 1)	25	TD_1
Contact exposure from surface contamination	Moist desquamation	Derma of skin (Tissue 6R)	10 [d]	TD_{6R}
Total body exposure from a distant source or immersion	Note c	Torso (Tissue 7)	1 [c]	TD_7

[a] A description of the symbols and indices can be found in Annex I and II.

[b] Soft tissue over an area of 100 cm^2 and to a depth of about 0.5 cm below the body surface.

[c] The value is the minimum threshold dose for developing any severe deterministic effect from uniform irradiation of the whole body. The threshold level of 1 Gy was selected because it is the lower bound of the threshold levels for onset of severe deterministic effects in the red bone marrow, thyroid, lens of the eye and reproductive organs as shown Table I-3 of Ref. [15].

[d] Exposure at this level to at least 100 cm^2 of the skin is assumed to be required to result in severe deterministic health effects [12]. The dose is to skin structures at a depth of 40 mg/cm^2 (or 0.4 mm) under the surface.

TABLE 9. THRESHOLD LEVELS OF COMMITTED RBE-WEIGHTED DOSE FROM INTERNAL EXPOSURE

Exposure pathway	Effect	Target organ or tissue	Threshold level		
			Value (Gy-Eq)	Δ (d)	Symbol [a]
Inhalation and ingestion	Haematopoietic syndrome	Red marrow [b, c] (Tissue 2)	0.2 [d] / 2 [e]	30	$TD_2(\Delta)$
Inhalation	Pneumonitis	Alveolar-interstitial region of respiratory tract (Tissue 3R)	30	30	$TD_{3R}(\Delta)$
Inhalation and ingestion	Gastrointestinal syndrome	Colon (Tissue 4)	20	30	$TD_4(\Delta)$
Inhalation and ingestion	Hypothyroidism	Thyroid (Tissue 5)	2 [f]	365 [g]	$TD_5(\Delta)$

[a] A description of the symbols and indices can be found in Annex I and II.

[b] For cases of supportive medical care.

[c] Radionuclides with $Z \geq 90$ compared with $Z \leq 89$ have different biokinetic processes, hence different dynamics of dose formation in red marrow due to internal exposure. Therefore, radionuclides have been divided into two groups to avoid the over-conservatism in evaluating the risk of the health effect concerned.

[d] For radionuclides with $Z \geq 90$.

[e] For radionuclides with $Z \leq 89$.

[f] The value from Appendix A of Ref. [12] was used.

[g] Considering the biological and physical half-life of the radionuclides that result in significant thyroid dose (isotopes of I and Te) these dose factors were in fact for a commitment period of much less than 365 days; however, the commitment period (Δ) of 365 days is assigned to this reference level.

According to the risk model, the risk of developing deterministic health effects in an organ or tissue T, $R_{S,T}$, depends upon the hazard function characterizing a given effect. The hazard function, $H_T\{T_S, \dot{AD}_T(t)\}$, depends upon the history of exposure during the exposure period, $(0, T_S)$, as defined by exposure scenario S. The general expression for the hazard function as given in Ref. [14] is:

$$H_T\{T_S, \dot{AD}_T(t)\} = [\ln(2)]\left[\int_0^{T_S} \frac{\dot{AD}_T(t)}{\theta_T^{\infty} + \theta_T^1 / \dot{AD}_T(t)}\,dt\right]^{V_T}, \quad (6)$$

where:

$\dot{AD}_T(t)$ is the instantaneous RBE-weighted dose rate in the organ or tissue T, at a time t after the start of exposure, ((Gy-Eq)/h);

θ_T^{∞} is a parameter characterizing the radiosensitivity of a given organ or tissue and is equal to the asymptotic value of the RBE-weighted dose that theoretically results in the condition affecting 50% of those exposed to a very high dose rate (brief exposure), (Gy-Eq);

θ_T^1 is a parameter characterizing the effectiveness of radiation injury repair, $((Gy\text{-}Eq)^2/h)$; and

V_T is a parameter that determines the shape (steepness) of the dose-response curve for deterministic health effects in organ T. The shape of the dose response curve reflects a variability in human radiosensitivity and the ability to compensate for radiation-induced injury in the organ or tissue.

The parameters of the risk model [15] used in the risk approach are listed in Table 10.

TABLE 10. PARAMETERS USED IN THE RISK MODEL OF DEVELOPING SELECTED SEVERE DETERMINISTIC HEALTH EFFECTS

Health effect	Critical organ	Exposure [a]	Parameter [b]			
			RBE	θ_T^∞ (Gy-Eq)	θ_T^1 ((Gy-Eq)^2/h)	V_T
Haematopoietic syndrome [c]	Red marrow	External γ	1	4.5	0.1	6
		External n^0	3			
		Internal β, γ	1			
		Internal α	2			
Pneumonitis	Lung [d]	Internal β, γ	1	10 [d]	30	12
		Internal α	7			
GI Syndrome	Colon	Internal β, γ	1	15	4	10
		Internal α	0 [e]	NE	NE	NE
		External n^0	3			
Moist desquamation	Skin [f]	External β, γ	1	20	NE	5
Acute radiation throiditis	Thyroid	Intake of some iodine isotopes [g]	0.2	240	NE	1.9
		Other thyroid seekers	1			
Necrosis	Soft tissue [h]	External β, γ	1	25	NE	∞ [i]

[a] External β, γ exposure includes the dose from bremsstrahlung produced within the source materials.

[b] The central estimate of the value. "NE" means "not estimated".

[c] For cases with supportive medical treatment. With only minimal treatment, θ_T^∞ is 3 Gy-Eq and θ_T^1 is 0.07 (Gy-Eq)^2/h [12].

[d] The values of θ_T^∞ presented are those for lung irradiation of children and adults of 40 years old and younger. For older individuals these values should be divided by two [12], [14, Table 2.4].

[e] For alpha-emitters uniformly distributed in the contents of the colon, it is assumed that irradiation of the walls of the intestine is negligible.

[f] For a skin area of 100 cm^2 which is considered life threatening [12]. Skin dose should be calculated for a depth of 0.4 mm, as recommended in [19], para. (305), (306), and (310) in [17] and section 3.4.1 in [18].

[g] Uniform irradiation of the critical tissue of the thyroid gland is assumed to be five times more likely to produce deterministic health effects than internal exposure to low energy beta-emitting isotopes of iodine such as ^{131}I, ^{129}I, ^{125}I, ^{124}I and ^{123}I [12]. Thyroid seeking radionuclides have a heterogeneous distribution in thyroid tissues. Iodine-131 emits low energy beta particles that leads to a reduced effectiveness of irradiation of critical thyroid tissues due to the dissipation of their energy in other tissues. The listed-value for θ_T^∞ corresponds to a committed absorbed dose in the thyroid of 1200 Gy due to internal exposure after intake of ^{131}I.

[h] Tissue at a depth of 0.5 cm below the body surface over an area of more than 100 cm^2 results in severe deterministic effects [15, 25].

[i] Indicated the hazard function is a very step.

The risk model did not consider the development of a deterministic effect in time, e.g. probability of death in days or weeks after irradiation, but defined the value of $R_{S,T}$ (expressed in %) as:

$$\frac{R_{S,T}}{100} = 1 - \exp\left[- H_T \{T_S, \dot{AD}_T(t)\} \right]. \quad (7)$$

Scenarios involving external exposure (Appendix II, Scenarios I, II, V and VI) used in calculating the D-values, considered exposure at a fixed dose rate. The hazard function for the special case of exposure with a fixed dose rate is given in Ref. [15]:

$$H_T(AD_T) = [\ln(2)]\left[\frac{\dot{AD}_T \times T_S}{AD_{T,50}}\right]^{V_T}, \quad (8)$$

where

$AD_{T,50}$ is the value of RBE-weighted dose that theoretically results in the condition affecting 50% of those exposed;

$$AD_{T,50} = \theta_T^{\infty} + \theta_T^{1}\left(\dot{AD}_T\right)^{-1}; \quad (9)$$

$\dot{AD}_T$ is the constant RBE-weighted dose rate in the organ or tissue T, ((Gy-Eq)/h);

T_S is the duration of irradiation, (h), defined for the scenario concerned and given in Table 11; and

θ_T^{∞}, θ_T^{1} and $\dot{AD}_T$ are parameters of the hazard function given in Table 10.

For purposes of the risk approach, a value of RBE-weighted dose that theoretically affects 5% of exposed people, $AD_{T,05}$, was used as the threshold dose of external exposure at a fixed dose rate, TD_T. This value is the solution of Eq. (7) for R=5%.

$$TD_T = \left[\theta_T^{\infty} + \theta_T^{1}\left(\dot{AD}_T\right)^{-1}\right] \times \exp\left(-\frac{2.6}{V_T}\right). \quad (10)$$

The risk model did not consider recovery and variability in the development of the injury in a soft tissue. Therefore, the threshold value of the RBE-weighted dose for this effect, TD_1, is equal to the corresponding value of θ_1^{∞} and does not depend on the history of the exposure. The risk model did consider recovery and variability in the development of an injury in the torso and red marrow. It also considered variability only, in the development of injury in the skin. Therefore threshold values of RBE-weighted dose for these effects are lower than the corresponding values of θ_1^{∞}, as determined by Eq. (10). Values of the threshold dose for considering deterministic effects are given in Table 8.

For internal exposure due to an intake of a radionuclide, the RBE-weighted dose rate ($\dot{AD}_T$) in any organ or tissue is a function of time defined by the biokinetic of the radionuclide in the human body given by:

$$\dot{AD}_T(t) = I \times \dot{Ad}_T(t), \quad (11)$$

where:

I is the intake of radionuclide concerned; and

$\dot{Ad}_T(t)$ is the RBE-weighted dose rate in organ T, at time t after the intake of 1 Bq of this radionuclide.

The hazard function for the special case where the history of exposure is given by Eq. (11), is provided in Ref. [15]:

$$H_T(I) \cong [\ln(2)] \times (I)^{2 \times V_T} \times \left[\int_0^{\infty} \frac{\dot{Ad}_T(t)}{I \times \theta_T^{\infty} + \left(\dot{Ad}_T(t) \right)^{-1} \theta_T^{1}} dt \right]^{V_T}, \quad (12)$$

where:

I is the intake of the radionuclide concerned;

$\dot{Ad}_T(t)$ is the RBE-weighted dose rate in organ T, at time t after the intake of 1 Bq of this radionuclide; and

θ_T^{∞}, θ_T^{1} and V_T are parameters of the hazard function given in Table 10.

The risk of developing severe deterministic effects after an intake of a radionuclide is characterized by a threshold level of intake, $I_{T,05}$, equal to that intake of radioactive material that theoretically leads to the development of severe deterministic effects in organ T, in 5% of those exposed. The value of $I_{T,05}$ for any radionuclide and route of intake can be obtained from the numerical solution of Eq. (7) for R=5% and the hazard function given by Eq. (12). For a given route of intake and given effect, the value of $I_{T,05}$ depends on the chemical and physical properties of the radionuclide, as described in Ref. [15]. A model calculation shows that these values range over orders of magnitude due to the radionuclide's half-life. The effects of the chemical form of an aerosol (absorption type) and size (AMAD) are much smaller, but also exist. Overall, values of $I_{T,05}$ range over eight orders of magnitude for the radionuclides listed in Table 1. Therefore, this quantity could not be used as the basis for a general threshold value appropriate for evaluation of internal exposure from an intake of any radionuclide. A practical solution to this difficulty was to use a committed RBE-weighted dose, defined by Eq. (4), instead of intake as the basis for the emergency response criteria. This is a mathematical function converting the intake of the radioactive material (activity taken into a human body) into the dosimetry quantity. The threshold intake is an inverse function of a radionuclide's half-life, so the smaller the half-life, the greater the intake threshold. A committed dose conversion factor has an opposite dependence: the smaller the half-life, the smaller the conversion factor. Thus, if a value of Δ is optimal, the conversion of a threshold intake into the threshold value of committed RBE-weighted dose can lead to a significant decrease in the range of threshold values. It was shown in Ref. [15] that the value of 30 days for the committed period Δ is optimal. For instance, in the case of radiation pneumonitis, conversion of the values of threshold intake into threshold levels of 30-day committed RBE-weighted dose leads to a decrease in the range of threshold values from 8 orders of magnitude to a factor of only 3.

Threshold levels of the committed RBE-weighted dose for internal exposure used in the risk approach to calculating the D_2-values, are given in Table 9. The threshold value of the committed RBE-weighted dose, over a period Δ after intake, corresponding to the threshold intake is:

$$TD_T(\Delta) = \int_0^{\Delta} \dot{AD}_{T,05}(t)dt = I_{T,05} \times \int_0^{\Delta} \dot{Ad}_T(t)dt = I_{T,05} \times AF_{T,S}(\Delta), \quad (13)$$

where:

$I_{T,05}$ is the threshold value of intake for developing a severe deterministic health effect in organ T, (Bq);

$\dot{A}d_T(t)$ is the RBE-weighted dose rate in organ T, at time t after an intake of 1 Bq of the radionuclide concerned; and

$AF_{T,S}(\Delta)$ is a committed RBE-weighted dose conversion factor of internal exposure of organ T, due to an intake of a radionuclide by a route defined in scenario S, ((Gy-Eq)/Bq).

APPENDIX II
SCENARIOS FOR DETERMINING D-VALUES

II.1. EXPOSURE TO NON-DISPERSED MATERIAL

In this report, non-dispersed radioactive material means an unshielded and encapsulated radioactive source. Since the radioactive material is sealed, only external exposure from non-dispersed radioactive material is considered.

There are two scenarios involving local exposure to an adjacent source that were considered in determining a dangerous source quantity:

(a) The "hand" scenario involves a source being carried in the hand; and
(b) The "pocket" scenario involves a source being carried in a pocket.

History indicates that the time when the source is likely to be carried on the body (e.g. in a pocket) is limited to about 10 hours and in the hand is limited to about 1 hour. Therefore analysis shows that the "pocket" scenario is more limiting than the “hand” scenario and therefore it was used when calculating the D_1-values for sources that are small enough to be cared in a hand or placed in a pocket.

II.1.1. Scenario I: "Pocket" scenario

Scenario I is referred to as the "pocket" scenario. It was used to determine that amount of unshielded radioactive material which, if adjacent to the human body, would be considered dangerous as a source of local external exposure. External exposure from an unshielded source being carried in the hand or a pocket is the most common cause of severe radiation-induced injuries and deaths involving uncontrolled (stolen or lost) sources (see Appendix VII).

Experience [27] also indicates that radiation induced necrosis of soft tissue over an area of about 50-100 cm^2 and to a depth of about 0.5 cm in many parts of the body (e.g. in the thigh or chest) from carrying a source in a pocket can [26, 31] lead to a substantial decrease in the quality of life. Furthermore, experience shows [32] that a source carried in a pocket moves both laterally and longitudinally over time.

The dose conversions factors for the dose from an adjacent sources (pocket scenario) were calculated in way to simulate the dose from a moving source that results in necrosis of the surface layer of soft tissue over an area of about 50-100 cm^2. This is described in Appendix IV.

It was further assumed that it is unreasonable to carry a mass of 500 g. Therefore, this value was established as the mass limit for the "pocket" scenario. The parameters for Scenario I are listed in Table 11.

In the expert approach, the average absorbed dose according to pocket scenario in soft tissue is given by:

$$D_{1,I}^{L+H}(A) = DF_{1,I}^{L+H} \times T_I \times A\,, \qquad (14)$$

where:

$D_{1,I}^{L+H}(A)$ absorbed dose (Gy) in the soft tissue according to the pocket scenario from an adjacent source of activity A;

$DF_{1,I}^{L+H}$ is the absorbed dose rate conversion factor for absorbed dose in soft tissue according to the pocket scenario, (Gy/(Bq×s)). For high LET it is given in Table 13 and for low LET it is numerically equal to the RBE-weighted dose rate conversion factor $AF_{1,I}$ given in Table 15

T_I is the duration of exposure for Scenario I, (s), and is given in Table 11; and

A is the initial activity of the radionuclide concerned in the adjacent source, (Bq).

In the risk approach, the RBE-weighted dose absorbed dose (Gy-Eq) in the soft tissue according to the pocket scenario from an adjacent source of activity A is given by:

$$AD_{1,I}(A) = AF_{1,I} \times T_I \times A\,, \tag{15}$$

where:

$AD_{1,I}(A)$ is the RBE-weighted dose in soft tissue in accordance with Scenario I from an adjacent source with activity A, (Gy-Eq);

$AF_{1,I}$ is the conversion factor for the RBE-weighted dose rate is the conversion factor for absorbed dose (Gy) in soft tissue according to the pocket scenario, ((Gy-Eq)/(Bq×s)), and is given in Table 14 and Table 15;

T_I is the duration of exposure for Scenario I, (s), and is given in Table 11; and

A is the initial activity of the radionuclide concerned in the adjacent source, (Bq).

II.1.2. Scenario II: "Room" scenario

Scenario II is referred to as the "room" scenario. It was used to determine the amount of radioactive material that would be considered dangerous if it was left unshielded in an inhabited area (e.g. bedroom or workplace) for an extended period. External exposure from a distant unshielded source in a room is a common cause of radiation-induced severe injuries and deaths involving uncontrolled (stolen or lost) sources (see Appendix VII). In this scenario, an unshielded, encapsulated source was assumed to expose the total body from a distance of about 1 metre for 100 hours.

There is a strong dependence between the onset of severe deterministic effects from whole body exposure and the dose rate and duration of exposure. Experience [13, 15] suggests that the dose rate that can result in an absorbed dose in excess of the reference levels within 100 hours (e.g. 10 mGy/h to the red marrow) is a reasonable lower bound for evaluation. This gives the exposure rate that can result in severe deterministic effects from an uncontrolled source being unknowingly kept nearby (e.g. in a room). It is particularly appropriate if the exposure is fractionated. The assumptions are supported by documented experience, where the smallest source reported (see Appendix VII) to result in accidental fatalities for the room scenario gave a dose rate to the red marrow at 1 metre of between 20-50 mGy/h. Consequently, for the “room” scenario the duration of exposure was set at 100 h.

If a mass of over 1×10^6 g was required to produce a dose rate 10 mGy/h from an unshielded source, then the source should be regarded as unlimited because it was considered virtually impossible for that mass to produce this dose rate due to limitations resulting from shelf shielding . Consequently, the mass of 1×10^6 g was established as the mass limit for the "room" scenario. The parameters for Scenario II are listed in Table 11.

In the expert approach, the exposure of the torso from a source at a distance of 1 m is used for establishing the D_1-values in accordance with Scenario II. For simplicity it is assumed that the dose to the red bone marrow can be used to approximate the dose to all the organs in the torso. The absorbed dose in the torso from a radioactive source with an initial activity A, at a distance of 1 metre, is given by:

$$D_{7,II}^{L+H}(A) = DF_{2,II}^{L+H} \times T_{II} \times A, \quad (16)$$

where:

$D_{7,II}^{L+H}(A)$ is the absorbed dose in the torso at 1 m from a source with activity A, (Gy);

$DF_{2,II}^{L+H}$ is the absorbed dose rate conversion factor for external exposure of the red marrow[6] from a source 1 m from the body, (Gy/(Bq×s). For high LET it is given in Table 13and for low LET it is numerically equal to the RBE-weighted dose rate conversion factor given in Table 15;

T_{II} is the duration of exposure for Scenario II, (s) and is given in Table 11; and,

A is the initial activity of the radionuclide concerned in the distant source, (Bq).

In the risk approach the exposure of the torso from a source at a distance of 1 m is used for establishing the D_1-values in accordance with Scenario II. For simplicity is assume that the dose to the red bone marrow can be use to approximate the dose to all the organs in the torso. The RBE-weighted dose in the torso from a source with an initial activity A, at a distance of 1 m is given by:

$$AD_{7,II}(A) = AF_{2,II} \times T_{II} \times A \quad (17)$$

where:

$AD_{7,II}(A)$ is the RBE-weighted dose rate in the torso at 1 m from a source with an activity A, (Gy-Eq);

$AF_{2,II}$ is the RBE-weighted dose rate conversion factor for external exposure of the red marrow[6] at 1 m from a source, ((Gy-Eq)/(Bq×s)), and is given in Table 14 and Table 15;

T_{II} is the duration of exposure for Scenario II, (s), and is given in Table 11; and

A is the initial activity of the radionuclide concerned in the distant source, (Bq).

II.2. EXPOSURE TO DISPERSED MATERIAL

Dispersed radioactive material results from leakage, dismantlement or other disruption of a sealed radioactive source such as in a fire or explosion (e.g. RDD). Dispersion of a radioactive source containing a radioactive noble gas can lead to external exposure of the whole body from immersion in a local cloud. Dispersion of a radioactive source that does not contain a radioactive noble gas, can lead to contamination of the surroundings. This contamination in turn can cause internal exposure and contact exposure of the skin.

II.2.1. Scenarios IIIE and IIIR: "Inhalation" scenarios

Scenario III is referred to as the "inhalation" scenario. It was used to determine the amount of dispersible radioactive material that would be considered dangerous due to the risk of its inhalation. Internal exposure from inhalation of airborne material can be the cause of radiation-induced severe deterministic effects involving radioactive material dispersed as a result of a fire or explosion.

The dosimetric characteristics of airborne material depend on its chemical and physical properties. For inhalation, particulate material is assigned to one of three default lung absorption types defined by the ICRP human respiratory tract model [16]. Radioactive gases and vapours, if inhaled, are also assigned

[6] For simplicity it is assumed that the dose to the red bone marrow can be used to approximate the dose to all the organs in the torso.

to one of three classes, based on the initial pattern of absorption in the respiratory tract. The expert (Scenario IIIE) and risk (Scenario IIIR) assigned radioactive materials dispersed in an emergency to different absorption types as detailed below.

The amount of radioactive material inhaled, relative to the mass of the source is referred to as the "respirable intake fraction", F_{III}. It is a product of two factors: the respirable release fraction of the initial activity, RRF, and the inhalation intake fraction, IF_H:

$$F_{III} = RRF \times IF_H , \tag{18}$$

where:

(a) The respirable release fraction of the initial activity, RRF, is the fraction of dispersible material that can be released in the form of an aerosol with an AMAD less than 10 μm. The largest reported RRFs are for fires involving volatile or combustible material [33], or for explosions involving fine powders [34]. For these forms of material, a reasonable upper bound for the RRF is about 0.1 [33, 34]. For most material considered dispersible, an RRF of 0.1 would greatly exceed the actual value [33, 34]. Therefore this conservative value was used in evaluating F_{III} in Eq. (18).

(b) The inhalation intake fraction, IF_H, is the amount of the respirable fraction assumed to be inhaled by the individual during an emergency. The value of IF_H was assumed to be 1×10^{-3}, which is consistent with the fraction of air inhaled by a person who is in a 300 m^3 room for 0.5 hour [35]. This value far exceeds the intake fraction of 1×10^{-6} considered reasonable for a person at 100 m from an outside airborne release (e.g. for material in a fire or explosion) [33]. An airborne concentration that can result in an intake of more than 1×10^{-6} results in dense smoke and debris [33] and a person would be expected to move out of such a plume rather quickly. Therefore, a value of 1×10^{-3} was considered probably the conservative upper bound of the intake fraction and was used in evaluating F_{III} in Eq. (18).

Therefore the "respirable intake fraction", F_{III}. is assumed to be 1×10^{-4} of the radioactive material present in the source.

History shows that the maximum inhalation intake seen in an accident was of the order of 100 g [33]. Therefore, taking this into account, the value of F_{III}, 1×10^{6} g was set as the mass limit for this scenario. The parameters for Scenarios IIIE and IIIR are listed in Table 11.

The expert approach (Scenario IIIE), for the dose to the lung and red marrow, assigned dispersed and inhaled material to any lung absorption type that is valid for public exposure, as given in Table II-VIII from Ref. [11]. Furthermore, it assumed that the inhaled material belonged to the type or form that results in the highest dose to the thoracic region of the respiratory tract. A value of 1 μm was taken for the AMAD of particulate airborne material. For the thyroid the inhaled material was for class 'D' from Ref. [28]. The committed absorbed dose in tissue T, caused by inhalation of airborne material is given in the expert approach by:

$$D^{R}_{T,IIIE}(A,\Delta) = DF^{R}_{T,IIIE}(\Delta) \times F_{III} \times A , \tag{19}$$

where:

$D^{R}_{T,IIIE}(A,\Delta)$ is the committed absorbed dose from radiation R, in time Δ after intake, in organ or tissue T, from inhalation of radioactive material produced by dispersion of a source with an initial activity of A, (Gy);

Δ is the time interval for determining the committed dose, and is given in Table 6;

$DF^{R}_{T,IIIE}(\Delta)$ is the committed absorbed dose conversion factor of radiation R, in organ or tissue T, from inhalation, (Gy/Bq), and is given in Table 16 and Table 17;

F_{III} is the respirable intake fraction for Scenario III, and is given in Table 11; and

A is the initial activity of the radionuclide concerned in the dispersed source, (Bq).

In the risk approach (Scenario IIIR), it was assumed that the dispersed and inhaled material would not be chemically changed after dispersion and may be in any airborne form and may be assigned to any of the absorption types valid for occupational exposure as given in Table II-V and Table II-IX of Ref. [11]. It was also assumed that the inhaled material belonged to the type or form that results in the highest dose to the organ concerned. A value of 1 μm was taken for the AMAD. The committed RBE-weighted dose in tissue T, caused by inhalation of airborne material is given in the risk approach by:

$$AD_{T,IIIR}(A,\Delta) = AF_{T,IIIR}(\Delta) \times F_{III} \times A, \qquad (20)$$

where:

$AD_{T,IIIR}(A,\Delta)$ is the committed RBE-weighted dose, in time Δ after intake, in organ or tissue T, from inhalation of radioactive material produced by dispersion of a source with an initial activity A, (Gy-Eq);

Δ is the time interval for determining the committed dose, and is given in Table 9;

$AF_{T,IIIR}(\Delta)$ is the committed RBE-weighted dose conversion factor in organ or tissue T, from inhalation, ((Gy-Eq)/Bq), and is given in Table 18;

F_{III} is the respiratory intake fraction from Scenario III, and is given in Table 11; and

A is the initial activity of the radionuclide concerned in the dispersed source, (Bq).

II.2.2. Scenario IV: "Ingestion" scenario

Scenario IV is referred to as the "ingestion" scenario. It was used to determine the amount of dispersible radioactive material that would be considered dangerous due to the risk of its ingestion. Internal exposure from ingestion intake of radioactive material can be the cause of radiation-induced severe deterministic effects involving leaking radionuclide sources or soluble radioactive material dispersed in a body of drinking water.

The amount of radioactive material ingested, relative to the mass of the source is referred to as the "ingestion intake fraction", F_{IV}. Historically, the maximum ingestion intake fraction ever reported was for the Goiânia accident [36]. During this accident, a source containing 51 TBq of a very fine powder, water-soluble form of ^{137}Cs was stolen and dispersed. It led to an inadvertent ingestion by a child of about 1 GBq of ^{137}Cs. This was about 1×10^{-5} of the material present in the source. Consequently, in this scenario, intake by inadvertent ingestion was assumed to be 1×10^{-5} of the radioactive material present in the source based on this experience.

The ingestion intake fraction for contamination of a source of drinking water was estimated using the following conservative considerations:

(a) the radioactive material is 100% water-soluble;
(b) the radioactive material is uniformly mixed in 1×10^{6} litres of water, which is much smaller than the through-put of virtually all the public water supplies in cities; and
(c) a person drinks 2 litres of contaminated water per day for a period of 5 days.

These assumptions project intake, by drinking contaminated water, of about a value of 1×10^{-5} of the material in the dispersed source. Therefore it is considered reasonable use an ingestion intake fraction (F_{IV}) of 1×10^{-5} for the both inadvertent ingestion and ingestion of contaminated water.

The maximum value of 1×10^{6} g was set for the mass limit of dispersible material for Scenario IV. This value is the same as that used in Scenario III. The parameters for Scenario IV are listed in Table 11.

The absorbed dose conversion factors for per unit intake by ingestion are generally of the same order of magnitude as for intake by inhalation. Furthermore the intake assumed for inhalation is 10 time higher than for ingestion. Therefore, the expert approach did not explicitly consider ingestion because for intake the inhalation scenario is controlling.

In the risk approach, it was assumed that the material would not be chemically changed after dispersion and may be assigned to the ingestion type given in Table II-IV from Ref. [11], which would give the highest committed RBE-weighted dose in the organ considered. The committed absorbed dose in tissue T, caused by ingestion of the dispersed material is given in the expert approach by:

$$AD_{T,IV}(A,\Delta) = AF_{T,IV}(\Delta)\times F_{IV}\times A\,, \qquad (21)$$

where:

$AD_{T,IV}(A,\Delta)$ is the committed RBE-weighted dose, in time Δ after intake, in organ T, from ingestion of radioactive material produced by dispersion of a source with an initial activity of A, (Gy-Eq);

Δ is the time interval for determining the committed dose, and is given in Table 9;

$AF_{T,IV}(\Delta)$ is the committed RBE-weighted dose conversion factor for organ T, from ingestion, ((Gy-Eq)/Bq), and is given in Table 19;

F_{IV} is the ingestion intake fraction for Scenario IV, and is given in Table 11; and

A is the initial activity of the radionuclide concerned in the dispersed source, (Bq).

II.2.3. Scenario V. "Contamination" scenario

Scenario V is referred to as the "Contamination" scenario. It was used to determine the amount of dispersible radioactive material that would be considered as dangerous due to contact irradiation of a local area of the skin. External contact exposure of the skin from radioactive material distributed over a local area of the body surface can cause severe deterministic health effects in skin. Experience also shows [37] that if severe deterministic effects in skin accompany a total body exposure, it can lead to other radiation-induced injuries and death. In this scenario, the skin contamination scenario from Ref. [35] was used to set the parameters. Scenario V assumes that a 1×10^{-2} fraction (F_v in Table 11) of the radioactive material leaks from a source and uniformly contaminates a surface over an area of 1 m^2 (S_v in Table 11). This surface contamination then leads to skin contamination at 10% of the surface value (R_v in Table 11). The skin is assumed to be exposed for 5 hours (T_v in Table 11).

The maximum thickness of uncontrolled contamination of the hand was assumed as about 0.1 g/cm^2. Therefore, taking into account the parameters for contact exposure to the dispersed material, a value of 1×10^{6} g was set for the mass limit of the dispersible material. The parameters for Scenario V are listed in Table 11.

The expert and risk approaches used Scenario V for evaluating the dose from contact exposure of different regions of the skin as discussed in Appendix V and VI.

In the expert approach, the absorbed dose to the basal membrane of skin (Tissue 6E) is given by:

$$D^{L}_{6E,V}(A) = \frac{R_V \times T_V \times DF^{L}_{6E,V} \times F_V}{S_V} A \,, \tag{22}$$

where:

$D^{L}_{6E,V}(A)$ is the absorbed dose to the basal membrane of the skin from dispersion of the radioactive material in a source with an initial activity A, (Gy);

$DF^{L}_{6E,V}$ is the absorbed dose conversion factor for the basal membrane of the skin from skin contamination, (Gy/(Bq×s/cm^2)), and is given in Table 16;

S_V, F_V, R_V and T_V are parameters for Scenario V, and are given in Table 11; and

A is the initial activity of the radionuclide concerned in the dispersed source, (Bq).

In the risk approach, the RBE-weighted dose in the derma of the skin (Tissue 6R) is given by:

$$AD_{6R,V}(A) = \frac{R_V \times T_V \times AF_{6R,V} \times F_V}{S_V} A \,, \tag{23}$$

where:

$AD_{6R,V}(A)$ is the RBE-weighted dose in skin derma from dispersion of a source with an initial activity of A, (Gy-Eq);

$AF_{6R,V}$ is the RBE-weighted dose rate conversion factor for contact exposure of the derma of the skin, ((Gy-Eq)/(s×Bq/cm^2)), and is given in Table 19;

S_V, F_V, R_V and T_V are parameters for Scenario V, and are given in Table 11; and

A is the initial activity of the radionuclide concerned in the dispersed source, (Bq).

II.2.4. Scenario VI: "Immersion" scenario

Scenario VI is referred to as the "immersion" scenario. It was used to determine the amount of radioactive noble gas that if dispersed in a room would be considered dangerous as a source of external exposure. The exposure scenario from Ref. [35] was used as a basis for the "immersion" scenario. Scenario VI assumes that the noble gas is uniformly dispersed in a 300 m^3 room and that a person in the room is exposed for 0.5 hours. Dilution of the radioactive gas due to air exchange was not considered. Room immersion is considered to be limiting because any noble gas dispersion in an outside environment would lead to very rapid dispersion and much lower concentrations.

The maximum value of 1×10^6 g was set for the mass limit of dispersible material for Scenario VI. This value is the same as that used in Scenario III. The parameters for Scenario VI are listed in Table 11.

In the expert approach, the absorbed dose in the torso from an external exposure due to immersion in a radioactive noble gas is given by:

$$D^{L}_{7,VI}(A) = \frac{T_{VI} \times F_{VI} \times DF^{L}_{2,VI}}{V_{VI}} A \,, \tag{24}$$

where:

$D^{L}_{7,VI}(A)$ is the absorbed dose from low-LET radiation in the torso from external exposure due to immersion in a radioactive noble gas produced by dispersion of a source with an initial activity A, (Gy);

$DF^{L}_{2,VI}$ is the absorbed dose rate conversion factor for external exposure of the red marrow[7] due to immersion in the radioactive noble gas, (Gy/(Bq×s/m^3)). For immersion in radionuclides emitting low LET radiation, the value of the absorbed dose rate conversion factor $DF^{L}_{2,VI}$ was taken as being numerically equal to the RBE-weighted dose rate conversion factor $AF_{2,VI}$, for the same radionuclide. The factors for the relevant radionuclides are given in Table 20;

F_{VI}, V_{VI} and T_{VI} are the parameters for Scenario VI, and are given in Table 11;

A is the initial activity of the radionuclide concerned in the dispersed source, (Bq).

In the risk approach, the RBE-weighted dose in the torso from external exposure due to immersion in a radioactive noble gas is given by:

$$AD_{7,VI}(A) = \frac{T_{VI} \times F_{VI} \times AF_{2,VI}}{V_{VI}} A \quad , \tag{25}$$

where:

$AD_{7,VI}(A)$ is the RBE-weighted dose in the torso from external exposure due to immersion in the radioactive noble gas produced by dispersion of a source with an initial activity A, (Gy-Eq);

$AF_{2,VI}$ is the RBE-weighted dose rate conversion factor for external exposure of the red marrow[7] due to immersion in the radioactive noble gas, ((Gy-Eq)/(Bq×s/m^3)), and is given in Table 20;

F_{VI}, V_{VI} and T_{VI} are the parameters for Scenario VI, and are given in Table 11; and

A is the initial activity of the radionuclide concerned in the dispersed source, (Bq).

II.3. SUMMARY OF SCENARIO PARAMETERS

Table 11 contains a summary of the parameters for the scenarios used in developing D-values.

7 For simplicity it is assumed that the dose to the red bone marrow can be used to approximate the dose to all the organs in the torso.

TABLE 11. PARAMETERS FOR SCENARIOS USED IN DEVELOPING D-VALUES

Scenario		Parameter		
	Title	Symbol	Value	Definition
I	"Pocket"	T_I	3.6×10^{4} s	Duration of exposure
		M_I	5×10^{2} g	Mass limit
II	"Room"	T_{II}	3.6×10^{5} s	Duration of exposure
		M_{II}	1×10^{6} g	Mass limit
III	"Inhalation"	F_{III}	1×10^{-4}	Respirable intake fraction
		M_{III}	1×10^{6} g	Mass limit.
IV	"Ingestion"	F_{IV}	1×10^{-5}	Ingestion intake fraction
		M_{IV}	1×10^{6} g	Mass limit
V	"Skin contamination"	F_V	1×10^{-2}	Fraction of material dispersed
		S_V	1×10^{4} cm^2	Area of contaminated surface
		R_V	1×10^{-1}	Ratio of skin to surface contamination
		T_V	1.8×10^{4} s	Duration of exposure
		M_V	1×10^{6} g	Mass limit
VI	"Immersion"	F_{VI}	1	Fraction of material released into room
		V_{VI}	3×10^{2} m^3	Volume of room
		T_{VI}	1.8×10^{3} s	Duration of exposure
		M_{VI}	1×10^{6} g	Mass limit

APPENDIX III
CALCULATION OF D-VALUES

The scheme for determining the D-value of a given radionuclide was based on algorithms for finding the minimum activity of a radionuclide in a source that could cause severe deterministic effects, if it was uncontrolled. The expert and risk approaches used different algorithms to consider the scenarios and criteria for the onset of severe deterministic health effects. For each scenario and approach, the initial activity A (Bq) that could result in severe deterministic effects was calculated. The D-value was then typically established as the minimum activity calculated for the applicable scenarios. However, in establishing the D-values the mass of the activity that was considered dangerous was also assessed in order to determine if the mass was too large to be a credible threat (unlimited) or to determine if the mass exceeded a limit established to ensure that criticality was not a concern.

This section provides a summary of the algorithms used to calculate the D-values. The basis for the parameters describing the scenarios are provided in Appendix II and the basis for the criteria for the onset of severe deterministic effects is provided in Appendix I.

III.1. THE EXPERT APPROACH

III.1.1. Calculating the $^{E}D_{1}$-VALUE

The scheme for calculating the $^{E}D_{1}$-value is shown in Fig. 2. It includes two external exposure scenarios:

(a) The "pocket" scenario (Scenario I) that involves local exposure from an adjacent source; and
(b) The "room" scenario (Scenario II) that involves exposure of the total body from a distant source.

Pocket scenario. The initial activity $^{E}A_{1,I}$, (Bq), which according to the expert approach, can cause severe deterministic health effects in Tissue 1 (soft tissue) in accordance with Scenario I, ("pocket" scenario) is the solution of Eq. (14) for a dose equal to RD_{1}^{L+H}, and is given by:

$$^{E}A_{1,I} = \frac{1}{T_I \times DF_{1,I}^{L+H}} RD_{1}^{L+H}, \tag{26}$$

where:

RD_{1}^{L+H} is the reference level of absorbed dose for the onset of severe deterministic health effects in soft tissue (Gy), and is given in Table 5;

$DF_{1,I}^{L+H}$ is the absorbed dose conversion factor for absorbed dose in soft tissue according to the pocket scenario, (Gy/(Bq×s)). For high LET it is given in Table 13 and for low LET it is numerically equal to the RBE-weighted dose rate conversion factor $AF_{1,I}$ given in Table 15; and

T_I is the duration of exposure for Scenario I, (s), and is given in Table 11.

Room scenario. In this scenario, irradiation of the torso was assumed to result from an exposure to a source at about 1 metre from the body surface. For simplicity, based on Ref [11], it is assumed that the dose to the red bone marrow can be used to approximate the dose to all the organs in the torso. The initial activity $^{E}A_{7,II}$, (Bq), which according to the expert approach can cause severe deterministic

effects in Tissue 7 (torso) in accordance with Scenario II, ("room" scenario) is the solution of Eq. (16) for a dose equal to RD_7^{L+H}, and is given by:

$$ {}^{E}A_{7,II} = \frac{1}{T_{II} \times DF_{2,II}^{L+H}} RD_7^{L+H}, \tag{27} $$

where:

RD_7^{L+H} is the reference level of absorbed dose for the onset of severe deterministic health effects in the torso from external exposure, (Gy)., and is given in Table 5;

$DF_{2,II}^{L+H}$ is the absorbed dose rate conversion factor for external exposure of the red marrow[8] from a source 1 m from the body, (Gy/(Bq×s)). For high LET it is given in Table 13 and for low LET it is numerically equal to the RBE-weighted dose rate conversion factor $AF_{2,II}$ given in Table 15; and

T_{II} is the duration of exposure for Scenario II, (s), and is given in Table 11.

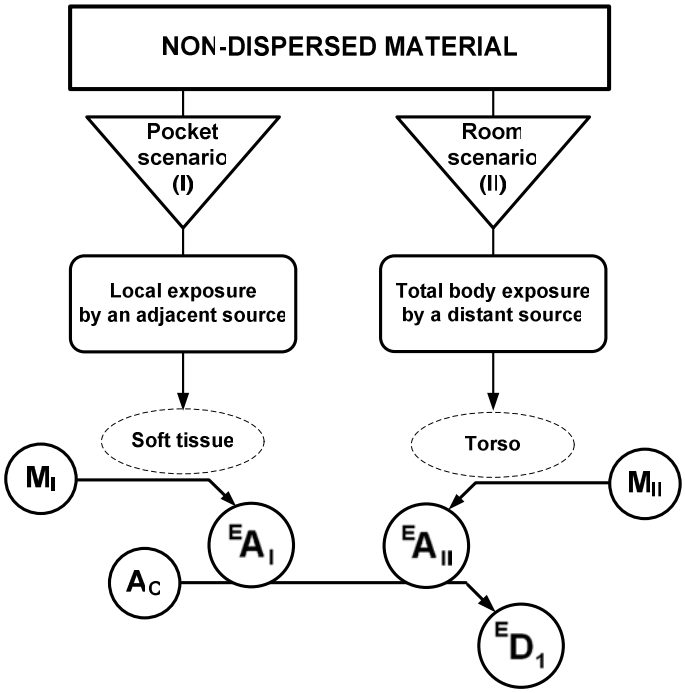

FIG. 2. Scheme for calculating the ${}^{E}D_1$ *-value.*

Establishing the ${}^{E}D_1$ *-value.* The ${}^{E}D_1$ -value is the smallest of three activities:

[8] For simplicity it is assumed that the dose to the red bone marrow can be used to approximate the dose to all the organs in the torso.

$$ {}^{E}D_1 = \min\left\{ {}^{E}A_I, {}^{E}A_{II}, A_C \right\}, \tag{28} $$

where:

A_C is the criticality limit activity, (Bq), and is given in Table 28;

${}^{E}A_I$ and ${}^{E}A_{II}$ are the initial activities of a radionuclide considered dangerous after a consideration of their mass, as defined in Eq (29) and (30), (Bq):

$$ {}^{E}A_I = \begin{cases} {}^{E}A_{1,I} & \text{if } M \le M_I \\ \text{Unlimited} & \text{if } M > M_I \end{cases}, \tag{29} $$

where:

${}^{E}A_{1,I}$ is the initial activity given by Eq. (26), (Bq);

M is the mass[9] of material with activity ${}^{E}A_{1,I}$, (g); and

M_I is the mass limit for Scenario I, (g), and is given in Table 11,

and

$$ {}^{E}A_{II} = \begin{cases} {}^{E}A_{7,II} & \text{if } M \le M_{II} \\ \text{Unlimited} & \text{if } M > M_{II} \end{cases}, \tag{30} $$

where:

${}^{E}A_{7,II}$ is the initial activity given by Eq. (27), (Bq);

M is the mass[9] of material with activity ${}^{E}A_{7,II}$, (g); and

M_{II} is the mass limit (g) for Scenario II given in Table 11.

The ${}^{E}D_1$-value for a radionuclide is unlimited if the values of ${}^{E}A_I$, ${}^{E}A_{II}$ and A_C for this radionuclide are unlimited. The ${}^{E}D_1$-values are listed in Table 1 and Table 24.

III.1.2. Calculating the ${}^{E}D_2$-VALUE

The scheme for calculating the ${}^{E}D_2$-value is shown in Fig. 3. It includes four scenarios of exposure to dispersed radioactive material:

(a) Inhalation (Scenario IIIE);
(b) Ingestion (Scenario IV);
(c) Skin contamination (Scenario V); and
(d) Immersion in a radioactive noble gas (Scenario VI).

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[9] The mass of the radioactive material (g) is equal to its activity (Bq) divided by its specific activity (Bq/g) as given in Table 26.

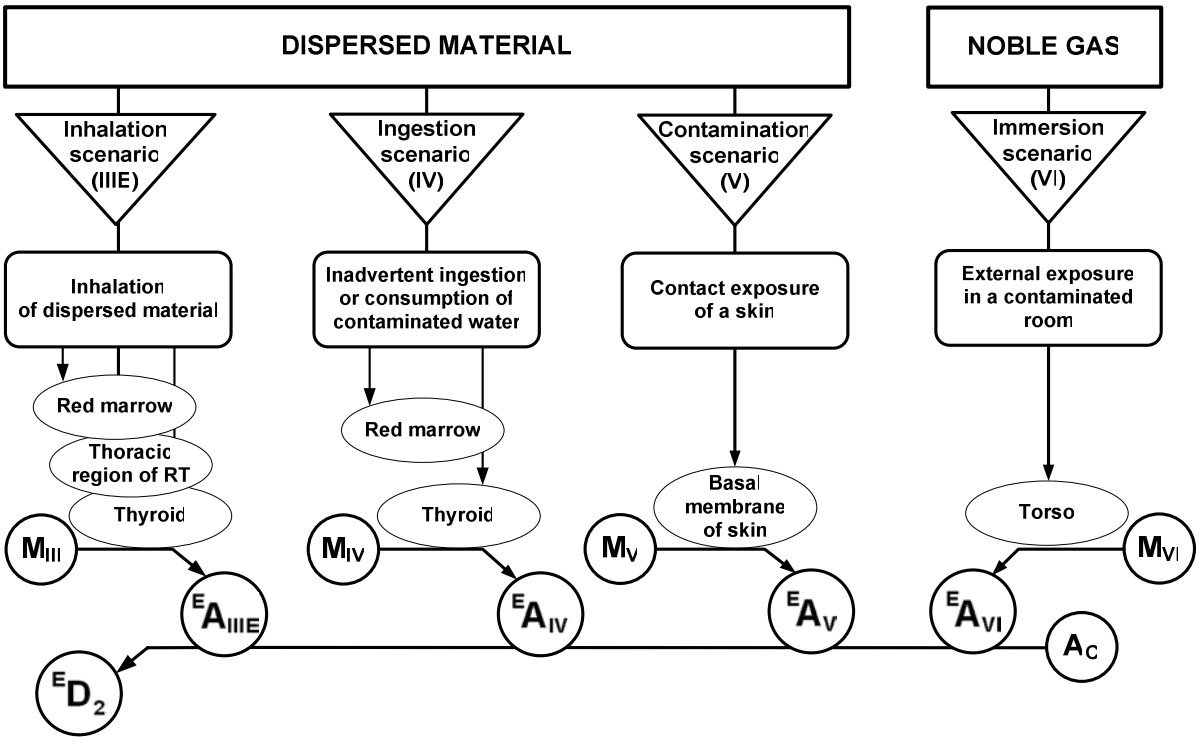

FIG. 3. Scheme for calculating the $^{E}D_2$ *-value.*

*Inhalation***.** Exposure of the red marrow (Tissue 2), thoracic region of the respiratory tract (Tissue 3E) and thyroid (Tissue 5) following inhalation were considered.

The initial activity $^{E}A_{2,IIIE}$, (Bq), which according to the expert approach can cause severe deterministic health effects in Tissue 2 (red marrow) in accordance with Scenario III (inhalation) is the solution of Eq. (19) for a dose equal to $RD_2^{L+H}(\Delta)$, and is given by:

$$^{E}A_{2,IIIE} = \frac{1}{F_{III} \times DF_{2,IIIE}^{L+H}(\Delta)} RD_2^{L+H}(\Delta), \tag{31}$$

where:

$RD_2^{L+H}(\Delta)$ is the reference level of the 2 day committed absorbed dose for internal exposure of red marrow for the onset of severe deterministic health effects (Gy), and is given in Table 6;

$DF_{2,IIIE}^{L+H}(\Delta)$ is the 2-day committed absorbed dose conversion factor for internal exposure of red marrow due to inhalation (Gy/Bq), and is given in Table 16; and

F_{III} is the respirable intake fraction for Scenario III given in Table 11.

The initial activity $^{E}A_{3E,IIIE}$, (Bq), that according to the expert approach can cause severe deterministic health effects in Tissue 3E (thoracic region of the respiratory tract) in accordance with Scenario IIIE, (inhalation) was calculated using different reference levels for the onset of deterministic effects and dose conversion factors for each of three groups of radionuclides:

(a) Type S[10] aerosols of long-lived emitters of high LET radiation (group HS);
(b) Strontium-90 in the form of $^{90}SrTiO_3$ (group LS)[11];
(c) Other emitters of low LET radiation (group L).

The initial activity is the solution of Eq. (19) for a dose equal to $RD_{3E}^{R}(\Delta)$, and is given by:

$$ {}^{E}A_{3E,IIIE} = \frac{1}{F_{III} \times DF_{3E,IIIE}^{R}(\Delta)} RD_{3E}^{R}(\Delta), \tag{32} $$

where:

$RD_{3E}^{R}(\Delta)$ is the reference level of the committed absorbed dose for internal exposure in the thoracic region of the respiratory tract for onset of severe deterministic health effects for radionuclides in group R (HS, LS, or L), (Gy). Values are given in Table 6;

$DF_{3E,IIIE}^{R}(\Delta)$ is the committed absorbed dose conversion factor for internal exposure of the thoracic region of the respiratory tract due to inhalation intake of a radionuclide in group R (HS, LS, or L), (Gy/Bq). The values for groups HS, L and LS are given in Table 16; and

F_{III} is the respirable intake fraction defined in Scenario III, and given in Table 11.

The initial activity ${}^{E}A_{5,IIIE}$, (Bq), which according to the expert approach, can cause severe deterministic health effects in Tissue 5 (thyroid) in accordance with Scenario IIIE (inhalation) is the solution of Eq. (19) for a dose equal to $RD_{5}^{L}(\Delta)$, and is given by:

$$ {}^{E}A_{5,IIIE} = \frac{1}{F_{III} \times DF_{5,IIIE}^{L}(\Delta)} RD_{5}^{L}(\Delta), \tag{33} $$

where:

$RD_{5}^{L}(\Delta)$ is the reference level of committed absorbed dose for internal exposure of the thyroid, for the onset of severe deterministic health effects (Gy), and is given in Table 6;

$DF_{5,IIIE}(\Delta)$ is the committed absorbed dose conversion factor for internal exposure of the thyroid due to an inhalation intake (Gy/Bq), and is given in Table 17;

F_{III} is the respirable intake fraction defined in Scenario III, and is given in Table 11.

Ingestion. In the "ingestion" scenario (Scenario IV) two alternatives were considered. In the first it was assumed that the source was leaking and handled, resulting in the inadvertent ingestion of radioactive material. In the second alternative it was assumed that the leaking source was placed in a public water supply, resulting in water contamination and consumption. The absorbed dose conversion factors for the colon, red marrow and thyroid per unit intake by ingestion are generally of the same order of magnitude as for inhalation. Therefore, the values of the initial activity ${}^{E}A_{T,IIIE}$, from inhalation calculated in accordance with the "inhalation" scenario (Scenario IIIE) and assuming an inhalation of 10^{-4} of the material dispersed, would be less than that calculated assuming an ingestion intake fraction of 10^{-5} as defined in either alternative of Scenario IV. Therefore, it was concluded the D-value for the initial activity ${}^{E}A_{T,IIIE}$ based on the inhalation scenario is a reasonable limit below which ingestion

[10] Type S denotes slow absorption from the lung [11].
[11] Inhalation of $SrTiO_3$ is treated as a special case as discussed in Appendix II.

would not be considered a significant threat. Consequently, ingestion exposure to the colon, red marrow and thyroid were not considered separately.

Skin contamination. The initial activity ${}^{E}A_{6E,V}$, (Bq) that according to the expert approach can cause severe deterministic health effects in Tissue 6E (basal membrane of the skin), in accordance with Scenario V, is the solution of Eq. (22) for a dose equal to RD_{6E}^{L+H}, and is given by:

$$ {}^{E}A_{6E,V} = \frac{S_V}{F_V \times R_V \times T_V \times DF_{6E,V}^{L}} RD_{6E}^{L+H}, \tag{34} $$

where:

RD_{6E}^{L+H} is the reference level of absorbed dose to the basal membrane of the skin for the onset of severe deterministic health effects, (Gy), and is given in Table 5;

$DF_{6E,V}^{L}$ is the absorbed dose conversion factor for contact exposure of the basal membrane of the skin, (Gy/(Bq×s/cm^2)), and is given in Table 16;

S_V is the area of the primary contaminated surface for Scenario V, (cm^2), and is given in Table 11;

F_V is the fraction of material dispersed for Scenario V, and is given in Table 11;

R_V is the ratio of skin to surface contamination for Scenario V, and is given in Table 11; and

T_V is the duration of exposure for Scenario V, (s), and is given in Table 11.

Immersion. Since ^{85}Kr is a noble gas, its release is an external hazard. The initial activity ${}^{E}A_{7,VI}$, (Bq), of a noble gas, that according to the expert approach can cause severe deterministic health effects in Tissue 7 (torso) in accordance with Scenario VI (immersion) is the solution of Eq. (24) for a dose equal to RD_{7}^{L+H}, and is given by:

$$ {}^{E}A_{7,VI} = \frac{V_{VI}}{T_{VI} \times DF_{2,VI}^{L}} RD_{7}^{L+H}, \tag{35} $$

where:

RD_{7}^{L+H} is the reference level of absorbed dose for the onset of severe deterministic health effects in torso from external exposure, (Gy), and is given in Table 5;

$DF_{2,VI}^{L}$ is the absorbed dose rate conversion factor for external exposure of the red marrow[12] due to immersion in a radioactive noble gas (Gy/(Bq×s/m^3)). For ^{85}Kr it was taken as numerically equal to the RBE-weighted dose rate conversion factor $AF_{2,VI}$ for ^{85}Kr. Values are given in Table 20;

V_{VI} is the volume of the room for Scenario VI, (m^3), and is given in Table 11;

T_{VI} is the duration of exposure for Scenario VI, (s), and is given in Table 11; and

F_{VI} is the fraction of material released into room, and is given in Table 11.

[12] For simplicity it is assumed that the dose to the red bone marrow can be used to approximate the dose to all the organs in the torso.

Establishing the ${}^{E}D_2$ *-value.* The ${}^{E}D_2$ -value was calculated differently for the radioactive noble gas, ^{85}Kr, then for other radionuclides.

For materials other than noble gases, the ${}^{E}D_2$ -value, (Bq), is given by:

$$ {}^{E}D_2 = \min\left\{ {}^{E}A_{IIIE}, {}^{E}A_V, A_C \right\}, \tag{36} $$

where:

A_C is the criticality limit activity, (Bq), and is given in Table 28;

${}^{E}A_{IIIE}$ and ${}^{E}A_V$ are the initial activities, (Bq), and are given by Eq. (37) and (38):

$$ {}^{E}A_{IIIE} = \begin{cases} \min\left\{ {}^{E}A_{2,IIIE}, {}^{E}A_{3E,IIIE}, {}^{E}A_{5,IIIE} \right\} & \text{if } M \le M_{III} \\ \text{Unlimited} & \text{if } M > M_{III} \end{cases}, \tag{37} $$

where:

${}^{E}A_{2,IIIE}$, ${}^{E}A_{3E,IIIE}$, and ${}^{E}A_{5,IIIE}$ are the initial activities given by Eq. (31), (32), and (33), (Bq);

M is the mass[9] of material with an activity equal to the $\min\left\{ {}^{E}A_{2,IIIE}, {}^{E}A_{3E,IIIE}, {}^{E}A_{5,IIIE} \right\}$, (g); and

M_{III} is the mass limit for Scenario III, (g), and is given in Table 11;

and

$$ {}^{E}A_V = \begin{cases} {}^{E}A_{6E,V} & \text{if } M \le M_V \\ \text{Unlimited} & \text{if } M > M_V \end{cases}, \tag{38} $$

where:

${}^{E}A_{6E,V}$ is the initial activity given by Eq. (34), (Bq);

M is the mass[9] of material with activity ${}^{E}A_{6E,V}$, (g); and

M_V is the mass limit for Scenario V, (g), and is given in Table 11.

For ^{85}Kr, ${}^{E}D_2$ is equal to the value of the initial activity ${}^{E}A_{2,VI}$ defined by Eq. (35):

$$ {}^{E}D_2 \equiv {}^{E}A_{2,VI} \tag{39} $$

The ${}^{E}D_2$ -value for a given material, other than a noble gas, is unlimited if the values of A^{E}_{IIIE}, ${}^{E}A_V$ and A_C are unlimited. It is also unlimited for a radioactive noble gas, if values of ${}^{E}A_{2,VI}$ are unlimited. The ${}^{E}D_2$ -values obtained by means of the expert approach are listed in Table 1 and Table 24.

III.2. THE RISK APPROACH

III.2.1. Calculating the ${}^{R}D_1$-VALUE

The scheme used for calculating the ${}^{R}D_1$-value is shown in Figure 4. It includes two scenarios of exposure to a non-dispersed radioactive source:

(a) The "pocket" scenario (Scenario I) that involves local exposure to an adjacent source; and
(b) The "room" scenario (Scenario II) that involves whole body exposure to a distant source.

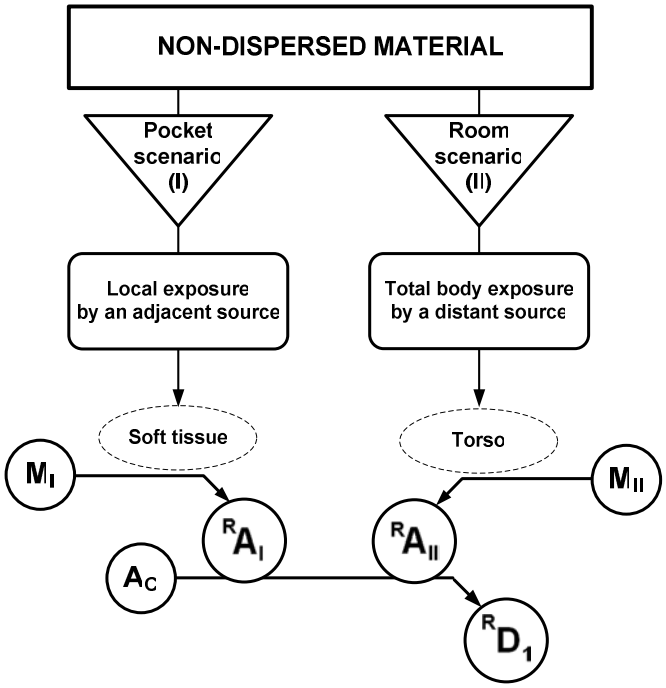

FIG. 4. Scheme for determining the ${}^{R}D_1$-value.

Pocket scenario. The initial activity ${}^{R}A_{1,I}$, (Bq), which according to the risk approach can cause severe deterministic health effects in Tissue 1 (soft tissue) in accordance with Scenario I, ("pocket" scenario), is the solution of Eq. (15) for a dose equal to TD_1, and is given by:

$$ {}^{R}A_{1,I} = \frac{1}{T_I \times AF_{1,I}} TD_1, \tag{40} $$

where:

TD_1 is a threshold level of the RBE-weighted dose for the onset of severe deterministic effects in soft tissue, (Gy-Eq), and is given in Table 8;

$AF_{1,I}$ is the conversion factor for the RBE-weighted dose rate in soft tissue according to the pocket scenario, ((Gy-Eq)/(Bq×s)), and is given in Table 14 and Table 15; and,

T_I is the duration of exposure for Scenario I, (s), and is given in Table 11.

Room scenario. In this scenario, irradiation of the torso was assumed to result from an exposure to a source at about 1 metre from the body surface. For simplicity, based on Refs [15, 21] it was assumed that the dose to the red bone marrow can be used to approximate the dose to all the organs in the torso.

The initial activity ${}^{R}A_{7,II}$, (Bq), which according to the risk approach can cause severe deterministic health effects in Tissue 7 (torso) in accordance with Scenario II, ("room" scenario), is the solution of Eq. (17) for a dose equal to TD_7, and is given by:

$$ {}^{R}A_{7,II} = \frac{1}{T_{II} \times AF_{2,II}} TD_7 , \tag{41} $$

where:

TD_7 is the threshold level of the RBE-weighted dose for the onset of severe deterministic health effects in the torso, (Gy-Eq), and is given in Table 8;

$AF_{2,II}$ is the RBE-weighted dose rate conversion factor for external exposure of the red marrow[13] to a source at a distance of 1 m, ((Gy-Eq)/(Bq×s)), and is given in Table 14 and Table 15,

T_{II} is the duration of the exposure for Scenario II, (s), and is given in Table 11.

Establishing the ${}^{R}D_1$*-value.* The ${}^{R}D_1$-value is the minimum value of the three activities ${}^{R}A_I$, ${}^{R}A_{II}$, and A_C, and is given by:

$$ {}^{R}D_1 = \min\left\{ {}^{R}A_I , {}^{R}A_{II}, A_C \right\}, \tag{42} $$

where:

A_C is the criticality limit activity, (Bq), and is given in Table 28;

${}^{R}A_I$, ${}^{R}A_{II}$ are the minimum initial activities after consideration of mass, (Bq) as defined by Eqs. (43) and (44):

$$ {}^{R}A_I = \begin{cases} {}^{R}A_{1,I} & \text{if } M \le M_I \\ \text{Unlimited} & \text{if } M > M_I \end{cases}, \tag{43} $$

where:

${}^{R}A_{1,I}$ is the initial activity, and is given by Eq. (40), (Bq);

M is the mass[9] of material with activity ${}^{R}A_{1,I}$, (g); and

M_I is the mass limit (g) for Scenario I given in Table 11;

$$ {}^{R}A_{II} = \begin{cases} {}^{R}A_{7,II} & \text{if } M \le M_{II} \\ \text{Unlimited} & \text{if } M > M_{II} \end{cases}, \tag{44} $$

where:

[13] For simplicity it is assumed that the dose to the red bone marrow can be used to approximate the dose to all the organs in the torso.

$^{R}A_{7,II}$ is the initial activity given by Eq. (41), (Bq);

M is the mass of material with activity $^{R}A_{7,II}$, (g); and

M_{II} is the mass limit for Scenario II given in Table 11.

The $^{R}D_1$-value for a given radionuclide is unlimited if the values of $^{R}A_I$, $^{R}A_{II}$ and A_C are unlimited. $^{R}D_1$-values are listed in Table 1 and Table 24 (for those radionuclides where the expert approach was also used).

III.2.2. Calculating the $^{R}D_2$-VALUE

The scheme used for calculating the $^{R}D_2$-value is shown in Figure 5. It includes four scenarios of exposure to dispersed radioactive material:

(a) Inhalation (Scenario IIIR);
(b) Ingestion (Scenario IV);
(c) Skin contamination (Scenario V); and
(d) Immersion in radioactive noble gas (Scenario VI).

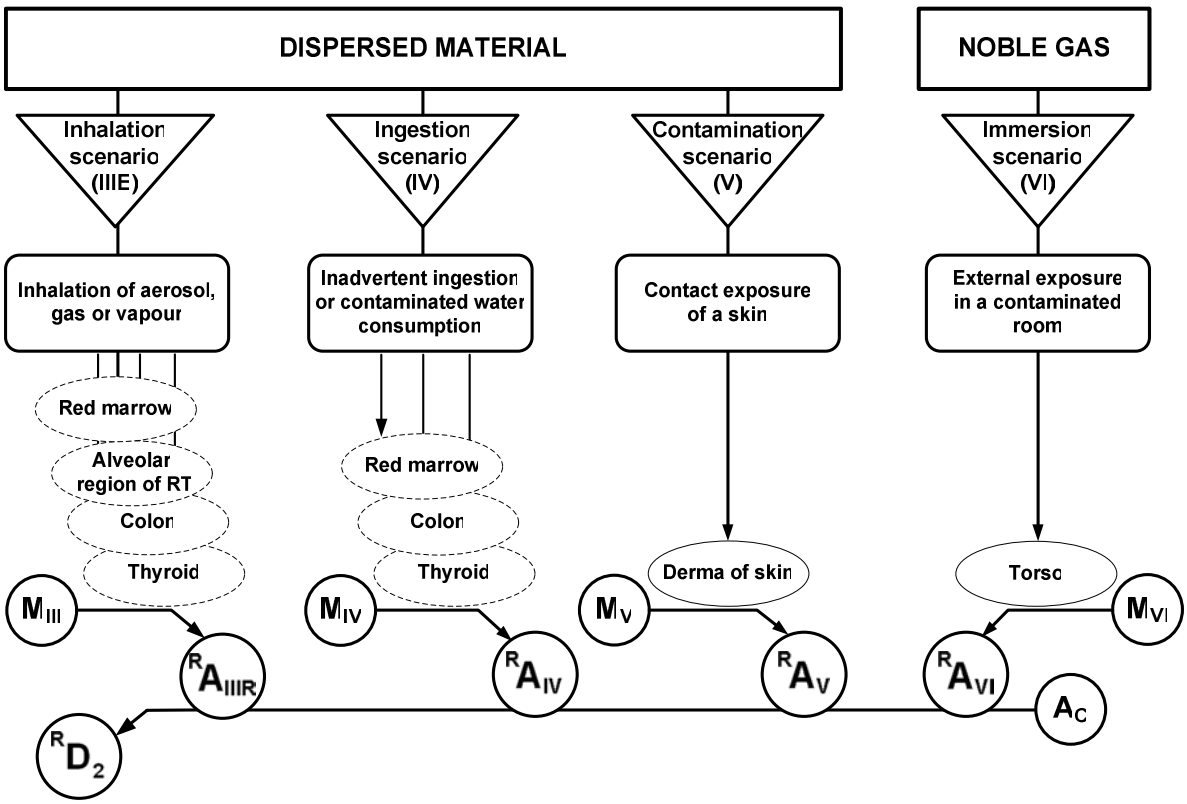

FIG. 5. Scheme for determining the $^{R}D_2$-value.

Inhalation. Exposure of the red marrow (Tissue 2), the alveolar-interstitial (AI) region of the respiratory tract (Tissue 3R), the colon (Tissue 4) and the thyroid (Tissue 5) by inhalation were considered. The initial activity $^{R}A_{T,IIIR}$, (Bq), that according to the risk approach can cause severe deterministic health effects in tissue T[14] in accordance with the Scenario IIIR (inhalation), is the solution of Eq. (20) for a dose equal to $TD_T(\Delta)$, and is given by:

$$ {}^{R}A_{T,IIIR} = \frac{1}{F_{III} \times AF_{T,IIIR}(\Delta)} TD_T(\Delta), \quad (45) $$

where:

$TD_T(\Delta)$ is the threshold level of the committed RBE-weighted dose in tissue T[14] from internal exposure, for the onset of severe deterministic health effects (Gy-Eq), and is given in Table 9;

$AF_{T,IIIR}(\Delta)$ is the committed RBE-weighted dose conversion factor for internal exposure of tissue T, due to inhalation intake, ((Gy-Eq)/Bq), and is given in Table 18; and

F_{III} is the respirable intake fraction for Scenario III given in Table 11.

Ingestion. Exposure of the red marrow (Tissue 2), colon (Tissue 4) and thyroid (Tissue 5) by ingestion were considered. The initial activity ${}^{R}A_{T,IV}$, (Bq), that according to the risk approach can cause severe deterministic health effects in tissue T[15] in accordance with Scenario IV (ingestion), is the solution of Eq. (21) for a dose equal to $TD_T(\Delta)$, and is given by:

$$ {}^{R}A_{T,IV} = \frac{1}{F_{IV} \times AF_{T,IV}(\Delta)} TD_T(\Delta), \quad (46) $$

where:

$TD_T(\Delta)$ is the threshold level of the committed RBE-weighted dose from internal exposure to tissue T[15], (Gy-Eq), and is given in Table 9;

$AF_{T,IV}(\Delta)$ is the committed RBE-weighted dose conversion factor for internal exposure of tissue T, due to ingestion intake, ((Gy-Eq)/Bq), and is given in Table 19; and,

F_{IV} is the ingestion intake fraction for Scenario IV, and is given in Table 11.

Skin contamination. The initial activity ${}^{R}A_{6R,V}$, (Bq), which according to the risk approach can cause severe deterministic health effects in Tissue 6R (derma of the skin) in accordance with Scenario V (skin contamination), is the solution of Eq. (23) for a dose equal to TD_{6R}, and is given by:

$$ {}^{R}A_{6R,V} = \frac{S_V}{F_V \times R_V \times T_V \times AF_{6R,V}} TD_{6R}, \quad (47) $$

where:

TD_{6R} is the threshold level of the RBE-weighted dose in the derma of the skin for the onset of severe deterministic health effects, (Gy-Eq), and is given in Table 8;

$AF_{6R,V}$ is a RBE-weighted dose rate conversion factor for contact exposure of the derma of the skin due to surface contamination, ((Gy-Eq)/(s×Bq/cm^2)), and is given in Table 19;

F_V is the fraction of the radioactive material dispersed in Scenario V, and is given in Table 11;

S_V is the area of the primary contaminated surface for Scenario V, (cm^2), and is given in Table 11;

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[14] Exposure of the red marrow (Tissue 2), the AI region of the respiratory tract (Tissue 3R), the colon (Tissue 4), and the thyroid (Tissue 5) are considered.

[15] Irradiation of red marrow (Tissue 2), colon (Tissue 4), and thyroid (Tissue 5) are considered.

R_V is the ratio of skin to surface contamination for Scenario V, and is given in Table 11; and

T_V is the duration of exposure for Scenario V, (s), and is given in Table 11.

Immersion. The activity of a radioactive noble gas ${}^{R}A_{7,VI}$, (Bq), which according to the risk approach can cause severe deterministic health effects in Tissue 7 (torso) in accordance with Scenario VI (immersion), is the solution of Eq. (25) for a dose equal to TD_7, and is given by:

$$ {}^{R}A_{7,VI} = \frac{V_{VI}}{T_{VI} \times AF_{2,VI}} TD_7 , \tag{48} $$

where:

TD_7 is the threshold level of the RBE-weighted dose in the torso for the onset of severe deterministic health effects, (Gy-Eq), and is given in Table 8;

$AF_{2,VI}$ is the RBE-weighted dose rate conversion factor for external exposure of the red marrow[16] due to immersion in a radioactive noble gas, ((Gy-Eq)/(Bq×s/m^3)), and is given in Table 20;

V_{VI} is the volume of the room for Scenario VI, (m^3), and is given in Table 11;

T_{VI} is the duration of exposure for Scenario VI, (s), and is given in Table 11; and

F_{VI} is the fraction of material released into room and is given in Table 11.

Establishing the ${}^{R}D_2$ *-value.* The ${}^{R}D_2$ -values were calculated differently for radioactive noble gasses than for other radionuclides.

For materials other than a noble gas, the ${}^{R}D_2$ -value, (Bq), is the minimum value of initial activities ${}^{R}A_{IIIR}$, ${}^{R}A_{IV}$, ${}^{R}A_{V}$, and A_C, and is given by:

$$ {}^{R}D_2 = \min\{{}^{R}A_{IIIR}, {}^{R}A_{IV}, {}^{R}A_{V}, A_C\} , \tag{49} $$

where:

A_C is the criticality limit activity, (Bq), and is given in Table 28; and

${}^{R}A_{IIIR}$, ${}^{R}A_{IV}$, and ${}^{R}A_{V}$ are the minimum initial activities after consideration of mass, (Bq) as defined by Eq. (50), (51) and (52):

$$ {}^{R}A_{IIIR} = \begin{cases} \min\left\{{}^{R}A_{2,IIIR}, {}^{R}A_{3R,IIIR}, {}^{R}A_{4,IIIR}, {}^{R}A_{5,IIIR}\right\} & \text{if } M \le M_{III} \\ \text{Unlimited} & \text{if } M > M_{III} \end{cases} , \tag{50} $$

where:

[16] For simplicity it is assumed that the dose to the red bone marrow can be used to approximate the dose to all the organs in the torso.

${}^{R}A_{T,IIIR}$ are the initial activities given by Eq. (45), (Bq);

M is the mass[9] (g), of radioactive material with an activity equal to $\min\left\{{}^{R}A_{2,IIIR}, {}^{R}A_{3R,IIIR}, {}^{R}A_{4,IIIR}, {}^{R}A_{5,IIIR}\right\}$; and

M_{III} is the mass limit (g) for Scenario III given in Table 11.

$$ {}^{R}A_{IV} = \begin{cases} \min\left\{{}^{R}A_{2,IV}, {}^{R}A_{4,IV}, {}^{R}A_{5,IV}\right\} \text{ if } M \le M_{IV} \\ \text{Unlimited if } M > M_{IV} \end{cases}, \tag{51} $$

where:

${}^{R}A_{T,IV}$ are the initial activities given by Eq. (46), (Bq);

M is the mass[9], (g), of radioactive material with an activity equal to $\min\left\{{}^{R}A_{2,IV}, {}^{R}A_{4,IV}, {}^{R}A_{5,IV}\right\}$; and

M_{IV} is the mass limit (g) for Scenario IV;

$$ {}^{R}A_{V} = \begin{cases} {}^{R}A_{6R,V} \text{ if } M \le M_{V} \\ \text{Unlimited if } M > M_{V} \end{cases}, \tag{52} $$

where:

${}^{R}A_{6R,V}$ is the initial activity given by Eq. (47), (Bq);

M is the mass[9], (g), of the radioactive material with an activity ${}^{R}A_{6R,V}$; and

M_{V} is the mass limit (g) for Scenario V given in Table 8.

For noble gasses, the ${}^{R}D_{2}$-value, (Bq), is the smallest of activities A_{C} and ${}^{R}A_{VI}$ and is given by:

$$ {}^{R}D_{2} = \min\left\{{}^{R}A_{VI}, A_{C}\right\}, \tag{53} $$

where:

A_{C} is the criticality limit, (Bq), and is given in Table 28;

${}^{R}A_{VI}$ is the initial activity given by Eq. (54), (Bq):

$$ {}^{R}A_{VI} = \begin{cases} {}^{R}A_{7,VI} \text{ if } M \le M_{VI} \\ \text{Unlimited if } M > M_{VI} \end{cases}, \tag{54} $$

where:

${}^{R}A_{7,VI}$ is the initial activity given by Eq. (48), (Bq);

M is the mass[9], (g), of the radioactive material with activity ${}^{R}A_{7,VI}$, (g); and

M_{VI} is the mass limit for Scenario VI given in Table 11 (g).

The ${}^{R}D_2$ -value for a given radioactive material, other than a noble gas, is unlimited if the values of ${}^{R}A_{IIIR}$, ${}^{R}A_{IV}$, ${}^{R}A_{V}$ and A_C are unlimited. It is unlimited for a radioactive noble gas if the values of ${}^{R}A_{VI}$ and A_C for this radionuclide are unlimited. The ${}^{R}D_2$ -values are listed in Table 1 and Table 24 (for those radionuclides where the expert approach was also used).

APPENDIX IV
EXTERNAL DOSE RATE CONVERSION FACTORS

This appendix details the calculation of the dose rate conversion factors for the characterization of the sources of external exposure in accordance with Scenarios I and II. Two types of conversion factors were used in the expert and risk approaches for calculating the D_1-values:

(a) dose rate conversion factors characterizing sources emitting only low LET radiation; and,
(b) dose rate conversion factors characterizing sources emitting a combination of high LET and low LET radiation.

The dose rate conversion factors for low LET emitters used in the expert and risk approaches are listed in Table 15 and the dose rate conversion factors used for high LET are listed in Table 14 and Table 13. The factors depend upon the exposure scenario and the energies and intensities of the radiations emitted from the source. The latter depends upon the emissions from the radionuclide encapsulated in the source as well as the interactions of this primary radiation with the material of the source. The energies and intensities of the radiations emitted by the radionuclides were taken from ICRP Publication 38 [38]. The impact of the in-growth of progeny on the dosimetry characteristics of a source was taken into account as described in Appendix VIII.

The source was assumed to consist of uniformly distributed radioactive material encapsulated in stainless steel. Since the source is encapsulated, the alpha particles and electrons emitted (beta and conversion electrons) do not escape the source. Beta particles and conversion electrons, however, give raise to bremsstrahlung as the electrons are slowed down within the source material and the stainless steel. Bremsstrahlung production in the material of the source was considered for beta emitters. Self-absorption within the source was also considered. The values of the dose conversion factors for beta emitters included the estimated bremsstrahlung as well as the gamma emission.

The geometry of the encapsulated source was assumed to be a right cylinder of diameter 0.5 cm and length 1.5 cm. The geometry of the external exposure of the human body to the non-dispersed source was defined by the exposure scenario being evaluated:

(a) Scenario I ("pocket" scenario) calculates the dose averaged over a mass of ~ 63 g on the centreline with the source length assumed to be a cylinder of radius 10 cm, height of 0.2 cm centred on the source located 2 cm above. The circular face of the cylinder being parallel to the length of the source. This is to approximate the dose from a moving source carried by a person for several hours as discussed in Appendix II.
(b) Scenario II ("room" scenario) considered exposure of an adult reference man to a small, unshielded, isotropic, encapsulated source, which is perpendicular from the centre his torso at a distance of 1 m. The material between the source and the torso is air with a density of 1.2×10^{-3} g/cm^3.

IV.1. LOW LET RADIATION

IV.1.1. Dose factors used in the expert approach

Dose factors characterizing the external exposure to sources of low LET radiation[17] include:

(a) photons arising from nuclear transformation of a radionuclide in the source; and

[17] Material prepared by K.F. Eckerman from Oak Ridge National Laboratory, Oak Ridge, TN, U.S.

(b) bremsstrahlung photons arising from interactions of beta particles with the material of the source.

The radionuclide-specific dose conversion factors

(a) $DF^{L}_{I,I}$, is the dose rate for absorbed dose in soft tissue according to the pocket scenario (Scenario I) (Gy/(Bq×s)); and,
(b) $DF^{L}_{2,II}$, representing the absorbed dose rate in the red marrow for a source of low LET radiation located one metre from the body (Scenario II),

are given as:

$$DF^{L}_{T,S} = \sum_{i}^{n} Y^{\gamma}_{i}\, d^{\gamma}_{T,S}(E_{\gamma,i}) + \\ + \sum_{j}^{m} Y^{e}_{j} \int_{E_0}^{E_{e,j}} S(E_{\gamma}, E_{e,j})\, d^{\gamma}_{T,S}(E_{\gamma})\, dE_{\gamma} + \int_{E_0}^{E^{0}_{e}} S_{\beta}(E_{\gamma}, E^{0}_{e})\, d^{\gamma}_{T,S}(E_{\gamma})\, dE_{\gamma}, \quad (55)$$

where:

$DF^{L}_{T,S}$ is the dose conversion factor for absorbed dose in organ or tissue T, irradiated by a low LET radiation from a source as described in scenario S, (Gy/(Bq×s));

$d^{\gamma}_{T,S}(E_{\gamma})$ is an absorbed dose response function equal to the absorbed dose in an organ or tissue T, that is irradiated by a photon from a monoenergetic source with an energy E_{γ} as described in scenario S, (Gy/(Bq×s)).

The three terms given in Eq. (55) are, respectively:

(a) the contribution of discrete photons of energy $E_{\gamma,i}$ and intensity Y^{γ}_{i} per nuclear transformation;
(b) the contribution of the continuous bremsstrahlung spectrum $S(E_{\gamma}, E_{e,j})$ arising from the slowing down of each conversion electron of yield Y^{e}_{j} and kinetic energy $E_{e,j}$; and,
(c) the contribution of the continuous bremsstrahlung spectrum $S_{\beta}(E_{\gamma}, E^{0}_{e})$ arising from a beta spectrum with maximum energy E^{0}_{e}.

The lower limit of the integrals in the second and third terms, E_0, is 10 keV.

The treatment of bremsstrahlung production in the derivation of D-values was based on the work of Dillman and Eckerman [39] as discussed in Appendix C of Federal Guidance Report No. 12 [40]. $S(E_{\gamma}, E_{e})\, dE_{\gamma}$ is defined as the number of bremsstrahlung photons with an energy between E_{γ} and E_{γ} + dEγ arising from a monoenergetic electron of initial kinetic energy E_e. The scaled bremsstrahlung spectrum $S'(E_{\gamma}, E_{e})$ is then defined as:

$$S'(E_{\gamma}, E_{e}) = 100 \frac{E_{\gamma}}{E_{e}} S(E_{\gamma}, E_{e}) \text{ for } 0 \leq E_{\gamma} \leq E_{e}, \quad (56)$$

and expressed in (%). It is tabulated in Ref. [39] for materials of different stopping power. Bremsstrahlung yield, the percentage of the electron energy converted to bremsstrahlung, Y_{BS}, is:

$$Y_{BS}(E_e) = \int_0^{E_e} S'(E_\gamma, E_e)\, dE_\gamma \ . \tag{57}$$

The scaled bremsstrahlung spectrum $S'(E_\gamma, E_e)$ and the bremsstrahlung yield for stainless steel ($Z \approx 26$) are given in Table 12.

If a beta spectrum of maximum energy E_e^0 is considered, and $n_\beta(E_e, E_e^0)\, dE_e$ is the number of beta particles with an energy between E_e and $E_e + dE_e$, then the resultant bremsstrahlung spectrum is:

$$S_\beta(E_\gamma, E_e^0) = \frac{1}{100 E_\gamma} \int_{E_\gamma}^{E_e^0} n_\beta(E_e, E_e^0)\, S'(E_\gamma, E_e)\, E_e dE_e \tag{58}$$

TABLE 12. SCALED BREMSSTRAHLUNG SPECTRA FROM ELECTRONS IN STAINLESS STEEL

E_e	E_γ/E_e						
(MeV)	0	0.05	0.10	0.20	0.30	0.40	0.50
0.001	17.7	14.5	12.4	9.93	8.30	6.97	5.76
0.0025	11.0	9.67	8.78	7.69	6.71	5.75	4.79
0.005	9.28	8.77	8.29	7.38	6.44	5.49	4.55
0.01	9.05	8.72	8.31	7.32	6.28	5.26	4.29
0.025	9.28	8.87	8.32	7.04	5.86	4.78	3.82
0.05	9.75	8.84	7.97	6.44	5.18	4.13	3.23
0.075	9.66	8.63	7.67	6.01	4.73	3.71	2.86
0.1	9.66	8.46	7.39	5.67	4.40	3.40	2.59
0.2	9.49	7.88	6.62	4.81	3.58	2.65	1.94
0.3	9.30	7.45	6.11	4.30	3.11	2.25	1.61
0.4	9.11	7.13	5.74	3.95	2.80	1.99	1.40
0.5	8.87	6.87	5.47	3.70	2.59	1.82	1.27
0.6	8.72	6.66	5.25	3.52	2.44	1.70	1.17
0.8	8.47	6.35	4.95	3.26	2.24	1.54	1.06
1	8.26	6.13	4.75	3.10	2.12	1.46	0.992
1.2	8.09	5.96	4.60	3.00	2.04	1.40	0.955
1.4	7.92	5.82	4.49	2.92	1.98	1.37	0.933
1.6	7.77	5.71	4.40	2.86	1.95	1.35	0.920
1.8	7.64	5.62	4.33	2.81	1.93	1.33	0.913
2	7.56	5.55	4.27	2.78	1.91	1.33	0.910
2.5	7.34	5.39	4.15	2.73	1.88	1.32	0.908
3	7.13	5.24	4.06	2.69	1.87	1.31	0.911
4	6.72	5.02	3.93	2.63	1.85	1.31	0.920
5	6.38	4.84	3.82	2.59	1.84	1.31	0.928
6	6.10	4.69	3.74	2.56	1.82	1.31	0.934
8	5.66	4.44	3.58	2.49	1.79	1.31	0.938
10	5.35	4.24	3.44	2.41	1.76	1.29	0.934

Continuation of Table 12.

E_e			$E\gamma/E_e$			Yield
(MeV)	0.60	0.70	0.80	0.90	0.95	(%)
0.001	4.57	3.41	2.27	1.13	0.567	0.0063
0.0025	3.84	2.88	1.93	0.968	0.484	0.0122
0.005	3.61	2.69	1.78	0.883	0.439	0.0229
0.01	3.36	2.47	1.61	0.793	0.393	0.0443
0.025	2.93	2.11	1.35	0.652	0.319	0.104
0.05	2.43	1.73	1.09	0.520	0.254	0.188
0.075	2.13	1.49	0.933	0.439	0.213	0.260
0.1	1.90	1.32	0.815	0.380	0.184	0.325
0.2	1.37	0.921	0.550	0.248	0.118	0.543
0.3	1.11	0.724	0.422	0.185	0.087	0.724
0.4	0.952	0.611	0.349	0.150	0.069	0.885
0.5	0.851	0.538	0.303	0.128	0.059	1.03
0.6	0.782	0.490	0.274	0.114	0.052	1.18
0.8	0.698	0.433	0.239	0.097	0.044	1.47
1	0.653	0.404	0.221	0.089	0.039	1.75
1.2	0.628	0.388	0.211	0.084	0.037	2.03
1.4	0.615	0.379	0.206	0.081	0.035	2.31
1.6	0.608	0.375	0.203	0.079	0.034	2.59
1.8	0.604	0.373	0.201	0.078	0.033	2.88
2	0.603	0.373	0.201	0.077	0.032	3.17
2.5	0.605	0.375	0.201	0.076	0.031	3.88
3	0.609	0.379	0.202	0.075	0.030	4.59
4	0.620	0.387	0.207	0.076	0.030	5.98
5	0.630	0.395	0.212	0.077	0.031	7.35
6	0.638	0.402	0.216	0.078	0.031	8.68
8	0.647	0.411	0.220	0.080	0.031	11.3
10	0.648	0.414	0.223	0.081	0.032	13.7

To calculate the dose factors for Scenario I, the absorbed dose response function, $d_{1,I}^{\gamma}(E_{\gamma})$ from photons emitted within the source was calculated for the average over tissues in a cylinder of radius 10 cm and length of 0.2 cm. This was intended to approximate the dose from a moving sources carried in a pocket. These calculations were performed using the MCNP computer code assumes a slab of the soft-tissue of the composition specified in ICRU Publication 44 [41]. The absorbed depth-dose response functions as a function of the photon energy emitted is shown in Figure 6 (solid curve). Some of the data below 30 keV were based on extrapolations from higher energies whenever the Monte Carlo results were judged to be unreliable at these low energies.

To calculate dose factors for Scenario II, the absorbed dose response function, $d^{\gamma}_{2,II}(E_{\gamma})$ from photons emitted within the source were calculated for exposure of an adult reference man to a small, unshielded, isotropic, encapsulated source, which is perpendicular from the centre his torso at a distance of 1 m. The material between the source and the torso is air with a density of 1.2×10^{-3} g/cm^3.These calculations were performed using the ALGAMP code of the Oak Ridge National Laboratory (ORNL) [40] for a point source. The distribution in energy and intensity of photons for the point source was based on MCNP calculations of the emission from the unshielded source. The absorbed dose response function in the red marrow as a function of emitted photon energy is shown in Figure 6 (dashed curve). Some of the data for photons of energy less than 30 keV were based on extrapolation from the higher energy whenever the Monte Carlo calculations were judged to be unreliable at these low energies.

The mean free path[18] of photons in air is about 50 m for photons with an energy of 10 keV and 400 m for photons with an energy of 1 MeV [42]. Therefore, multiple scattering of photons in the air on their way from the source to the surface of the human body (the sky shine effect) is negligible and was not considered. As shown in ICRP Publication 74 [43], the average absorbed dose of low-LET radiation in red marrow does not significantly differ from that to any of the organs that are considered to be part of the torso. Therefore, the dose rate conversion factors for the red bone marrow are used for calculations of the 'torso' dose.

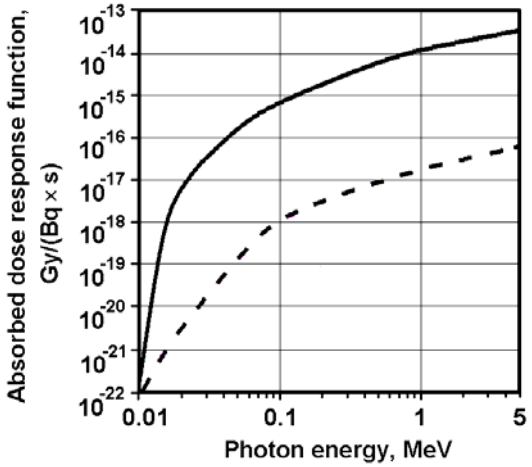

FIG. 6. Absorbed dose response functions from photons emitted within the encapsulated source. The solid curve applies to dose in soft tissue for Scenario I. The dashed curve applies to dose in red marrow for Scenario II.

IV.1.2. Dose factors used in the risk approach

As part of the risk approach, independent calculations were made to confirm that the dose rate conversion factors for exposure to an adjacent sources (Scenario I) were reasonable. These independent calculations were for an adjacent source emitting photons with energy more than 50 keV. In this case, the dose rate conversion factors were calculated as the product of kerma constant of photons with given energy and the geometrical factor [44]. A kerma constant was calculated using the code "RadSum 32 Code: A Win 32 version" [45] The geometric factor used was based on the data used in the expert approach as described above.

[18] Mean free path is an average distance that a particle or photon travels between a specified type (or types) of interaction in a given medium.

Calculations showed that for photons with energy more than 50 keV that the dose rate conversion factors calculated for the following geometries are equal with uncertainty of about 2%:

(a) The dose rate is the average over a cylinder of radius 10 cm and length of 0.2 cm; (This the basis for the calculation of the dose rate conversion factor used in the expert approach)

(b) The dose rate is the average over Cylinder A (shown in Figure 7) which has a radius of 10 cm (area of 314 cm^2) and length 0.5 cm; and

(c) The dose rate is the minimal dose rate in Cylinder M (Figure 7) which has an area 100 cm^2 (radius of about 6 cm) and a depth of 0.5 cm.

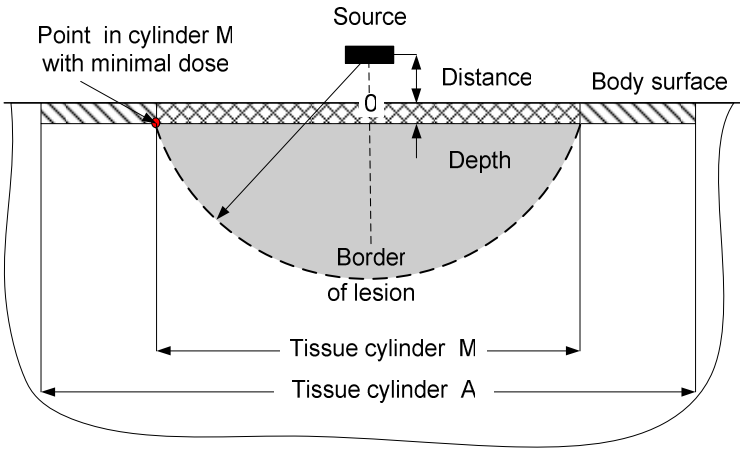

FIG. 7. Geometries for adjacent source dose factor verification.

In cases (b) and (c) the source is centred on the cylinder at a distance of 1.5 cm above the face of the cylinder and dose is estimated staring at a depth of 0.5 cm below the surface. A dose exceeding the threshold for necrosis causes lesion in soft tissue. In Fig. 7 the border of lesion from adjacent source is shown as a semi-spherical surface at which dose is equal to the threshold for necrosis of soft tissue (TD1), given in Table 8 and equal to 25 Gy-Eq. Irradiation of soft tissue by this source is heterogeneous. Fig. 8 shows the transformation of approximate dose value within tissue cylinder analogous to cylinder A. This is for a gamma emitter with an activity equal to the A1,I value given by Eq. (46) for exposure Scenario I. The dose is maximal in the centre of irradiated tissue cylinder right under source and drops quickly with a distance from the centre. Fig. 9 shows average dose in approximate circle area from the adjacent source with activity equal to the A1,I as a function of a radius of area. Figure 10 shows the area in cylinder A where the dose from this source would exceed 25 Gy. This demonstrates that area where the dose is above 25 Gy is apparently in good agreement with the experience concerning necrosis formation during emergencies involving sources being carried in pockets.

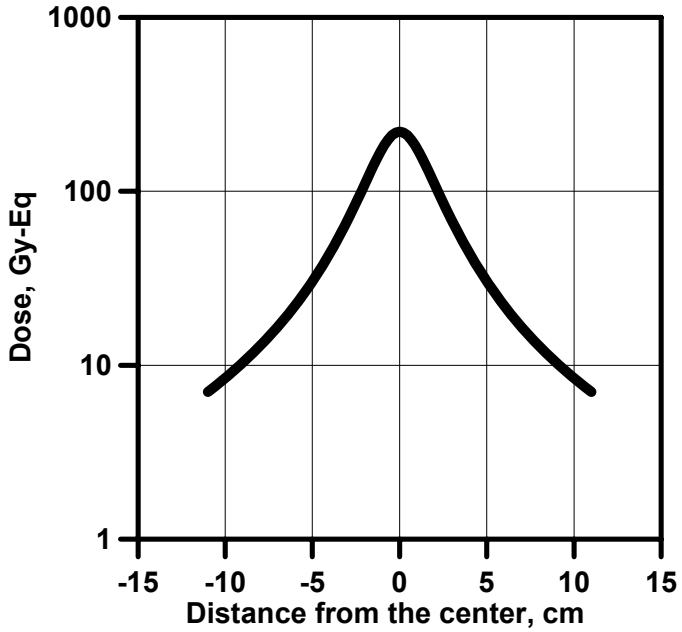

FIG 8. Approximate dose for an $A_{1,1}$ activity source at a given distance from the normal to a source at 2 cm above the base of tissue cylinder (at 1.5 cm above the body surface).

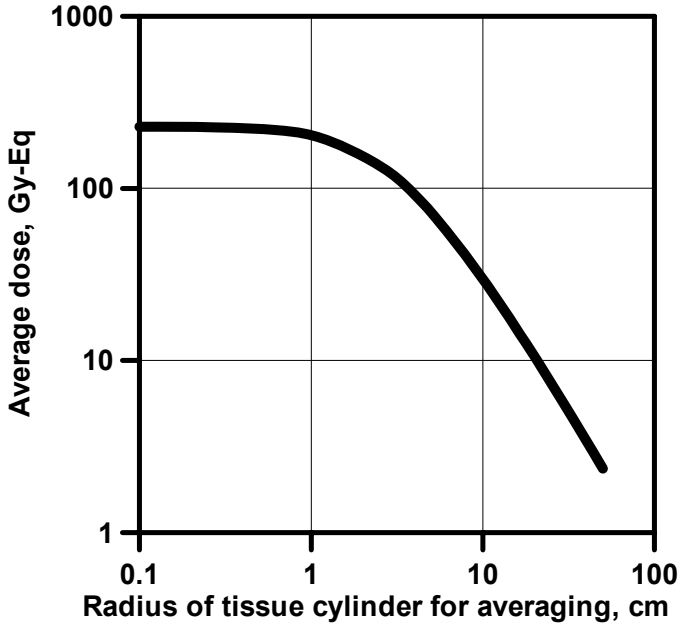

FIG 9. Average dose in approximate circle area from the source described in FIG.8 as a function of a radius of area.

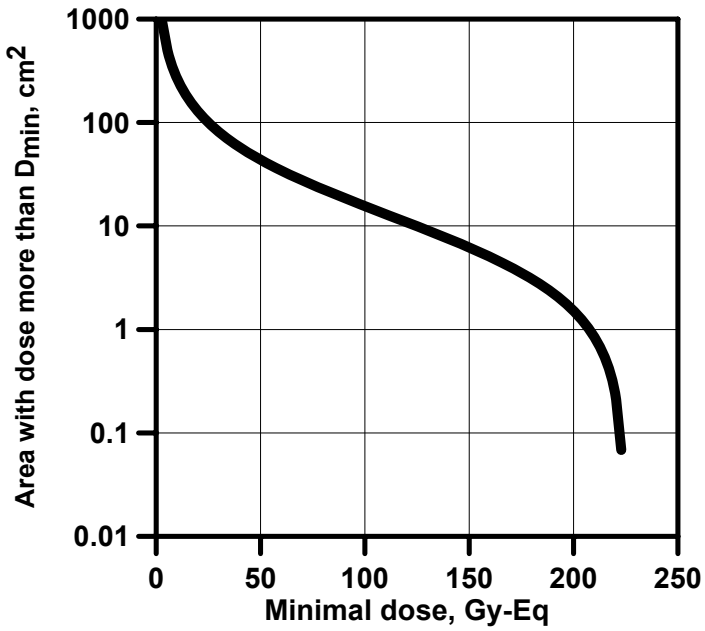

FIG 10. Approximate area where the dose would exceed 25 Gy-Eq for a source at 2cm above the base of tissue cylinder (at 1.5 cm above the body surface).

Dose conversion factors, $AF_{1,I}$, for irradiation of soft tissue by an adjacent source (Scenario I), is given as:

$$AF_{1,I} = RBE^{L} \times DF_{1,I}^{L}, \tag{59}$$

where:

$AF_{1,I}$ is the dose conversion factor for the RBE-weighted dose in soft tissue irradiated by an adjacent source as described in Scenario I, ((Gy-Eq)/(Bq×s));

RBE^{L} is the RBE for low LET radiation and is equal to unity ((Gy-Eq)/Gy); and

$DF_{1,I}^{L}$ is the dose conversion factor for absorbed dose in soft tissue irradiated by a low LET radiation from an adjacent source as described in Scenario I, (Gy/(Bq×s)).

Dose conversion factors, $AF_{1,I}$, for irradiation of red marrow by a distant source (Scenario II), are given as:

$$AF_{2,II} = RBE^{L} \times DF_{2,II}^{L}, \tag{60}$$

where:

$AF_{2,II}$ is the dose conversion factor for the RBE-weighted dose in red marrow irradiated by a distant source as described in Scenario II, ((Gy-Eq)/(Bq×s));

RBE^{L} is the RBE for low LET radiation and is equal to unity ((Gy-Eq)/Gy);

$DF_{2,II}^{L}$ is the dose conversion factor for absorbed dose in red marrow irradiated by a low LET radiation from a distant source as described in Scenario I, (Gy/(Bq×s)).

The RBE for low LET radiation is equal to unity as given in Table 10. Therefore, the dose rate conversion factor for RBE-weighted dose in the case of a source emitting only low LET radiation is numerically equal to the corresponding absorbed dose rate conversion factor.

IV.2. HIGH LET RADIATION

For external exposure, the only high LET radiation of interest is neutrons. There were several significant sources of neutrons that needed to be evaluated as possibly dangerous. Nuclear characteristics of some common neutron sources are listed in Table 27. Sources containing ^{252}Cf and solid mixtures of ^{241}Am/^{9}Be or ^{239}Pu/^{9}Be are the most important sources of neutrons. Neutron sources also emit photons; therefore, the dose rate from a neutron source must include this low LET radiation arising from nuclear decay or spontaneous fission, as well as the high LET neutron radiation.

IV.2.1. Dose factors used in the expert approach

For ^{252}Cf sources of neutrons, the absorbed dose rate conversion factors were estimated using the effective dose rate from Ref. [46]. The effective dose rate from neutrons was divided by 10 to estimate the absorbed dose rate factor for high LET radiation[19], $DF_{2,II}^{H+L}$, in red marrow at a distance of 1 m from the source (Scenario II). The absorbed dose rate factor, $DF_{1,I}^{H+L}$ for soft tissue according to the pocket scenario (Scenario I) was assumed to be 1000 times higher than the value of $DF_{2,II}^{H+L}$.

For ^{241}Am/^{9}Be and ^{239}Pu/^{9}Be neutron sources the absorbed dose rate conversion factors were estimated using the dose equivalent rate from Ref. [47]. This reference at Table 3.1 gives a formula for the dose equivalent dose rate from a point isotropic source of neutrons with an energy of 2 MeV. This is equal to the average energy of neutrons emitted by an unshielded ^{241}Am/^{9}Be or ^{239}Pu/^{9}Be source:

$$h^{n}_{point}(r) \approx 4.2\times10^{-10}\,\frac{Y_n}{4\pi r^2}\,, \qquad (61)$$

where:

$h^{n}_{point}(r)$ is the dose equivalent rate constant for a point isotropic source of neutrons with an energy of 2 MeV, (Sv/(Bq×s));

r is the distance from the point source, (cm); and

Y_n is a neutron yield of the source, the number of neutrons emitted in 1 s from a source of unit activity of alpha-emitting radionuclide, (neutrons/(Bq×s)).

Reference [47] gives, in Table 7.5, similar yields of about 6×10^{-5} neutron/(Bq×s) for both ^{241}Am/^{9}Be and ^{239}Pu/^{9}Be neutron sources[20]. For this yield, Eq. (61) gives a dose equivalent rate of high LET radiation at 2 cm from a source of approximately 4×10^{-16} Sv/(Bq×s). When this is added to the photon dose of 8.7×10^{-17} Gy/(Bq×s) for low LET radiation emitted in alpha decay of ^{241}Am from Table 15, the total dose equivalent is approximately 5×10^{-16} Sv/(Bq×s). The value of $DF_{1,I}^{H+L}$, the dose conversion factor for exposure to an adjacent source as defined in Scenario I, was considered equal to this. It was also assumed that the dose conversion factor for exposure to a source at 1 metre, $DF_{2,II}^{H}$ was 1/1000 of $DF_{1,I}^{H+L}$. The values of $DF_{1,I}^{L+H}$ and $DF_{2,II}^{L+H}$ for the neutron emitters addressed by the expert approach used for evaluating the D_1-values are listed in Table 13. These values roughly estimates the absorbed dose in terms of dose equivalent for 2 MeV neutrons. Therefore, this will

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[19] The contribution of low LET radiation to the effective dose from ^{252}Cf does not exceed 6% [46].

[20] The same value is given in Table 27.

significantly overestimate the absorbed dose and hence the danger from external radiation from these sources as can be seen when compared to the doses calculated by the risk approach listed in Table 14.

IV.2.2. Dose factors used in the risk approach

The RBE-weighted dose rate conversion factor for a neutron source is composed of two partial dose conversion factors corresponding to the low LET radiation and the high LET radiation:

$$AF_{T,S} = AF^{L}_{T,S} + AF^{H}_{T,S}, \tag{62}$$

where:

$AF^{L}_{T,S}$ is the partial dose rate conversion factor corresponding to photons arising from nuclear alpha or beta decay, spontaneous fission, or from the (α,n) reaction, and is equal to the RBE-weighted dose rate delivered in accordance with scenario S, in tissue T, from a neutron source with an activity of 1 Bq, ((Gy-Eq)/(Bq×s)); and

$AF^{H}_{T,S}$ is the partial dose rate conversion factor for neutrons and is equal to the RBE-weighted dose rate delivered in accordance with scenario S, in tissue T, from a neutron source with an activity of 1 Bq, ((Gy-Eq)/(Bq×s)).

Values of the RBE-weighted dose rate conversion factors used in the risk approach for calculating D_1-values for neutron (high LET) sources, are listed in Table 14.

The partial dose rate conversion factors for photons arising from nuclear alpha or beta decay, spontaneous fission, or the (α,n) reaction, $AF^{L}_{T,S}$, were calculated from the basic nuclear data regarding emission of low LET radiation by sources of neutrons, and are given in Table 27. The dose response functions $d^{\gamma}_{1,I}(E_{\gamma})$ and $d^{\gamma}_{2,II}(E_{\gamma})$ that were used for calculating dose rate conversion factors for radionuclides emitting low LET radiation were the same as used for the expert approach and are proportional to the photon energy for photons greater than 0.1 MeV. Analysis of these dependencies based on values of $AF_{1,II}$ and $AF_{7,II}$ calculated for radionuclide sources of monoenergetic photons, such as ^{109}Cd, ^{169}Yb, ^{57}Co, ^{174}Lu, ^{99m}Tc, ^{203}Hg, ^{135}Xe, ^{51}Cr, ^{115m}In, ^{131}I, ^{87m}Sr, ^{113m}In, ^{198}Au, ^{103}Ru, ^{85}Kr, ^{135m}Xe, ^{74}As, ^{106}Rh, ^{132}Cs, $^{137+}$Cs, ^{110}Ag, ^{95}Nb, ^{210}Po, ^{54}Mn, ^{86}Rb, ^{65}Zn, ^{123}Sn, ^{60}Co, ^{41}Ar, ^{40}K and ^{42}K gives the following dependencies for RBE-weighted dose response functions:

$$dA^{\gamma}_{T,S}(E_{\gamma}) \cong \alpha^{\gamma}_{T,S} \times Y^{\gamma}_{i} \times E_{\gamma}, \tag{63}$$

where:

$dA^{\gamma}_{T,S}(E_{\gamma})$ is the RBE-weighted dose response function equal to the RBE-weighted dose in organ or tissue T, irradiated by a photon from a monoenergetic source with an energy E_{γ} as described in scenario S, ((Gy-Eq)/(Bq×s));

$\alpha^{\gamma}_{T,S}$ is an organ and scenario specific exposure factor, ((Gy-Eq)/MeV);

Y^{γ}_{i} is yield of the monoenergetic photons in nuclear decay, (photon/(Bq×s)); and

E_{γ} is the energy of the monoenergetic photon arising in one nuclear transformation, (MeV/photon).

Therefore, the partial RBE-weighted dose rate conversion factors are equal to:

$$AF^{L}_{T,S} = \alpha^{\gamma}_{T,S} \times \sum_{i} \left(Y^{\gamma}_{i} \, E_{\gamma,i} \right), \tag{64}$$

where:

$AF^{L}_{T,S}$ is the partial RBE-weighted dose rate conversion factor for low LET radiation arising from spontaneous fission or the (α,n) reaction, and is equal to the RBE-weighted dose rate delivered in accordance with scenario S, in tissue T, from a neutron source with an activity[21] of 1 Bq, ((Gy-Eq)/(Bq×s));

$\sum_{i} \left(Y^{\gamma}_{i} \, E_{\gamma,i} \right)$ is the photon energy yield[21] from the neutron source, (MeV/(Bq×s)), and is given in Table 27;

$\alpha^{\gamma}_{T,S}$ is an organ and scenario specific exposure factor equal to:

(a) $\alpha^{\gamma}_{1,I} = 9.6 \times 10^{-15}$ (Gy-Eq)/MeV for exposure of soft tissue by an adjacent source; and

(b) $\alpha^{\gamma}_{2,II} = 1.4 \times 10^{-17}$ (Gy-Eq)/MeV for exposure of red marrow by a distant source.

The partial RBE-weighted dose rate conversion factor for a red marrow irradiated by neutrons from spontaneous fission or the (α,n) reaction in accordance with Scenario II, $AF^{H}_{2,II}$, was calculated from the dosimetry data for neutron irradiation of the red marrow in rotational (ROT) geometry given in Table A.31 from Ref. [43]:

$$AF^{H}_{2,II} = \frac{Y^{n}(S_n)}{4\pi r^{2}_{II}} RBE^{H}_{2} \times \int_{0}^{\infty} S_n(E_n) \times d^{n}_{FG,ROT}(E_n) dE_n \, , \tag{65}$$

where:

$AF^{H}_{2,II}$ is the partial RBE-weighted dose rate conversion factor for neutrons from spontaneous fission, or the (α,n) reaction, delivered in accordance with Scenario II to the red marrow , ((Gy-Eq)/(Bq×s));

$S_n(E_n)dE_n$ is the neutron spectrum given as the probability of emission of neutrons with an energy between E_n and $E_n + dE_n$, by the neutron source;

$d^{n}_{FG,ROT}(E_n)$ is the absorbed dose response function equal to the absorbed dose from neutron radiation in the red marrow per unit fluence of neutrons with energy E_n incident in rotational (ROT) geometry on the body of reference man, (Gy×cm^2), and is given in Table A.31 from Ref. [43]:

(a) $\int_{0}^{\infty} S_n(E_n) \times d^{n}_{FG,ROT}(E_n) dE_n = 4.0 \times 10^{-11}$ Gy×cm^2 for ^{252}Cf; and

(b) $\int_{0}^{\infty} S_n(E_n) \times d^{n}_{FG,ROT}(E_n) dE_n = 4.3 \times 10^{-11}$ Gy×cm^2 for ^{241}Am/^{9}Be.

RBE^{H}_{2} is the RBE for the development of severe deterministic effects in red marrow caused by external exposure to neutrons, and is given in Table 10;

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[21] Activity of considered neutron sources is expressed in number of alpha-transformation per one second.

$Y^n(S_n)$ is the neutron yield[21] from a neutron source, (neutron/(Bq×s)), and is given in Table 27; and,

r_{II} is the distance between the neutron source and the target tissue, (cm), defined in Scenario II, and is equal to 100 cm.

The data for the unmodified spectra of neutrons given in Ref. [48] were used as $S_n(E_n)$:

(a) the neutron spectrum from spontaneous fission of ^{252}Cf was used as a reference for all emitters of neutrons arising from spontaneous fission; and

(b) the neutron spectrum from an ^{241}Am/^{9}Be source was also used in the case of ^{239}Pu/^{9}Be source.

The partial RBE-weighted dose rate conversion factor for soft tissue irradiated by neutrons from spontaneous fission or the (α,n) reaction in accordance with Scenario I, $AF^H_{1,I}$, was calculated from $AF^H_{2,II}$ considering the exposure geometries for the pocket scenario (Scenario I) and the exposure factors $\alpha^{\gamma}_{T,S}$ defined for Eq. (64) is:

$$AF^H_{1,I} = \frac{\alpha^{\gamma}_{1,I}}{\alpha^{\gamma}_{7,II}} AF^H_{2,II} \cong 600 AF^H_{2,II}. \quad (66)$$

IV.3. LIST OF EXTERNAL DOSE CONVERSION FACTORS

TABLE 13. ABSORBED DOSE RATE CONVERSION FACTORS FOR SOFT TISSUE AND BONE MARROW FOR HIGH LET (NEUTRON) EMITTERS

Radio-nuclide	Adjacent source	Distant source
	Soft tissue	Red marrow
	$DF^{L+H\ a,c}_{1,I}$	$DF^{L+H\ b,c}_{2,II}$
	(Gy/(Bq×s))	(Gy/(Bq×s))
Cf-252	3.0 E-14	3.0 E-17
^{239}Pu/^{9}Be [c]	5.0 E-16	5.0 E-19
^{241}Am/^{9}Be [c]	5.0 E-16	5.0 E-19

[a] Dose rate conversion factor for absorbed dose in soft tissue in accordance with the pocket scenario.
[b] Dose rate in red marrow at a distance of 1 metre from a source.
[c] Doses from low LET and high LET radiation were taken into account and summed.
[e] The activity given is that of the alpha-emitting radionuclide, e.g., ^{239}Pu or ^{241}Am.

TABLE 14. RBE-WEIGHTED DOSE RATE CONVERSION FACTORS FOR SOFT TISSUE AND BONE MARROW FOR HIGH LET (NEUTRON) EMITTERS

Neutron source	Origin of neutrons	Soft tissue			Red marrow		
		$AF_{1,I}^{L}$	$AF_{1,I}^{H}$	$AF_{1,I}$	$AF_{2,II}^{L}$	$AF_{2,II}^{H}$	$AF_{2,II}$
		((Gy-Eq)/(Bq×s))	((Gy-Eq)/(Bq×s))	((Gy-Eq)/(Bq×s))	((Gy-Eq)/(Bq×s))	((Gy-Eq)/(Bq×s))	((Gy-Eq)/(Bq×s))
^{248}Cm	SF [a]	1.2E-14	1.4E-13	1.5E-13	2.1E-17	2.4E-16	2.6E-16
^{250}Cf	SF	1.1E-16	1.5E-15	1.6E-15	1.8E-19	2.4E-18	2.6E-18
^{252}Cf	SF	4.5E-15	6.0E-14	6.4E-14	7.5E-18	1.0E-16	1.1E-16
^{254}Cf	SF	1.6E-13	2.1E-12	2.3E-12	2.7E-16	3.5E-15	3.8E-15
$^{239}Pu/^{9}Be$ [b]	(α,n)	9.0E-18	4.0E-17	4.9E-17	1.5E-20	6.7E-20	8.2E-20
$^{241}Am/^{9}Be$ [b]	(α,n)	8.9E-17 [c]	5.0E-17	1.4E-16	9.4E-20 [c]	8.4E-20	1.8E-19

[a] Spontaneous fission.

[b] The activity given is that of the alpha-emitting radionuclide, e.g., ^{239}Pu or ^{241}Am.

[c] This radionuclide emits photons with an energy of about 60 keV for which Eq. (64) only gives a very rough estimate due to significant self-shielding. Therefore the value given here is the sum of the dose conversion factor for ^{241}Am from Table 15 (which does allow for self-shielding) and the factor calculated from Eq. (64) for neutrons arising in neutron production.

TABLE 15. RBE-WEIGHTED DOSE RATE CONVERSION FACTORS FOR EXTERNAL EXPOSURE FROM LOW LET EMITTERS

Radionuclides [a]	Adjacent source	Distant source
	Soft tissue	Red marrow
	$AF_{1,I}$ [b]	$AF_{2,II}$, [c]
	((Gy-Eq)/(Bq×s))	((Gy-Eq)/(Bq×s))
H-3	7.6E-27	2.9E-29
Be-7	5.2E-16	8.3E-19
Be-10	2.4E-18	3.6E-21
C-11	1.1E-14	1.8E-17
C-14	1.6E-20	1.8E-23
N-13	1.1E-14	1.8E-17
F-18	1.1E-14	1.8E-17
Na-22	2.2E-14	3.7E-17
Na-24	3.6E-14	6.3E-17
Mg-28	3.0E-14	5.1E-17
Al-26	2.6E-14	4.3E-17
Si-31	5.2E-17	8.2E-20
Si-32 +	5.2E-17	8.3E-20
P-32	5.2E-17	8.3E-20
P-33	9.3E-20	1.2E-22
S-35	1.9E-20	2.1E-23
Cl-36	6.4E-18	9.7E-21
Cl-38	1.4E-14	2.4E-17
Ar-37	0.0E+00	0.0E+00
Ar-39	2.0E-18	3.0E-21
Ar-41	1.3E-14	2.1E-17
K-40	1.5E-15	2.6E-18
K-42	3.1E-15	5.3E-18
K-43	1.0E-14	1.7E-17

Radionuclides [a]	Adjacent source	Distant source
	Soft tissue	Red marrow
	$AF_{1,I}$ [b]	$AF_{2,II}$, [c]
	((Gy-Eq)/ (Bq×s))	((Gy-Eq)/ (Bq×s))
Ca-41	0.0E+00	0.0E+00
Ca-45	1.1E-19	1.3E-22
Ca-47 +	1.1E-14	1.9E-17
Sc-44	2.2E-14	3.6E-17
Sc-46	2.0E-14	3.4E-17
Sc-47	9.7E-16	1.4E-18
Sc-48	3.3E-14	5.6E-17
Ti-44 +	2.3E-14	3.7E-17
V-48	2.9E-14	4.9E-17
V-49	0.0E+00	0.0E+00
Cr-51	3.3E-16	5.1E-19
Mn-52	3.4E-14	5.8E-17
Mn-53	0.0E+00	0.0E+00
Mn-54	8.6E-15	1.4E-17
Mn-56	1.6E-14	2.8E-17
Fe-52 +	3.2E-14	5.3E-17
Fe-55	0.0E+00	0.0E+00
Fe-59	1.2E-14	2.0E-17
Fe-60 +	1.1E-14	1.9E-17
Co-55 +	2.0E-14	3.3E-17
Co-56	3.4E-14	5.8E-17
Co-57	9.6E-16	1.4E-18
Co-58	1.0E-14	1.7E-17
Co-58m +	1.0E-14	1.7E-17
Co-60	2.4E-14	4.1E-17
Ni-59	0.0E+00	0.0E+00
Ni-63	2.3E-22	1.2E-25
Ni-65	5.4E-15	9.1E-18
Cu-64	2.0E-15	3.2E-18
Cu-67	1.0E-15	1.6E-18
Zn-65	5.8E-15	9.8E-18
Zn-69	8.3E-18	1.2E-20
Zn-69m+	4.4E-15	7.0E-18
Ga-67	1.4E-15	2.1E-18
Ga-68	1.0E-14	1.7E-17
Ga-72	2.6E-14	4.3E-17
Ge-68 +	1.0E-14	1.7E-17
Ge-71	1.9E-23	4.9E-24
Ge-77 +	1.1E-14	1.8E-17
As-72	1.9E-14	3.1E-17
As-73	1.9E-17	1.8E-20
As-74	8.0E-15	1.3E-17
As-76	4.7E-15	7.7E-18
As-77	9.2E-17	1.4E-19
Se-75	3.7E-15	5.8E-18
Se-79	2.2E-20	2.4E-23
Br-76	2.5E-14	4.2E-17
Br-77	3.3E-15	5.2E-18
Br-82	2.7E-14	4.4E-17
Kr-81	5.6E-17	8.7E-20

Radionuclides [a]	Adjacent source	Distant source
	Soft tissue	Red marrow
	$AF_{1,I}$ [b]	$AF_{2,II}$, [c]
	((Gy-Eq)/ (Bq×s))	((Gy-Eq)/ (Bq×s))
Kr-85	2.7E-17	4.3E-20
Kr-85m	1.5E-15	2.2E-18
Kr-87	7.9E-15	1.3E-17
Rb-81	6.4E-15	1.0E-17
Rb-83	5.2E-15	8.4E-18
Rb-84	9.4E-15	1.6E-17
Rb-86	1.0E-15	1.7E-18
Rb-87	2.2E-19	2.9E-22
Sr-82	1.2E-14	1.9E-17
Sr-85	5.3E-15	8.6E-18
Sr-85m +	6.8E-15	1.1E-17
Sr-87m	3.4E-15	5.2E-18
Sr-89	4.3E-17	6.8E-20
Sr-90 +	1.5E-16	2.4E-19
Sr-91 +	1.1E-14	1.8E-17
Sr-92 +	1.6E-14	2.7E-17
Y-87 +	8.1E-15	1.3E-17
Y-88	2.5E-14	4.3E-17
Y-90	1.5E-16	2.4E-19
Y-91	8.2E-17	1.3E-19
Y-91m +	5.7E-15	9.1E-18
Y-92	3.1E-15	5.1E-18
Y-93	1.2E-15	1.9E-18
Zr-88 +	2.9E-14	5.0E-17
Zr-93 +	6.0E-20	4.0E-23
Zr-95 +	1.6E-14	2.6E-17
Zr-97 +	1.6E-14	2.6E-17
Nb-93m	2.8E-19	1.9E-22
Nb-94	1.6E-14	2.7E-17
Nb-95	7.9E-15	1.3E-17
Nb-97	6.9E-15	1.1E-17
Mo-93 +	1.6E-18	1.1E-21
Mo-99 +	2.5E-15	3.9E-18
Tc-95m	7.1E-15	1.1E-17
Tc-96	2.6E-14	4.2E-17
Tc-96m +	2.6E-14	4.2E-17
Tc-97	2.3E-18	1.3E-21
Tc-97m	4.6E-18	4.2E-21
Tc-98	1.5E-14	2.4E-17
Tc-99	2.1E-19	2.8E-22
Tc-99m	1.1E-15	1.6E-18
Ru-97	2.2E-15	3.4E-18
Ru-103 +	5.0E-15	7.9E-18
Ru-105 +	9.0E-15	1.4E-17
Ru-106 +	2.6E-15	4.3E-18
Rh-99	5.9E-15	9.4E-18
Rh-101	2.3E-15	3.6E-18
Rh-102	2.2E-14	3.6E-17
Rh-102m	6.0E-15	9.7E-18
Rh-103m	7.5E-19	3.4E-22

Radionuclides [a]	Adjacent source	Distant source
	Soft tissue	Red marrow
	$AF_{1,I}$ [b]	$AF_{2,II}$, [c]
	((Gy-Eq)/ (Bq×s))	((Gy-Eq)/ (Bq×s))
Rh-105	8.0E-16	1.2E-18
Pd-103 +	8.0E-18	4.8E-21
Pd-107	3.9E-24	2.3E-27
Pd-109	4.3E-17	5.8E-20
Ag-105	5.2E-15	8.3E-18
Ag-108m	1.7E-14	2.8E-17
Ag-110m	2.8E-14	4.7E-17
Ag-111	2.8E-16	4.4E-19
Cd-109	3.4E-17	3.3E-20
Cd-113m	1.6E-18	2.3E-21
Cd-115 +	4.0E-15	6.4E-18
Cd-115m	2.7E-16	4.4E-19
In-111	3.7E-15	5.7E-18
In-113m	2.7E-15	4.1E-18
In-114m	9.1E-16	1.4E-18
In-115m	1.6E-15	2.4E-18
Sn-113 +	2.7E-15	4.2E-18
Sn-117m	1.3E-15	1.9E-18
Sn-119m	9.4E-18	3.9E-21
Sn-121m +	5.9E-18	3.0E-21
Sn-123	1.0E-16	1.7E-19
Sn-125	7.3E-15	1.2E-17
Sn-126 +	2.1E-14	3.3E-17
Sb-122	4.7E-15	7.6E-18
Sb-124	1.8E-14	3.0E-17
Sb-125 +	4.4E-15	7.0E-18
Sb-126	3.0E-14	4.8E-17
Te-121	5.9E-15	9.4E-18
Te-121m +	7.2E-15	1.1E-17
Te-123m	1.2E-15	1.8E-18
Te-125m	4.3E-17	2.1E-20
Te-127	5.4E-17	8.4E-20
Te-127m +	6.7E-17	9.1E-20
Te-129	6.1E-16	9.8E-19
Te-129m +	7.2E-16	1.1E-18
Te-131m +	1.9E-14	3.1E-17
Te-132 +	2.6E-14	4.2E-17
I-123	1.4E-15	2.1E-18
I-124	1.1E-14	1.8E-17
I-125	4.9E-17	2.1E-20
I-126	4.7E-15	7.4E-18
I-129	3.5E-17	1.7E-20
I-131	4.0E-15	6.2E-18
I-132	2.3E-14	3.9E-17
I-133	6.6E-15	1.1E-17
I-134	2.7E-14	4.4E-17
I-135	1.8E-14	3.1E-17
Xe-122	1.1E-14	1.7E-17
Xe-123 +	7.4E-15	1.2E-17
Xe-127	2.5E-15	3.8E-18

Radionuclides [a]	Adjacent source	Distant source
	Soft tissue	Red marrow
	$AF_{1,I}$ [b]	$AF_{2,II}$, [c]
	((Gy-Eq)/ (Bq×s))	((Gy-Eq)/ (Bq×s))
Xe-131m	5.1E-17	5.3E-20
Xe-133	2.0E-16	2.4E-19
Xe-135	2.5E-15	3.9E-18
Cs-129	2.6E-15	4.1E-18
Cs-131	3.1E-17	1.3E-20
Cs-132	7.2E-15	1.1E-17
Cs-134	1.6E-14	2.7E-17
Cs-134m +	1.6E-14	2.6E-17
Cs-135	5.2E-20	6.4E-23
Cs-136	2.2E-14	3.6E-17
Cs-137 +	5.9E-15	9.6E-18
Ba-131 +	4.4E-15	6.9E-18
Ba-133	3.7E-15	5.7E-18
Ba-133m	2.3E-15	3.4E-18
Ba-140 +	2.4E-14	4.1E-17
La-137	3.8E-17	1.9E-20
La-140	2.2E-14	3.8E-17
Ce-139	1.2E-15	1.8E-18
Ce-141	6.1E-16	9.2E-19
Ce-143 +	2.7E-15	4.2E-18
Ce-144 +	7.6E-16	1.2E-18
Pr-142	6.6E-16	1.1E-18
Pr-143	8.2E-18	1.2E-20
Nd-147 +	1.2E-15	1.9E-18
Nd-149 +	3.9E-15	6.0E-18
Pm-143	3.0E-15	4.9E-18
Pm-144	1.6E-14	2.6E-17
Pm-145	6.8E-17	4.8E-20
Pm-147	8.5E-20	1.1E-22
Pm-148m	2.1E-14	3.4E-17
Pm-149	1.2E-16	1.9E-19
Pm-151	3.2E-15	5.0E-18
Sm-145 +	1.7E-16	1.2E-19
Sm-147	0.0E+00	0.0E+00
Sm-151	3.6E-21	1.7E-24
Sm-153	3.1E-16	4.0E-19
Eu-147	4.6E-15	7.4E-18
Eu-148	2.2E-14	3.7E-17
Eu-149	3.9E-16	5.4E-19
Eu-150b	4.6E-16	7.3E-19
Eu-150a	1.5E-14	2.4E-17
Eu-152	1.1E-14	1.9E-17
Eu-152m	2.9E-15	4.8E-18
Eu-154	1.2E-14	2.0E-17
Eu-155	3.5E-16	4.8E-19
Eu-156	1.3E-14	2.1E-17
Gd-146 +	2.7E-14	4.3E-17
Gd-148	0.0E+00	0.0E+00
Gd-153	4.9E-16	6.0E-19
Gd-159	4.5E-16	6.8E-19

Radionuclides [a]	Adjacent source	Distant source
	Soft tissue	Red marrow
	$AF_{1,I}$ [b]	$AF_{2,II}$, [c]
	((Gy-Eq)/ (Bq×s))	((Gy-Eq)/ (Bq×s))
Tb-157	6.4E-18	4.7E-21
Tb-158	7.7E-15	1.3E-17
Tb-160	1.1E-14	1.9E-17
Dy-159	1.2E-16	9.3E-20
Dy-165	2.4E-16	3.8E-19
Dy-166 +	4.7E-16	6.8E-19
Ho-166	2.9E-16	4.7E-19
Ho-166m	1.8E-14	2.9E-17
Er-169	2.8E-19	3.9E-22
Er-171	3.7E-15	5.7E-18
Tm-167	1.1E-15	1.6E-18
Tm-170	3.4E-17	4.3E-20
Tm-171	2.2E-18	2.2E-21
Yb-169	2.1E-15	3.0E-18
Yb-175	3.9E-16	6.1E-19
Lu-172	1.8E-14	3.1E-17
Lu-173	8.0E-16	1.1E-18
Lu-174	9.1E-16	1.4E-18
Lu-174m +	1.1E-15	1.6E-18
Lu-177	3.0E-16	4.6E-19
Hf-172 +	1.9E-14	3.1E-17
Hf-175	3.5E-15	5.3E-18
Hf-181	5.6E-15	8.8E-18
Hf-182 +	1.4E-14	2.3E-17
Ta-178a	9.7E-15	1.4E-17
Ta-179	1.1E-16	1.2E-19
Ta-182	1.2E-14	2.1E-17
W-178	7.7E-16	1.1E-18
W-181	1.5E-16	1.6E-19
W-185	9.5E-19	1.3E-21
W-187	4.8E-15	7.8E-18
W-188 +	6.5E-16	1.0E-18
Re-184	8.7E-15	1.4E-17
Re-184m +	1.0E-14	1.7E-17
Re-186	1.6E-16	2.2E-19
Re-187	0.0E+00	0.0E+00
Re-188	6.4E-16	1.0E-18
Re-189	6.3E-16	9.7E-19
Os-185	7.2E-15	1.1E-17
Os-191	4.6E-16	6.3E-19
Os-191m +	5.0E-16	6.7E-19
Os-193	6.9E-16	1.1E-18
Os-194 +	1.0E-15	1.7E-18
Ir-189	4.7E-16	6.3E-19
Ir-190	1.5E-14	2.3E-17
Ir-192	8.5E-15	1.3E-17
Ir-194	1.0E-15	1.7E-18
Pt-188 +	1.6E-14	2.7E-17
Pt-191	2.5E-15	3.8E-18
Pt-193	1.8E-21	2.3E-23

Radionuclides [a]	Adjacent source	Distant source
	Soft tissue	Red marrow
	$AF_{1,I}$ [b]	$AF_{2,II}$, [c]
	((Gy-Eq)/ (Bq×s))	((Gy-Eq)/ (Bq×s))
Pt-193m	5.0E-17	6.1E-20
Pt-195m	3.7E-16	4.7E-19
Pt-197	1.6E-16	2.2E-19
Pt-197m+	7.8E-16	1.1E-18
Au-193	1.2E-15	1.7E-18
Au-194	1.0E-14	1.7E-17
Au-195	4.0E-16	5.1E-19
Au-198	4.3E-15	6.7E-18
Au-199	7.5E-16	1.1E-18
Hg-194 +	1.0E-14	1.7E-17
Hg-195m +	3.2E-15	4.9E-18
Hg-197	3.3E-16	4.2E-19
Hg-197m +	9.8E-16	1.3E-18
Hg-203	2.4E-15	3.7E-18
Tl-200	1.3E-14	2.1E-17
Tl-201	5.3E-16	7.2E-19
Tl-202	4.6E-15	7.2E-18
Tl-204	9.4E-18	1.3E-20
Pb-201 +	7.9E-15	1.2E-17
Pb-202 +	4.6E-15	7.1E-18
Pb-203	2.8E-15	4.3E-18
Pb-205	2.6E-21	3.0E-23
Pb-210 +	1.8E-17	2.4E-20
Pb-212 +	1.4E-14	2.3E-17
Bi-205	1.6E-14	2.7E-17
Bi-206	3.3E-14	5.3E-17
Bi-207	1.5E-14	2.6E-17
Bi-210 +	1.3E-17	2.0E-20
Bi-210m	2.6E-15	4.0E-18
Bi-212 +	1.3E-14	2.2E-17
Po-210	8.8E-20	1.4E-22
At-211	1.3E-15	2.1E-18
Rn-222	1.7E-14	2.9E-17
Ra-223 +	2.8E-15	4.3E-18
Ra-224 +	1.4E-14	2.4E-17
Ra-225 +	2.3E-15	3.6E-18
Ra-226	1.7E-14	2.9E-17
Ra-228 +	2.1E-14	3.6E-17
Ac-225	2.2E-15	3.6E-18
Ac-227 +	3.7E-15	5.8E-18
Ac-228	2.3E-14	3.9E-17
Th-227 +	3.8E-15	5.8E-18
Th-228 +	1.4E-14	2.4E-17
Th-229 +	2.9E-15	4.4E-18
Th-230 +	2.3E-18	3.1E-21
Th-231	7.1E-17	9.4E-20
Th-232 +	7.7E-15	1.3E-17
Th-234 +	2.8E-16	4.4E-19
Pa-230 +	6.4E-15	1.0E-17
Pa-231 +	8.9E-16	1.3E-18

Radionuclides [a]	Adjacent source	Distant source
	Soft tissue	Red marrow
	$AF_{1,I}$ [b]	$AF_{2,II}$, [c]
	((Gy-Eq)/ (Bq×s))	((Gy-Eq)/ (Bq×s))
Pa-233	1.9E-15	2.9E-18
U-230 +	1.8E-16	2.8E-19
U-232 +	1.0E-14	1.8E-17
U-233	2.7E-18	3.9E-21
U-234 +	8.2E-19	9.8E-22
U-235 +	1.5E-15	2.2E-18
U-236	4.5E-19	4.9E-22
U-238 +	2.8E-16	4.4E-19
Np-235	6.5E-18	8.4E-21
Np-236b +	4.1E-16	6.2E-19
Np-236a	8.8E-16	1.3E-18
Np-237 +	2.0E-15	3.1E-18
Np-239	1.4E-15	2.1E-18
Pu-236	5.8E-16	9.9E-19
Pu-237	3.1E-16	4.4E-19
Pu-238	3.7E-19	3.0E-22
Pu-239	5.9E-19	7.9E-22
Pu-240	3.6E-19	2.9E-22
Pu-241 +	1.1E-20	1.7E-23
Pu-242	3.1E-19	2.6E-22
Pu-244 +	3.5E-15	5.7E-18
Am-241	8.7E-17	9.1E-20
Am-242m +	1.0E-16	1.4E-19
Am-243 +	1.7E-15	2.6E-18
Am-244	8.1E-15	1.3E-17
Cm-240	5.2E-16	8.9E-19
Cm-241 +	4.8E-15	7.6E-18
Cm-242	4.7E-19	3.3E-22
Cm-243	1.1E-15	1.7E-18
Cm-244	3.5E-19	2.0E-22
Cm-245	6.5E-16	9.6E-19
Cm-246	3.2E-19	1.9E-22
Cm-247	3.4E-15	5.3E-18
Bk-247	8.2E-16	1.2E-18
Bk-249	5.9E-17	9.2E-20
Cf-248 +	4.7E-19	2.4E-22
Cf-249	3.4E-15	5.3E-18
Cf-251	1.0E-15	1.6E-18
Cf-253	6.1E-17	9.6E-20

[a] In growth of radioactive progeny was taken into account when calculation the dose factors for all the radionuclides as described in Appendix VIII. An "+" indicates the radionuclides for which the progeny were significant sources of dose for the scenarios considered.

[b] RBE-weighted dose rate conversion factor for soft tissue in accordance with the pocket scenario.

[c] RBE-weighted dose rate in the red marrow at a distance of 1 metre from the source.

APPENDIX V
INHALATION, IMMERSION AND SKIN DOSE CONVERSION FACTORS USED IN THE EXPERT APPROACH

Dose conversion factors used for calculating ${}^{E}D_2$-values included factors for inhalation, skin contamination and immersion.

V.1. INHALATION

Inhalation of dispersed radioactive material was assumed as a major pathway in calculating the ${}^{E}D_2$-values**.** Details on the chemical and physical properties of the radioactive material as well as the "inhalation scenario" (Scenario IIIE) are described in Appendix II. The values of dose conversion factors used in calculating the ${}^{E}D_2$-values are listed in Table 16 and Table 17. Except where noted, the dose factors for red marrow and respiratory track were based on the absorbed "lung" dose rate database contained in Ref. [49]. This database presents dose factors for all three particulate lung absorption types as defined in the ICRP Human Respiratory Tract Model [11, 16] (i.e. F, M, and S) assuming an AMAD of 1 micron. Other physical forms (e.g. gas and vapour) were also considered. It should be noted that the "lung dose" in Ref. [49] is the weighted sum of the absorbed dose to the different tissues of the thoracic region of the respiratory tract. This is analogous to effective dose and reflects non-uniform internal exposure of the tissues of the respiratory tract. These tissues have different radiosensitivity with regard to developing stochastic health effects. Thus to avoid confusion, the name "thoracic region" is used for the critical organ that was assumed to develop serious lung injury in the expert approach. As discussed in Ref. [15], it would have been more appropriate to use the dose to the alveolar region of the respiratory tract for the evaluation of pneumonitis as was done in the risk approach.

Dose factors for materials containing the same radionuclide, but assigned to different lung absorption rates are different. In the expert approach for the red marrow and respiratory track, the dose factor for the adsorption type or form that gave the highest committed organ dose was used. For each radionuclide, Table 17 contain values of the maximum dose conversion factor for a given organ or tissue. The types of materials taken into account in evaluating the ${}^{E}D_2$-values from Scenario IIIE were taken from Table II-VIII of Ref. [11]. The conversion factors and scenario parameters used are for exposure of the reference adult member of the public. Use of these conversion factors for other age groups will lead to an overestimation of the committed dose. Values for the 365-day committed dose from high LET radiation in the thoracic region of the respiratory tract were estimated by multiplying the 30-day committed absorbed dose from Ref. [49] by four, based on expert judgment. The dose conversion factor for ^{252}Cf was not provided in [49]. Therefore, it was estimated by multiplying the dose conversion factor for ^{241}Am by the ratio of the effective dose for ^{252}Cf and the effective dose for ^{241}Am from [11]. This ratio is about 0.5.

For thyroid exposure following inhalation the absorbed dose factors from ref. [28] were used. These factors are for a life time comment but considering the biological and physical half-life of the radionuclides that result in significant thyroid dose (isotopes of I and Te) these dose factors were in fact for a commitment period of much less than less than 365 days; however, the a commitment period (Δ) of 365 days.

V.2. SKIN CONTAMINATION

Dose conversion factors from Ref. [35] were used in the expert approach for estimating the contact exposure of the skin from surface contamination. These dose factors are for the basal layer of skin at 70 μm (7 mg/cm^2) below its surface. However, long term deterministic effects to the skin from exposure arise mainly at a depth of 300-500 μm, [17, 18]. Consequently, calculations based on these dose factors from Ref. [35] should be conservative when used to indicate the occurrence of severe

deterministic health effects. Dose conversion factors used in the expert approach for evaluating contact exposure of the skin are given in Table 16.

TABLE 16. INHALATION COMMITTED ABSORBED DOSE AND CONTAMINATION ABSORBED DOSE CONVERSION FACTORS

Radionuclide [a]	Inhalation			Contamination
	Red marrow	Respiratory tract Low LET	Respiratory tract High LET	Basal membrane of the skin
	$DF^{L+H}_{2,IIIE}(\Delta)$ [b]	$DF^{L}_{3E,IIIE}(\Delta)$ [c]	$DF^{HS}_{3E,IIIE}(\Delta)$ [d]	$DF^{L}_{6E,V}$ [e]
	(Gy/Bq)	(Gy/Bq)	(Gy/Bq)	(Gy/(Bq×s/cm^2))
H-3	2.2E-12	5.4E-12	NG [f]	0.0E+00
C-14	6.5E-12	1.1E-09	NG	8.8E-11
P-32	2.5E-10	3.6E-09	NG	4.7E-10
S-35	1.7E-11	1.1E-09	NG	9.4E-11
Cl-36	3.5E-11	2.8E-09	NG	4.4E-10
Cr-51	2.2E-12	1.1E-11	NG	2.8E-13
Fe-55	1.3E-11	5.6E-12	NG	2.8E-13
Co-57	7.4E-12	1.6E-10	NG	2.1E-11
Co-60	1.3E-10	2.4E-09	NG	2.9E-10
Ni-63	2.8E-12	1.1E-09	NG	2.8E-13
Zn-65	3.6E-11	1.5E-10	NG	6.7E-12
Ge-68	9.4E-11	3.4E-08	NG	4.2E-10
Se-75	2.4E-11	2.9E-10	NG	2.8E-11
Sr-89	2.5E-10	3.4E-09	NG	4.6E-10
Sr-90+	1.8E-10	( ) [g]	NG	8.8E-10
Y-90	3.4E-10	3.5E-09	NG	4.7E-10
Y-91	2.9E-10	3.5E-09	NG	4.6E-10
Zr-95+	1.2E-10	2.3E-09	NG	3.3E-10
Nb-95	5.9E-11	1.1E-09	NG	4.0E-10
Nb-95m+	6.0E-11	2.0E-09	NG	ND [h]
Mo-99+	7.7E-11	2.7E-09	NG	5.1E-10
Tc-99m	1.7E-12	8.4E-11	NG	6.5E-11
Ru-103+	9.0E-11	2.0E-09	NG	1.8E-10
Ru-106+	2.9E-10	5.7E-09	NG	4.9E-10
Pd-103+	4.9E-13	4.5E-10	NG	2.8E-13
Cd-109	5.2E-12	2.1E-09	NG	1.4E-10
Te-132+	3.3E-10	4.4E-09	NG	6.6E-10
I-125	2.9E-12	1.0E-10	NG	2.8E-13
I-129	5.2E-12	1.2E-09	NG	ND
I-131	3.3E-11	2.4E-09	NG	4.0E-10
Cs-134	1.1E-10	2.3E-09	NG	3.0E-10
Cs-137+	6.5E-11	2.9E-09	NG	4.4E-10
Ba-133	5.4E-11	8.9E-10	NG	2.7E-11
Ce-141	5.7E-11	2.9E-09	NG	4.8E-10
Ce-144+	3.4E-10	7.4E-09	NG	7.3E-10
Pm-147	2.7E-11	1.4E-09	NG	1.6E-10
Eu-152	1.4E-10	1.9E-09	NG	2.1E-10
Eu-154	2.0E-10	4.0E-09	NG	5.0E-10
Gd-153	2.9E-11	7.9E-10	NG	3.1E-11
Tm-170	2.0E-10	3.2E-09	NG	4.5E-10
Yb-169	8.6E-11	2.3E-09	NG	2.7E-10
Re-188	3.4E-11	2.3E-09	NG	5.2E-10
Ir-192	5.9E-11	3.0E-09	NG	4.5E-10

Radionuclide [a]	Inhalation			Contamination
	Red marrow	Respiratory tract Low LET	Respiratory tract High LET	Basal membrane of the skin
	$DF^{L+H}_{2,IIIE}(\Delta)$ [b]	$DF^{L}_{3E,IIIE}(\Delta)$ [c]	$DF^{HS}_{3E,IIIE}(\Delta)$ [d]	$DF^{L}_{6E,V}$ [e]
	(Gy/Bq)	(Gy/Bq)	(Gy/Bq)	(Gy/(Bq×s/cm^2))
Au-198	3.7E-11	2.4E-09	NG	4.6E-10
Hg-203	3.3E-11	2.8E-08	NG	2.5E-10
Po-210	2.1E-09	NG	3.9E-06	2.8E-13
Ra-226+	3.9E-09	NG	3.8E-06	1.0E-09
Th-230	2.3E-09	NG	3.4E-06	ND
Th-232	2.0E-09	NG	2.5E-06	ND
U-232	9.2E-10	NG	4.4E-06	1.5E-12
U-234	8.2E-10	NG	3.2E-06	ND
U-235+	2.8E-09	NG	3.2E-06	ND
U-237	3.8E-11	3.6E-09	NG	ND
U-238	7.3E-10	NG	2.8E-06	ND
U natural	ND	NG	2.8E-06	ND
U depleted	ND	NG	2.8E-06	ND
U enriched	ND	NG	3.2E-06	ND
Np-237+	1.8E-09	NG	3.5E-06	ND
Pu-238	1.7E-09	NG	4.4E-06	2.8E-13
Pu-239	1.6E-09	NG	3.9E-06	ND
Pu-240	1.6E-09	NG	3.9E-06	ND
Pu-241+	2.1E-11	NG	8.9 E-08	2.8E-13
Pu-242	1.5E-09	NG	3.6E-06	ND
Am-241	1.6E-09	NG	4.4E-06	7.4E-13
Cm-242	1.7E-09	NG	5.2E-06	2.8E-13
Cm-244	1.7E-09	NG	4.8E-06	2.8E-13
Cf-252	ND	2.3E-10	2.2E-06 [j]	ND

[a] In growth of radioactive progeny was taken into account before intake when calculation the dose factors for all the radionuclides as described in Appendix VIII. An "+" indicates the radionuclides for which the progeny were significant sources of dose for the scenarios considered.

b Dose conversion factor for the 2-day committed absorbed dose delivered to Tissue 2 (red marrow) due to inhalation of 1 Bq of a radionuclide emitting any combination of low LET and high LET radiation from Ref. [49].

[c] Dose conversion factor for the 2-day committed absorbed dose delivered to Tissue 3E (thoracic region of the respiratory tract) due to inhalation of 1 Bq of a radionuclide emitting low LET radiation from Ref. [49].

[d] Dose conversion factor for the 365-day committed absorbed dose delivered to Tissue 3E (thoracic region of the respiratory tract) due to inhalation of 1 Bq of a Type S aerosol of a radionuclide emitting high LET. The 365 day committed dose was assumed equal to 4 times the 30 day committed dose from Ref. [49].

[e] Dose conversion factor for the absorbed dose rate in Tissue 6E (basal membrane of the skin) delivered due to unit surface activity of a radionuclide emitting low LET radiation.

[f] "NG" means 'negligible".

[g] For the special case of the insoluble compound $^{90}SrTiO_3$, as discussed in Appendix I, the conversion factor for the 365-day committed absorbed dose to Tissue 3E (thoracic region of the respiratory tract), $DF^{LS}_{3E,IIIE}(\Delta)$ was used and is 3.7E-07 Gy/Bq.

[h] "ND" means "no data".

[i] The dose conversion factor for ^{252}Cf was estimated by multiplying the dose conversion factor for ^{241}Am times the ratio of the effective dose for ^{252}Cf and effective dose for ^{241}Am from [11]. This ratio is 0.5.

TABLE 17. THYROID COMMITTED ABSORBED DOSE FACTORS FROM INHALATION

Radionuclide [a]	Thyroid $DF^{L}_{5,IIIE}(\Delta)$ [b] (Gy/Bq)
Te-132+	5.8E-08
I-125	2.2E-07
I-129	1.6E-06
I-131	2.9E-07

[a] For all other radionuclides considered in the Expert approach the dose to the thyroid is negligible.

[b] The dose conversion factor for the 365-day committed absorbed dose in Tissue 5 (thyroid) due to an intake of 1 Bq of a thyroid-seeking radionuclide emitting low LET radiation. This taken as equal to the lifetime committed dose from ref. [28].

V.3. IMMERSION

The immersion dose factors from the Ref. [40] were used in the expert approach. Immersion in a semi-infinite cloud of radioactive noble gas was assumed, which would overestimate immersion in the 300 m^3 room of Scenario VI. In the expert approach, only ^{85}Kr was considered as a source of immersion. This radionuclide emits low LET radiation and, therefore, the absorbed dose rate conversion factor $DF^{L}_{2,VI}$ for it was taken as being numerically equal to the RBE-weighted dose conversion factor $AF_{2,VI}$ given for ^{85}Kr in Table 20.

APPENDIX VI
INHALATION, INGESTION, IMMERSION AND SKIN DOSE CONVERSION FACTORS USED IN THE RISK APPROACH

The dose conversion factors used for calculating ${}^{R}D_2$-values include factors for inhalation, ingestion, skin contamination and immersion. They are listed in Table 18, Table 19, and Table 20.

VI.1. INHALATION AND INGESTION

The ORNL dosimetry database [49] was the major source of data used for calculating dose conversion factors for inhalation and ingestion of dispersed radioactive material. An additional source of dosimetry data used in calculating the ${}^{R}D_2$-values was the ICRP dosimetry database [50]. Data from this source were used for radionuclides which were not present in the ORNL Dosimetry Database. In Table 18 and Table 19 such data are indicated by an asterisk (*).The conversion factors and scenario parameters reflect exposure of a reference adult member of the public. The use of these factors for other age groups will lead to an overestimation of the committed dose. The contribution to the dose factor from progenies present in the air breathed was taken into account as described in Appendix VIII. If this contribution exceeded several percent the parent radionuclide is marked by a cross (+) in the Tables.

The risk approach used a committed RBE-weighted dose from internal exposure of an organ or tissue T, via a pathway (exposure scenario) S, $AF_{T,S}(\Delta)$, for characterizing the intake of the radionuclide. This quantity is defined for Eq (4). For inhalation or ingestion, the ICRP assigns radioactive material to one of several inhalation or ingestion[22] types [11, 16]. Dose factors for materials containing the same radionuclide, but assigned to different types are different. For each radionuclide, the tables contain the maximum dose conversion factors for a given organ or tissue. The types of material taken into account in calculating the ${}^{R}D_2$-values in Scenario IIIR and Scenario IV were taken from Table II-V, Table II-IX and Table II-IV of Ref. [11]. The following committed dose conversion factors were used:

(a) $AF_{2,IIIR}(\Delta)$ is the dose conversion factor equal to the 30-day committed RBE-weighted dose delivered in accordance with Scenario IIIR in Tissue 2 (red marrow) due to an inhalation intake of 1 Bq of a radionuclide, (Gy-Eq)/Bq;

(b) $AF_{3R,IIIR}(\Delta)$ is the dose conversion factor equal to the 30-day committed RBE-weighted dose delivered in accordance with Scenario IIIR in Tissue 3R (alveolar-interstitial region of respiratory tract) due to an inhalation intake of 1 Bq of a radionuclide, (Gy-Eq)/Bq;

(c) $AF_{4,IIIR}(\Delta)$ is the dose conversion factor equal to the 30-day committed RBE-weighted dose delivered in accordance with Scenario IIIR in Tissue 4 (colon)[23] due to an inhalation intake of 1 Bq of a radionuclide, (Gy-Eq)/Bq;

(d) $AF_{5,IIIR}(\Delta)$ is the dose conversion factor equal to the 365-day committed RBE-weighted dose delivered in accordance with Scenario IIIR in Tissue 5 (thyroid) due to an inhalation intake of 1 Bq of a radionuclide, (Gy-Eq)/Bq;

(e) $AF_{2,IV}(\Delta)$ is the dose conversion factor equal to the 30-day committed RBE-weighted dose delivered in accordance with Scenario IV in Tissue 2 (red marrow) due to an ingestion intake of 1 Bq of a radionuclide, (Gy-Eq)/Bq;

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[22] Ingestion types are needed because of different gut absorption factors.

[23] The dose to the colon was calculated as the dose averaged over the mass of the large intestine in accordance with the ICRP recommendation in Ref. [20].

(f) $AF_{4,IV}(\Delta)$ is the dose conversion factor equal to the 30-day committed RBE-weighted dose delivered in accordance with Scenario IV in Tissue 4 (colon)[23] due to an ingestion intake of 1 Bq of a radionuclide, (Gy-Eq)/Bq; and

(g) $AF_{5,IV}(\Delta)$ is the dose conversion factor equal to the 365-day committed RBE-weighted dose delivered in accordance with Scenario IV in Tissue 5 (thyroid) due to an ingestion intake of 1 Bq of a radionuclide, (Gy-Eq)/Bq.

For inhalation and ingestion, the supplement to the ORNL dosimetry database [49] as well as dosimetry data in Ref. [51] contain values of dose rates of low LET and high LET radiation in 29 organs or tissues of humans of different ages (reference individuals in six age groups). For inhalation, only the data for aerosols with an AMAD of 1 μm are available. For each organ or tissue, absorbed dose rates are listed for 128 points of time from zero to 27 500 days after intake. When these databases were used for calculating the committed dose conversion factors, the value of $AF_{T,S}(\Delta)$ was calculated by the numerical integration of the absorbed dose rate:

$$AF_{T,S}(\Delta) = \int_0^{\Delta} \left[RBE_T^L \times \dot{d}_{T,S}^{L}(t) + RBE_T^H \times \dot{d}_{T,S}^{H}(t) \right] dt , \quad (67)$$

where:

$\dot{d}_{T,S}^{L}(t)$ and $\dot{d}_{T,S}^{H}(t)$ are the absorbed dose rate in an organ or tissue T, after an intake of 1 Bq of the radionuclide assigned to pathway S, (Gy/(Bq×s)), and are given in Refs. [49, 51];

RBE_T^L and RBE_T^H are the coefficients of relative biological effectiveness for low LET and high LET radiation for producing severe deterministic effects in organ or tissue T, ((Gy-Eq)/Gy), and are given in Table 10; and

Δ is an upper limit for the time of integration, (d), and is given in Table 10.

The ICRP dosimetry database [50] contains values of dose conversion factors $HF_{T,S}(\Delta)$ equal to the committed radiation-weighted dose as a function of time (Δ) after a single ingestion or inhalation intake of 1 Bq of a radionuclide by the public (reference individuals in six age groups) and workers. For radionuclides emitting only low LET radiation, values of $HF_{T,S}(\Delta)$, (Sv), and $AF_{T,S}(\Delta)$, (Gy-Eq), are numerically equal and are given by:

$$AF_{T,S}(\Delta) = \frac{RBE_T^L}{w_L} HF_{T,S}(\Delta) , \quad (68)$$

where:

RBE_T^L is the RBE for low LET radiation, ((Gy-Eq)/Gy), and is given in Table 10; and

w_L is the radiation weighted factor for low LET radiation equal to 1 Sv/Gy [20].

For most alpha-emitting radionuclides and radionuclides with a high probability of spontaneous fission (listed in Table 27), high LET radiation is the main contributor to the absorbed dose in the critical organ or tissue [15]. In this particular case:

$$AF_{T,S}(\Delta) = \frac{RBE_T^H}{w_H} HF_{T,S}(\Delta) , \quad (69)$$

where:

RBE_T^H is the effect-specific RBE for high LET radiation, ((Gy-Eq)/Gy), and is given in Table 10; and

w_H is the radiation weighting factor for high LET radiation equal to 20 Sv/Gy for alpha-particles as defined by the ICRP [20] and equal to 12 Sv/Gy for neutron radiation spectra of interest.

Equations (68) and (69) are valid for all radionuclides with Z<80 and most radionuclides with Z>81 listed in Table 1. The only exceptions are the following eight radionuclides: ^{210}Pb, ^{210}Bi, ^{210m}Bi, ^{228}Ra, ^{230}Pa, ^{236b}Np, ^{241}Pu, and ^{242m}Am. These radionuclides have complicated radioactive decay chains with progenies emitting radiations with different LET. These contribute significantly to the radiation weighted dose.

Inhalation committed RBE-weighted dose conversion factors used in the risk approach are given in Table 18.

TABLE 18. INHALATION COMMITTED RBE-WEIGHTED DOSE CONVERSION FACTORS

Radionuclide [a]	Inhalation			
	Red marrow	AI region	Colon	Thyroid
	$AF_{2,IIIR}(\Delta)$ [b]	$AF_{3R,IIIR}(\Delta)$ [c]	$AF_{4,IIIR}(\Delta)$ [d]	$AF_{5,IIIR}(\Delta)$ [e]
	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)
H-3	2.1E-11	2.1E-11	2.1E-11	NA [f]
Be-7	1.5E-11	1.0E-10	2.4E-11	NA
Be-10	7.1E-11	1.0E-08	1.9E-09	NA
C-11	2.0E-12	2.1E-12	2.2E-12	NA
C-14	2.8E-12	2.8E-12	2.8E-12	NA
N-13	0.0E+00	0.0E+00	0.0E+00	NA
F-18 (*)	2.7E-11	5.3E-11	2.9E-12	NA
Na-22	1.2E-09	7.5E-10	8.7E-10	NA
Na-24 (*)	1.5E-10	1.2E-10	1.1E-10	NA
Mg-28 (*)	5.5E-10	2.6E-09	2.4E-09	NA
Al-26	4.4E-09	2.0E-08	4.4E-09	NA
Si-31 (*)	4.3E-12	1.4E-10	1.2E-10	NA
Si-32 +	2.9E-09	2.8E-08	2.5E-09	NA
P-32	2.6E-09	1.3E-08	1.2E-09	NA
P-33	1.3E-10	1.8E-09	1.4E-10	NA
S-35	2.2E-10	1.5E-09	3.1E-10	NA
Cl-36	2.4E-10	9.3E-09	2.7E-10	NA
Cl-38 (*)	4.1E-12	8.2E-11	4.3E-12	NA
Ar-37(*)	0.0E+00	0.0E+00	0.0E+00	NA
Ar-39 (*)	0.0E+00	0.0E+00	0.0E+00	NA
Ar-41 (*)	0.0E+00	0.0E+00	0.0E+00	NA
K-40	8.4E-10	8.5E-10	2.3E-09	NA
K-42 (*)	7.6E-11	9.6E-11	1.2E-10	NA
K-43 (*)	6.7E-11	7.0E-11	9.5E-11	NA
Ca-41	3.2E-12	9.2E-11	1.9E-11	NA
Ca-45	8.3E-11	2.4E-09	5.2E-10	NA
Ca-47 +	2.6E-10	4.5E-09	2.3E-09	NA
Sc-44 (*)	1.7E-11	2.6E-10	3.1E-10	NA
Sc-46	5.5E-10	8.1E-09	1.7E-09	NA
Sc-47	9.9E-12	1.2E-09	8.7E-10	NA

Radionuclide [a]	Inhalation			
	Red marrow	AI region	Colon	Thyroid
	$AF_{2,IIIR}(\Delta)$ [b]	$AF_{3R,IIIR}(\Delta)$ [c]	$AF_{4,IIIR}(\Delta)$ [d]	$AF_{5,IIIR}(\Delta)$ [e]
	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)
Sc-48	1.8E-10	1.6E-09	1.8E-09	NA
Ti-44 +	2.1E-09	3.0E-08	5.6E-09	NA
V-48	7.5E-10	6.2E-09	2.2E-09	NA
V-49	5.5E-12	1.5E-10	3.3E-11	NA
Cr-51	1.0E-11	2.0E-10	4.7E-11	NA
Mn-52	8.3E-10	2.7E-09	1.5E-09	NA
Mn-53	2.7E-11	1.8E-10	3.7E-11	NA
Mn-54	5.6E-10	1.9E-09	5.5E-10	NA
Mn-56 (*)	2.1E-11	1.9E-10	1.8E-10	NA
Fe-52 +	8.8E-10	1.0E-09	1.6E-09	NA
Fe-55	4.7E-11	2.0E-10	3.8E-11	NA
Fe-59	1.5E-09	5.1E-09	1.3E-09	NA
Fe-60 +	1.4E-09	1.1E-08	2.1E-09	NA
Co-55 +(*)	6.1E-11	8.5E-10	1.3E-09	NA
Co-56	9.0E-10	1.1E-08	2.4E-09	NA
Co-57	3.8E-11	1.2E-09	2.3E-10	NA
Co-58	2.7E-10	3.3E-09	7.1E-10	NA
Co-58m +	1.5E-12	3.7E-11	3.4E-11	NA
Co-60	7.2E-10	9.3E-09	1.8E-09	NA
Ni-59	1.8E-11	2.3E-10	4.7E-11	NA
Ni-63	4.4E-11	5.7E-10	1.2E-10	NA
Ni-65 (*)	2.6E-10	1.3E-10	1.2E-10	NA
Cu-64 (*)	9.1E-12	1.5E-10	1.3E-10	NA
Cu-67	3.8E-11	8.7E-10	4.2E-10	NA
Zn-65	1.7E-10	1.6E-09	3.4E-10	NA
Zn-69 (*)	1.1E-13	2.4E-11	7.5E-12	NA
Zn-69m +(*)	1.7E-11	4.0E-10	6.4E-10	NA
Ga-67	4.5E-11	3.0E-10	2.5E-10	NA
Ga-68 (*)	5.6E-12	7.4E-11	3.2E-11	NA
Ga-72 (*)	1.3E-10	7.3E-10	1.2E-09	NA
Ge-68 +	2.9E-10	2.6E-08	2.3E-09	NA
Ge-71	5.9E-13	1.5E-10	2.1E-11	NA
Ge-77 +	3.5E-11	8.5E-10	2.4E-10	NA
As-72	9.1E-11	2.3E-09	2.3E-09	NA
As-73	1.1E-11	2.1E-09	3.9E-10	NA
As-74	1.9E-10	6.5E-09	1.6E-09	NA
As-76	3.8E-11	2.2E-09	2.2E-09	NA
As-77	6.5E-12	6.9E-10	5.8E-10	NA
Se-75	2.3E-10	1.4E-09	3.1E-10	NA
Se-79	5.6E-11	1.9E-09	3.7E-10	NA
Br-76 (*)	1.1E-10	1.1E-09	1.4E-10	NA
Br-77	2.9E-11	1.7E-10	4.7E-11	NA
Br-82	1.6E-10	9.2E-10	2.6E-10	NA
Kr-81	0.0E+00	0.0E+00	0.0E+00	NA
Kr-85	0.0E+00	0.0E+00	0.0E+00	NA
Kr-85m	0.0E+00	0.0E+00	0.0E+00	NA
Kr-87	0.0E+00	0.0E+00	0.0E+00	NA
Rb-81 (*)	1.0E-11	1.2E-11	9.0E-12	NA
Rb-83	4.1E-10	2.8E-10	3.6E-10	NA

Radionuclide [a]	Inhalation			
	Red marrow	AI region	Colon	Thyroid
	$AF_{2,IIIR}(\Delta)$ [b]	$AF_{3R,IIIR}(\Delta)$ [c]	$AF_{4,IIIR}(\Delta)$ [d]	$AF_{5,IIIR}(\Delta)$ [e]
	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)
Rb-84	8.4E-10	5.4E-10	7.4E-10	NA
Rb-86	1.1E-09	6.0E-10	1.0E-09	NA
Rb-87	2.9E-10	1.5E-10	2.6E-10	NA
Sr-82	4.3E-09	4.1E-08	1.0E-08	NA
Sr-85	2.8E-10	1.7E-09	3.2E-10	NA
Sr-85m +	8.5E-13	4.2E-12	2.2E-12	NA
Sr-87m (*)	3.9E-12	2.3E-11	2.3E-11	NA
Sr-89	1.9E-09	1.9E-08	4.2E-09	NA
Sr-90 +	3.7E-09	4.5E-08	8.4E-09	NA
Sr-91 +	5.3E-10	1.7E-08	4.2E-09	NA
Sr-92 +(*)	6.1E-11	4.1E-10	6.5E-10	NA
Y-87 +	8.6E-11	9.1E-10	6.4E-10	NA
Y-88	8.7E-10	5.7E-09	1.2E-09	NA
Y-90	1.0E-10	5.1E-09	4.4E-09	NA
Y-91	5.6E-10	2.0E-08	4.3E-09	NA
Y-91m +	1.3E-12	1.7E-11	5.1E-12	NA
Y-92 (*)	5.8E-12	4.5E-10	4.9E-10	NA
Y-93 (*)	1.6E-11	1.0E-09	1.6E-09	NA
Zr-88 +	6.5E-10	2.8E-09	5.5E-10	NA
Zr-93 +	1.7E-10	1.3E-09	2.3E-10	NA
Zr-95 +	1.7E-09	6.3E-09	1.2E-09	NA
Zr-97 +(*)	3.5E-10	1.9E-09	2.9E-09	NA
Nb-93m	6.6E-12	1.2E-09	2.2E-10	NA
Nb-94	5.7E-10	1.0E-08	2.0E-09	NA
Nb-95	2.1E-10	2.8E-09	6.5E-10	NA
Nb-97 (*)	1.9E-12	5.4E-11	2.4E-11	NA
Mo-93 +	1.8E-11	1.0E-09	1.5E-10	NA
Mo-99 +	2.0E-10	2.4E-09	2.0E-09	NA
Tc-95m	1.8E-10	1.9E-09	4.5E-10	3.3E-10
Tc-96	2.4E-10	1.3E-09	8.5E-10	6.8E-10
Tc-96m +	2.0E-12	1.3E-11	7.7E-12	1.2E-11
Tc-97	2.1E-12	4.6E-10	6.8E-11	7.0E-11
Tc-97m	1.8E-11	2.8E-09	6.3E-10	5.8E-10
Tc-98	4.1E-10	8.2E-09	1.8E-09	1.4E-09
Tc-99	2.1E-11	3.4E-09	7.3E-10	6.5E-10
Tc-99m (*)	1.7E-12	1.2E-11	7.9E-12	4.0E-11
Ru-97	3.8E-11	2.2E-10	4.2E-10	NA
Ru-103 +	4.1E-10	4.5E-09	2.8E-09	NA
Ru-105 +	2.4E-11	2.4E-10	7.7E-10	NA
Ru-106 +	2.6E-09	5.5E-08	2.7E-08	NA
Rh-99	1.6E-10	2.0E-09	5.6E-10	NA
Rh-101	1.2E-10	2.3E-09	4.0E-10	NA
Rh-102	7.5E-10	5.9E-09	1.5E-09	NA
Rh-102m	3.0E-10	7.7E-09	1.5E-09	NA
Rh-103m (*)	9.1E-14	3.2E-12	9.3E-13	NA
Rh-105	1.7E-11	4.8E-10	5.6E-10	NA
Pd-103 +	8.3E-12	1.2E-09	3.3E-10	NA
Pd-107	2.1E-12	3.7E-10	6.9E-11	NA
Pd-109 (*)	1.7E-12	5.1E-10	8.1E-10	NA

Radionuclide [a]	Inhalation			
	Red marrow	AI region	Colon	Thyroid
	$AF_{2,IIIR}(\Delta)$ [b]	$AF_{3R,IIIR}(\Delta)$ [c]	$AF_{4,IIIR}(\Delta)$ [d]	$AF_{5,IIIR}(\Delta)$ [e]
	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)
Ag-105	1.9E-10	1.9E-09	4.8E-10	NA
Ag-108m	7.5E-10	7.1E-09	1.7E-09	NA
Ag-110m	1.2E-09	9.5E-09	2.5E-09	NA
Ag-111	8.6E-11	4.9E-09	2.2E-09	NA
Cd-109	6.1E-11	3.7E-09	6.4E-10	NA
Cd-113m	1.2E-10	7.3E-09	1.3E-09	NA
Cd-115 +	7.3E-11	2.3E-09	2.1E-09	NA
Cd-115m	3.2E-10	1.9E-08	4.1E-09	NA
In-111	1.6E-10	3.6E-10	3.0E-10	NA
In-113m (*)	3.2E-12	2.1E-11	1.4E-11	NA
In-114m	1.5E-08	2.5E-08	6.0E-09	NA
In-115m (*)	1.6E-11	6.6E-11	8.6E-11	NA
Sn-113 +	3.1E-10	5.1E-09	1.2E-09	NA
Sn-117m	4.5E-10	3.2E-09	1.1E-09	NA
Sn-119m	1.2E-10	2.7E-09	5.9E-10	NA
Sn-121m +	2.0E-10	4.2E-09	9.2E-10	NA
Sn-123	7.0E-10	1.6E-08	3.7E-09	NA
Sn-125	1.7E-09	1.2E-08	5.1E-09	NA
Sn-126 +	3.0E-09	3.8E-08	9.4E-09	NA
Sb-122	4.1E-10	2.9E-09	2.7E-09	NA
Sb-124	1.4E-09	1.4E-08	3.4E-09	NA
Sb-125 +	7.5E-10	6.8E-09	1.5E-09	5.8E-10
Sb-126	1.1E-09	7.8E-09	2.9E-09	NA
Te-121	2.7E-10	1.1E-09	5.6E-10	6.7E-10
Te-121m +	6.8E-10	3.9E-09	1.2E-09	2.4E-09
Te-123m	5.2E-10	3.5E-09	8.4E-10	2.2E-09
Te-125m	4.7E-10	3.5E-09	7.8E-10	2.1E-09
Te-127 (*)	2.6E-11	1.5E-10	2.3E-10	5.9E-11
Te-127m +	1.3E-09	9.2E-09	2.0E-09	5.8E-09
Te-129 (*)	3.0E-11	5.1E-11	2.0E-11	7.5E-12
Te-129m +	2.2E-09	1.6E-08	3.9E-09	1.0E-08
Te-131m +	2.8E-10	1.5E-09	1.5E-09	1.1E-07
Te-132 +	5.4E-10	4.5E-09	3.4E-09	7.4E-10
I-123 (*)	7.4E-12	6.2E-12	7.2E-12	4.6E-08
I-124	1.4E-10	1.3E-10	7.8E-11	2.4E-08
I-125	1.5E-11	1.2E-11	1.5E-11	8.8E-08
I-126	1.3E-10	1.3E-10	7.2E-11	6.6E-08
I-129	2.1E-11	1.9E-11	3.3E-11	7.4E-10
I-131	9.1E-11	8.8E-11	6.1E-11	7.4E-08
I-132 (*)	3.1E-11	2.7E-11	3.0E-11	3.6E-09
I-133 (*)	4.5E-11	4.4E-11	5.3E-11	7.6E-08
I-134 (*)	1.9E-11	1.5E-11	1.4E-11	7.0E-10
I-135 (*)	2.7E-11	2.8E-11	3.0E-11	1.3E-08
Xe-122	0.0E+00	0.0E+00	0.0E+00	NA
Xe-123 +	8.3E-13	6.9E-13	8.0E-13	4.1E-10
Xe-127	0.0E+00	0.0E+00	0.0E+00	NA
Xe-131m	0.0E+00	0.0E+00	0.0E+00	NA
Xe-133	0.0E+00	0.0E+00	0.0E+00	NA
Xe-135	0.0E+00	0.0E+00	0.0E+00	NA

Radionuclide [a]	Inhalation			
	Red marrow	AI region	Colon	Thyroid
	$AF_{2,IIIR}(\Delta)$ [b]	$AF_{3R,IIIR}(\Delta)$ [c]	$AF_{4,IIIR}(\Delta)$ [d]	$AF_{5,IIIR}(\Delta)$ [e]
	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)
Cs-129	1.8E-11	1.9E-11	2.1E-11	NA
Cs-131	1.2E-11	2.0E-11	2.0E-11	NA
Cs-132	1.6E-10	1.5E-10	1.8E-10	NA
Cs-134	1.3E-09	1.2E-09	1.5E-09	NA
Cs-134m +	1.5E-12	3.2E-12	1.9E-12	NA
Cs-135	1.1E-10	1.2E-10	1.5E-10	NA
Cs-136	8.3E-10	7.9E-10	9.7E-10	NA
Cs-137 +	7.9E-10	7.6E-10	9.7E-10	NA
Ba-131 +	1.6E-10	3.0E-11	6.7E-10	NA
Ba-133	2.5E-10	4.0E-11	8.2E-10	NA
Ba-133m	8.7E-11	8.6E-12	1.0E-09	NA
Ba-140 +	1.3E-09	1.6E-09	6.2E-09	NA
La-137	4.5E-11	4.5E-10	8.6E-11	NA
La-140	3.0E-10	2.1E-09	2.5E-09	NA
Ce-139	8.0E-11	1.9E-09	3.7E-10	NA
Ce-141	1.1E-10	5.2E-09	1.2E-09	NA
Ce-143 +	4.0E-11	1.9E-09	1.7E-09	NA
Ce-144 +	8.9E-10	5.0E-08	9.7E-09	NA
Pr-142 (*)	1.3E-11	1.3E-09	2.0E-09	NA
Pr-143	8.3E-11	6.5E-09	2.1E-09	NA
Nd-147 +	1.4E-10	5.2E-09	1.8E-09	NA
Nd-149 +	2.9E-12	1.4E-10	1.1E-10	NA
Pm-143	1.3E-10	1.3E-09	2.4E-10	NA
Pm-144	6.3E-10	4.6E-09	9.5E-10	NA
Pm-145	2.7E-11	8.3E-10	1.5E-10	NA
Pm-147	6.0E-11	2.4E-09	4.6E-10	NA
Pm-148m	8.0E-10	1.0E-08	2.2E-09	NA
Pm-149	3.0E-11	1.7E-09	1.6E-09	NA
Pm-151	2.7E-11	8.1E-10	1.1E-09	NA
Sm-145 +	5.8E-11	1.5E-09	3.1E-10	NA
Sm-147 (*)	4.4E-09	5.3E-07	0.0E+00	NA
Sm-151	2.0E-11	6.6E-10	1.4E-10	NA
Sm-153	2.3E-11	1.0E-09	1.1E-09	NA
Eu-147	1.6E-10	1.8E-09	5.3E-10	NA
Eu-148	7.2E-10	4.6E-09	1.2E-09	NA
Eu-149	3.2E-11	6.1E-10	1.4E-10	NA
Eu-150b	6.2E-10	4.8E-09	1.1E-09	NA
Eu-150a (*)	5.1E-12	3.1E-10	5.2E-10	NA
Eu-152	5.4E-10	7.1E-09	1.6E-09	NA
Eu-152m	9.8E-12	3.9E-10	6.4E-10	NA
Eu-154	7.0E-10	1.2E-08	2.7E-09	NA
Eu-155	8.0E-11	2.3E-09	4.9E-10	NA
Eu-156	4.6E-10	9.4E-09	3.2E-09	NA
Gd-146 +	2.6E-09	8.9E-09	2.1E-09	NA
Gd-148 (*)	4.7E-08	7.7E-07	0.0E+00	NA
Gd-153	4.3E-10	1.9E-09	4.1E-10	NA
Gd-159 (*)	7.0E-11	4.4E-10	7.2E-10	NA
Tb-157	8.0E-12	2.2E-10	4.7E-11	NA
Tb-158	4.4E-10	5.7E-09	1.3E-09	NA

Radionuclide [a]	Inhalation			
	Red marrow	AI region	Colon	Thyroid
	$AF_{2,IIIR}(\Delta)$ [b]	$AF_{3R,IIIR}(\Delta)$ [c]	$AF_{4,IIIR}(\Delta)$ [d]	$AF_{5,IIIR}(\Delta)$ [e]
	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)
Tb-160	6.2E-10	9.5E-09	2.3E-09	NA
Dy-159	3.6E-11	6.5E-10	1.4E-10	NA
Dy-165 (*)	9.0E-13	8.3E-11	7.1E-11	NA
Dy-166 +	1.6E-10	5.2E-09	3.1E-09	NA
Ho-166	2.4E-11	1.4E-09	2.1E-09	NA
Ho-166m	7.9E-10	8.2E-09	1.8E-09	NA
Er-169	5.0E-11	1.5E-09	6.3E-10	NA
Er-171	1.0E-11	2.7E-10	4.3E-10	NA
Tm-167	9.7E-11	2.0E-09	8.6E-10	NA
Tm-170	4.4E-10	1.0E-08	2.3E-09	NA
Tm-171	3.7E-11	8.4E-10	1.8E-10	NA
Yb-169	2.0E-10	4.5E-09	1.1E-09	NA
Yb-175	2.8E-11	1.1E-09	7.2E-10	NA
Lu-172	3.2E-10	3.0E-09	1.4E-09	NA
Lu-173	1.1E-10	2.0E-09	3.7E-10	NA
Lu-174	1.1E-10	2.1E-09	4.0E-10	NA
Lu-174m +	1.7E-10	4.7E-09	9.2E-10	NA
Lu-177 (*)	5.7E-11	1.8E-09	9.7E-10	NA
Hf-172 +	3.2E-09	1.2E-08	2.8E-09	NA
Hf-175	6.6E-10	2.1E-09	5.3E-10	NA
Hf-181	1.8E-09	6.4E-09	1.7E-09	NA
Hf-182 +	1.6E-09	1.5E-08	3.0E-09	NA
Ta-178a (*)	5.1E-12	4.6E-11	4.1E-11	NA
Ta-179	1.4E-11	5.1E-10	9.4E-11	NA
Ta-182	4.4E-10	1.1E-08	2.2E-09	NA
W-178	1.3E-11	5.2E-12	3.3E-10	NA
W-181	5.3E-12	2.1E-12	1.0E-10	NA
W-185	1.4E-11	4.3E-12	8.0E-10	NA
W-187 (*)	2.4E-11	1.6E-11	9.2E-10	NA
W-188 +	1.2E-10	9.6E-10	4.5E-09	2.7E-09
Re-184	2.3E-10	3.0E-09	6.7E-10	6.3E-10
Re-184m +	2.3E-10	6.2E-09	1.1E-09	1.1E-09
Re-186	4.0E-11	2.3E-09	1.1E-09	1.9E-09
Re-187	1.4E-13	2.2E-11	3.9E-12	4.2E-12
Re-188 (*)	3.3E-11	1.0E-09	6.7E-10	2.8E-09
Re-189	2.1E-11	6.7E-10	4.4E-10	1.4E-09
Os-185	2.7E-10	2.4E-09	5.6E-10	NA
Os-191	7.3E-11	3.2E-09	9.5E-10	NA
Os-191m +	4.4E-12	1.9E-10	1.5E-10	NA
Os-193	2.4E-11	9.8E-10	1.3E-09	NA
Os-194 +	6.2E-10	3.4E-08	6.3E-09	NA
Ir-189	3.8E-11	1.3E-09	3.9E-10	NA
Ir-190	3.6E-10	4.4E-09	1.5E-09	NA
Ir-192	4.3E-10	9.4E-09	2.0E-09	NA
Ir-194 (*)	3.3E-11	1.4E-09	2.0E-09	NA
Pt-188 +	2.2E-10	5.1E-10	1.2E-09	NA
Pt-191	3.1E-11	2.7E-11	3.1E-10	NA
Pt-193	2.8E-12	3.4E-12	5.3E-11	NA
Pt-193m	2.0E-11	2.2E-11	5.6E-10	NA

Radionuclide [a]	Inhalation			
	Red marrow	AI region	Colon	Thyroid
	$AF_{2,IIIR}(\Delta)$ [b]	$AF_{3R,IIIR}(\Delta)$ [c]	$AF_{4,IIIR}(\Delta)$ [d]	$AF_{5,IIIR}(\Delta)$ [e]
	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)
Pt-195m	3.1E-11	3.4E-11	7.6E-10	NA
Pt-197 (*)	9.8E-12	1.3E-11	3.9E-10	NA
Pt-197m +(*)	2.3E-12	6.7E-12	5.1E-11	NA
Au-193	7.2E-12	1.3E-10	1.7E-10	NA
Au-194	5.4E-11	3.8E-10	3.9E-10	NA
Au-195	2.7E-11	2.4E-09	4.0E-10	NA
Au-198	5.7E-11	2.0E-09	1.5E-09	NA
Au-199	2.1E-11	9.6E-10	6.8E-10	NA
Hg-194 +	2.3E-09	4.0E-09	2.7E-09	NA
Hg-195m +	1.5E-09	1.2E-09	7.9E-10	NA
Hg-197	6.7E-10	3.8E-10	3.3E-10	NA
Hg-197m +	1.2E-09	5.5E-10	6.8E-10	NA
Hg-203	1.9E-09	3.1E-09	8.4E-10	NA
Tl-200	5.8E-11	5.5E-11	9.0E-11	NA
Tl-201	2.0E-11	2.2E-11	7.3E-11	NA
Tl-202	1.2E-10	1.1E-10	2.7E-10	NA
Tl-204	2.0E-10	2.0E-10	1.3E-09	NA
Pb-201 +	2.4E-11	1.6E-11	8.2E-11	NA
Pb-202 +	3.6E-10	2.4E-10	4.4E-10	NA
Pb-203	4.8E-11	2.8E-11	1.6E-10	NA
Pb-205	2.6E-11	6.0E-12	3.0E-11	NA
Pb-210 +	6.0E-08	1.2E-06	2.8E-09	NA
Pb-212 +(*)	1.1E-09	4.6E-09	0.0E+00	NA
Bi-205	2.8E-10	2.5E-09	8.7E-10	NA
Bi-206	3.8E-10	3.6E-09	1.9E-09	NA
Bi-207	4.2E-10	7.1E-09	1.6E-09	NA
Bi-210 +	1.8E-09	4.0E-08	2.1E-09	NA
Bi-210m	5.7E-10	1.2E-06	4.5E-09	NA
Bi-212 +(*)	1.8E-11	4.6E-09	0.0E+00	NA
Po-210	5.7E-08	1.2E-06	6.4E-15	NA
At-211	3.8E-10	2.8E-08	1.1E-12	NA
Rn-222	0.0E+00	0.0E+00	0.0E+00	NA
Ra-223 +	7.4E-09	3.0E-06	7.1E-09	NA
Ra-224 +	4.3E-09	1.2E-06	3.9E-09	NA
Ra-225 +	5.7E-08	2.8E-06	2.6E-09	NA
Ra-226	2.2E-09	1.1E-06	1.7E-09	NA
Ra-228 +	4.6E-08	8.4E-06	1.1E-08	NA
Ac-225	1.2E-07	3.4E-06	4.3E-09	NA
Ac-227 +	6.5E-08	8.5E-06	1.0E-08	NA
Ac-228	9.9E-11	2.9E-09	4.2E-10	NA
Th-227 +	1.8E-08	3.8E-06	4.2E-09	NA
Th-228 +	4.4E-08	8.1E-06	6.5E-09	NA
Th-229 +	1.5E-07	8.7E-06	6.9E-09	NA
Th-230 +	1.4E-08	1.3E-06	1.2E-10	NA
Th-231	7.5E-12	3.9E-10	5.2E-10	NA
Th-232 +	4.4E-08	7.0E-06	7.8E-09	NA
Th-234 +	8.4E-10	2.4E-08	6.1E-09	NA
Pa-230 +	2.2E-09	2.9E-07	7.5E-10	NA
Pa-231 +	3.3E-08	3.8E-06	3.3E-09	NA

Radionuclide [a]	Inhalation			
	Red marrow	AI region	Colon	Thyroid
	$AF_{2,IIIR}(\Delta)$ [b]	$AF_{3R,IIIR}(\Delta)$ [c]	$AF_{4,IIIR}(\Delta)$ [d]	$AF_{5,IIIR}(\Delta)$ [e]
	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)
Pa-233	2.6E-10	6.0E-09	1.5E-09	NA
U-230 +	5.2E-08	6.1E-06	3.1E-10	NA
U-232 +	5.1E-08	8.9E-06	6.2E-09	NA
U-233	1.0E-08	1.4E-06	4.9E-11	NA
U-234 +	1.0E-08	1.3E-06	1.0E-10	NA
U-235 +	9.6E-09	1.3E-06	1.7E-09	NA
U-236	9.4E-09	1.3E-06	8.8E-11	NA
U-238 +	1.0E-08	1.2E-06	6.7E-09	NA
Depleted U	9.3E-09	1.2E-06	5.5E-10	NA
Np-235	1.3E-11	5.2E-10	8.7E-11	NA
Np-236b +	1.2E-09	1.3E-07	2.6E-10	NA
Np-236a	2.9E-10	8.9E-09	1.6E-09	NA
Np-237 +	1.1E-08	1.2E-06	2.1E-09	NA
Np-239	3.4E-11	1.2E-09	1.2E-09	NA
Pu-236	1.4E-08	1.6E-06	1.1E-10	NA
Pu-237	3.3E-11	8.7E-10	1.5E-10	NA
Pu-238	1.4E-08	1.6E-06	8.3E-11	NA
Pu-239	1.3E-08	1.5E-06	5.2E-11	NA
Pu-240	1.3E-08	1.5E-06	8.3E-11	NA
Pu-241 +	9.9E-11	1.7E-08	3.9E-11	NA
Pu-242	1.2E-08	1.4E-06	6.8E-11	NA
Pu-244 +	1.3E-08	1.3E-06	6.4E-09	NA
Am-241	7.4E-09	1.3E-06	4.1E-10	NA
Am-242m +	7.0E-09	1.2E-06	1.7E-09	NA
Am-243 +	7.4E-09	1.3E-06	2.1E-09	NA
Am-244	1.9E-11	4.1E-10	5.4E-10	NA
Cm-240	5.7E-09	1.1E-06	7.5E-11	NA
Cm-241 +	2.7E-10	1.5E-08	1.2E-09	NA
Cm-242	7.7E-09	1.4E-06	7.0E-11	NA
Cm-243	8.0E-09	1.4E-06	1.1E-09	NA
Cm-244	7.8E-09	1.4E-06	6.4E-11	NA
Cm-245	7.3E-09	1.3E-06	5.3E-10	NA
Cm-246	7.3E-09	1.3E-06	5.9E-11	NA
Cm-247	6.9E-09	1.2E-06	1.5E-09	NA
Cm-248 (*)	2.7E-08	4.6E-06	ND	NA
Bk-247	1.6E-08	1.3E-06	5.0E-10	NA
Bk-249	4.7E-11	1.2E-09	2.3E-10	NA
Cf-248 +	1.7E-08	1.4E-06	4.5E-11	NA
Cf-249	1.7E-08	1.4E-06	5.0E-10	NA
Cf-250 [g]	1.7E-08	1.4E-06	4.3E-11	NA
Cf-251	1.7E-08	1.4E-06	1.5E-09	NA
Cf-252 (*)	3.3E-08	2.5E-06	ND	NA
Cf-253	5.1E-09	3.9E-07	5.2E-10	NA
Cf-254 (*)	1.1E-06	2.5E-05	1.2E-07	NA
$^{239}Pu/^{9}Be$ [g, h]	1.3E-08	1.5E-06	5.2E-11	NA
$^{241}Am/^{9}Be$ [g, h]	7.4E-09	1.3E-06	4.1E-10	NA

[a] In growth of radioactive progeny was taken into account when calculation the D values for all the radionuclides as described in Appendix VIII. A "+" indicates the radionuclides for which the progeny were

significant sources of dose for the scenarios considered. The factors are based on data from Ref. [49] except where noted by a "*" indicating that they are based on data from [50].

[b] 30-day (Δ)committed RBE-weighted dose in the red marrow due to inhalation of the radionuclide.

[c] 30-day (Δ)committed RBE-weighted dose in the AI region of respiratory tract due to inhalation of the radionuclide.

[d] 30-day (Δ)committed RBE-weighted dose in the colon due to inhalation of the radionuclide.

[e] 365-day committed RBE-weighted dose in the thyroid due to inhalation of the radionuclide.

[f] "NA" means "not applicable".

[g] The activity given is that of the alpha-emitting radionuclide, e.g., ^{239}Pu or ^{241}Am.

[h] The dose from neutrons was not considered as discussed in Section 5.

TABLE 19. INGESTION COMMITTED RBE-WEIGHTED DOSE AND CONTAMINATION RBE-WEIGHTED DOSE CONVERSION FACTORS

Radionuclides [a]	Ingestion			Contamination
	Red marrow	Colon	Thyroid	Derma of skin
	$AF_{2,IV}(\Delta)$ [b]	$AF_{4,IV}(\Delta)$ [c]	$AF_{5,IV}(\Delta)$ [d]	$AF_{6R,V}$ [e]
	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/(s×Bq/cm^2))
H-3	2.1E-11	2.2E-11	NA [f]	0.0E+00
Be-7	1.1E-11	9.6E-11	NA	7.1E-13
Be-10	1.1E-11	8.1E-09	NA	1.7E-10
C-11	1.8E-12	3.4E-12	NA	1.4E-11
C-14	2.3E-10	2.5E-10	NA	0.0E+00
N-13	0.0E+00	0.0E+00	NA	0.0E+00
F-18 (*)	6.5E-11	1.5E-11	NA	1.8E-10
Na-22	3.5E-09	2.6E-09	NA	9.0E-11
Na-24 (*)	3.9E-10	4.0E-10	NA	3.6E-10
Mg-28 (*)	9.7E-10	1.2E-08	NA	5.3E-10
Al-26	6.6E-10	1.9E-08	NA	3.4E-10
Si-31 (*)	8.4E-14	6.5E-10	NA	3.3E-10
Si-32 +	6.4E-09	9.1E-09	NA	3.6E-10
P-32	6.4E-09	5.5E-09	NA	3.6E-10
P-33	3.2E-10	6.5E-10	NA	1.3E-12
S-35	2.4E-10	2.8E-10	NA	0.0E+00
Cl-36	7.1E-10	8.7E-10	NA	2.1E-10
Cl-38 (*)	8.1E-12	1.5E-11	NA	4.3E-10
Ar-37(*)	0.0E+00	0.0E+00	NA	0.0E+00
Ar-39 (*)	0.0E+00	0.0E+00	NA	0.0E+00
Ar-41 (*)	0.0E+00	0.0E+00	NA	0.0E+00
K-40	2.5E-09	6.8E-09	NA	2.7E-10
K-42 (*)	2.1E-10	4.5E-10	NA	4.5E-10
K-43 (*)	1.8E-10	3.1E-10	NA	2.1E-10
Ca-41	1.8E-11	7.0E-11	NA	1.0E-12
Ca-45	4.7E-10	1.9E-09	NA	1.8E-12
Ca-47 +	1.1E-09	8.9E-09	NA	4.6E-10
Sc-44 (*)	4.7E-11	1.6E-09	NA	4.1E-10
Sc-46	3.8E-10	7.2E-09	NA	4.2E-11
Sc-47	1.9E-11	4.1E-09	NA	7.4E-11
Sc-48	4.1E-10	8.5E-09	NA	1.7E-10
Ti-44 +	5.4E-10	2.4E-08	NA	4.1E-10
V-48	5.5E-10	9.5E-09	NA	1.6E-10
V-49	2.2E-13	1.4E-10	NA	2.7E-12
Cr-51	9.6E-12	2.0E-10	NA	3.9E-12
Mn-52	8.0E-10	6.9E-09	NA	7.9E-11
Mn-53	1.1E-11	1.6E-10	NA	ND [f]
Mn-54	3.6E-10	1.7E-09	NA	1.3E-11
Mn-56 (*)	2.4E-11	1.0E-09	NA	3.6E-10
Fe-52 +	3.8E-10	8.4E-09	NA	6.5E-10
Fe-55	1.8E-11	1.7E-10	NA	4.1E-12
Fe-59	7.7E-10	5.5E-09	NA	4.5E-11
Fe-60 +	7.7E-10	8.3E-09	NA	3.4E-11
Co-55 +(*)	1.6E-10	6.2E-09	NA	ND
Co-56	7.8E-10	9.3E-09	NA	1.1E-10

Radionuclides [a]	Ingestion			Contamination
	Red marrow	Colon	Thyroid	Derma of skin
	$AF_{2,IV}(\Delta)$ [b]	$AF_{4,IV}(\Delta)$ [c]	$AF_{5,IV}(\Delta)$ [d]	$AF_{6R,V}$ [e]
	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/(s×Bq/cm^2))
Co-57	3.5E-11	9.0E-10	NA	1.1E-11
Co-58	2.4E-10	2.8E-09	NA	1.9E-11
Co-58m +	1.3E-12	1.6E-10	NA	2.3E-11
Co-60	5.8E-10	7.0E-09	NA	3.4E-11
Ni-59	6.4E-13	2.1E-10	NA	4.7E-12
Ni-63	1.6E-12	5.3E-10	NA	0.0E+00
Ni-65 (*)	7.1E-12	6.8E-10	NA	3.0E-10
Cu-64 (*)	1.9E-11	6.8E-10	NA	1.5E-10
Cu-67	7.0E-11	2.0E-09	NA	ND
Zn-65	7.3E-10	1.3E-09	NA	1.0E-11
Zn-69 (*)	5.6E-13	3.9E-11	NA	2.1E-10
Zn-69m +(*)	9.6E-11	2.0E-09	NA	2.4E-10
Ga-67	2.6E-11	1.2E-09	NA	9.2E-12
Ga-68 (*)	5.8E-12	2.0E-10	NA	3.9E-10
Ga-72 (*)	1.7E-10	6.3E-09	NA	2.7E-10
Ge-68 +	2.9E-10	7.0E-09	NA	4.0E-10
Ge-71	1.7E-12	6.2E-11	NA	4.8E-12
Ge-77 +	9.1E-11	7.5E-10	NA	4.8E-10
As-72	2.5E-10	1.1E-08	NA	ND
As-73	3.5E-11	1.7E-09	NA	1.0E-11
As-74	3.3E-10	7.0E-09	NA	2.0E-10
As-76	1.3E-10	1.1E-08	NA	4.0E-10
As-77	2.5E-11	2.8E-09	NA	1.4E-10
Se-75	5.8E-10	9.7E-10	NA	1.3E-11
Se-79	1.4E-10	6.6E-10	NA	0.0E+00
Br-76 (*)	2.9E-10	6.5E-10	NA	0.0E+00
Br-77	7.8E-11	1.5E-10	NA	0.0E+00
Br-82	4.3E-10	8.1E-10	NA	7.8E-11
Kr-81	0.0E+00	0.0E+00	NA	0.0E+00
Kr-85	0.0E+00	0.0E+00	NA	0.0E+00
Kr-85m	0.0E+00	0.0E+00	NA	0.0E+00
Kr-87	0.0E+00	0.0E+00	NA	0.0E+00
Rb-81 (*)	2.6E-11	3.4E-11	NA	ND
Rb-83	1.2E-09	1.1E-09	NA	ND
Rb-84	2.5E-09	2.2E-09	NA	1.1E-10
Rb-86	3.3E-09	3.1E-09	NA	3.3E-10
Rb-87	8.6E-10	7.9E-10	NA	3.0E-12
Sr-82	4.8E-09	3.5E-08	NA	3.9E-12
Sr-85	3.7E-10	1.1E-09	NA	1.3E-11
Sr-85m +	1.6E-12	1.1E-11	NA	2.0E-11
Sr-87m (*)	6.2E-12	1.2E-10	NA	6.4E-11
Sr-89	2.0E-09	1.4E-08	NA	3.2E-10
Sr-90 +	4.0E-09	3.3E-08	NA	5.0E-10
Sr-91 +	1.3E-10	1.8E-08	NA	3.2E-10
Sr-92 +(*)	6.4E-11	3.4E-09	NA	5.5E-10
Y-87 +	1.2E-10	3.0E-09	NA	ND
Y-88	4.7E-10	4.7E-09	NA	2.7E-11
Y-90	3.7E-13	2.1E-08	NA	3.9E-10
Y-91	2.4E-12	1.9E-08	NA	3.2E-10

Radionuclides [a]	Ingestion			Contamination
	Red marrow	Colon	Thyroid	Derma of skin
	$AF_{2,IV}(\Delta)$ [b]	$AF_{4,IV}(\Delta)$ [c]	$AF_{5,IV}(\Delta)$ [d]	$AF_{6R,V}$ [e]
	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/(s×Bq/cm^2))
Y-91m +	2.3E-12	2.7E-11	NA	2.6E-11
Y-92 (*)	4.8E-12	2.6E-09	NA	4.4E-10
Y-93 (*)	4.4E-12	8.3E-09	NA	4.2E-10
Zr-88 +	1.9E-10	2.1E-09	NA	3.7E-11
Zr-93 +	7.7E-12	1.0E-09	NA	5.4E-13
Zr-95 +	2.3E-10	5.1E-09	NA	4.7E-11
Zr-97 +(*)	1.2E-10	1.5E-08	NA	6.3E-10
Nb-93m	1.9E-12	9.3E-10	NA	5.4E-13
Nb-94	3.6E-10	8.3E-09	NA	8.8E-11
Nb-95	1.6E-10	2.8E-09	NA	9.3E-12
Nb-97 (*)	4.1E-12	1.4E-10	NA	2.9E-10
Mo-93 +	4.7E-11	4.3E-10	NA	3.6E-12
Mo-99 +	6.1E-10	4.9E-10	6.7E-11	2.3E-10
Tc-95m	1.9E-10	1.5E-09	5.1E-10	ND
Tc-96	4.5E-10	3.0E-09	1.0E-09	3.1E-11
Tc-96m +	3.9E-12	2.8E-11	1.1E-11	3.3E-11
Tc-97	3.5E-12	2.3E-10	1.1E-10	2.9E-12
Tc-97m	2.9E-11	2.2E-09	9.1E-10	4.9E-12
Tc-98	4.6E-10	6.1E-09	2.2E-09	5.0E-11
Tc-99	3.3E-11	2.5E-09	1.0E-09	8.7E-12
Tc-99m (*)	4.2E-12	3.7E-11	8.5E-11	2.5E-12
Ru-97	3.9E-11	7.2E-10	NA	1.1E-11
Ru-103 +	1.3E-10	4.3E-09	NA	1.0E-11
Ru-105 +	2.2E-11	1.5E-09	NA	2.6E-10
Ru-106 +	2.9E-10	4.4E-08	NA	4.5E-10
Rh-99	1.4E-10	2.5E-09	NA	2.4E-11
Rh-101	7.7E-11	1.7E-09	NA	8.4E-12
Rh-102	5.5E-10	4.5E-09	NA	8.6E-11
Rh-102m	1.5E-10	6.2E-09	NA	1.5E-10
Rh-103m (*)	5.0E-15	5.7E-12	NA	4.3E-13
Rh-105	1.2E-11	2.8E-09	NA	7.3E-11
Pd-103 +	1.5E-12	1.5E-09	NA	2.6E-12
Pd-107	4.2E-14	3.0E-10	NA	0.0E+00
Pd-109 (*)	8.0E-13	4.1E-09	NA	2.3E-10
Ag-105	1.4E-10	1.7E-09	NA	1.5E-11
Ag-108m	4.7E-10	5.5E-09	NA	3.5E-10
Ag-110m	7.3E-10	7.9E-09	NA	5.9E-11
Ag-111	2.2E-11	9.7E-09	NA	2.2E-10
Cd-109	1.5E-11	2.8E-09	NA	3.6E-12
Cd-113m	2.3E-11	5.7E-09	NA	0.0E+00
Cd-115 +	6.5E-11	1.0E-08	NA	3.5E-10
Cd-115m	6.8E-11	1.8E-08	NA	2.9E-10
In-111	7.4E-11	1.5E-09	NA	1.5E-11
In-113m (*)	2.4E-12	8.1E-11	NA	1.2E-10
In-114m	1.2E-09	2.8E-08	NA	6.2E-12
In-115m (*)	4.9E-12	4.8E-10	NA	2.2E-10
Sn-113 +	8.1E-11	5.1E-09	NA	1.2E-10
Sn-117m	6.7E-11	5.2E-09	NA	4.2E-12
Sn-119m	1.1E-11	2.6E-09	NA	2.2E-12

Radionuclides [a]	Ingestion			Contamination
	Red marrow	Colon	Thyroid	Derma of skin
	$AF_{2,IV}(\Delta)$ [b]	$AF_{4,IV}(\Delta)$ [c]	$AF_{5,IV}(\Delta)$ [d]	$AF_{6R,V}$ [e]
	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/(s×Bq/cm^2))
Sn-121m +	1.7E-11	4.0E-09	NA	3.5E-11
Sn-123	5.8E-11	1.6E-08	NA	2.9E-10
Sn-125	1.9E-10	2.4E-08	NA	6.7E-10
Sn-126 +	1.4E-09	4.0E-08	NA	3.3E-10
Sb-122	2.1E-10	1.2E-08	NA	3.1E-10
Sb-124	8.4E-10	1.4E-08	NA	2.0E-10
Sb-125 +	6.4E-10	5.7E-09	6.5E-10	3.7E-11
Sb-126	8.9E-10	1.2E-08	NA	2.2E-10
Te-121	3.3E-10	1.2E-09	2.4E-10	1.1E-11
Te-121m +	8.1E-10	2.9E-09	8.6E-10	1.7E-11
Te-123m	5.9E-10	2.7E-09	7.8E-10	3.5E-12
Te-125m	5.2E-10	2.8E-09	7.7E-10	3.8E-12
Te-127 (*)	1.0E-11	1.1E-09	1.7E-11	1.3E-10
Te-127m +	1.5E-09	7.1E-09	2.1E-09	5.3E-12
Te-129 (*)	9.4E-13	1.2E-10	7.5E-13	3.0E-10
Te-129m +	2.5E-09	1.4E-08	3.7E-09	1.1E-10
Te-131m +	3.4E-10	6.0E-09	9.3E-08	4.3E-10
Te-132 +	5.4E-10	1.3E-08	3.2E-08	3.0E-10
I-123 (*)	6.5E-12	1.2E-11	7.8E-10	4.4E-12
I-124	1.4E-10	1.4E-10	5.1E-08	ND
I-125	1.3E-11	2.4E-11	2.6E-08	4.3E-12
I-126	1.4E-10	1.2E-10	9.6E-08	1.0E-10
I-129	2.1E-11	5.4E-11	7.3E-08	2.2E-12
I-131	9.6E-11	1.2E-10	8.1E-08	1.1E-10
I-132 (*)	2.6E-11	4.6E-11	3.4E-09	2.9E-10
I-133 (*)	4.7E-11	1.1E-10	8.2E-08	2.6E-10
I-134 (*)	1.1E-11	2.1E-11	5.4E-10	3.5E-10
I-135 (*)	4.0E-11	7.3E-11	1.6E-08	2.3E-10
Xe-122	0.0E+00	0.0E+00	NA	0.0E+00
Xe-123 +	7.3E-13	1.3E-12	4.4E-10	0.0E+00
Xe-127	0.0E+00	0.0E+00	NA	0.0E+00
Xe-131m	0.0E+00	0.0E+00	NA	0.0E+00
Xe-133	0.0E+00	0.0E+00	NA	0.0E+00
Xe-135	0.0E+00	0.0E+00	NA	0.0E+00
Cs-129	4.7E-11	6.8E-11	NA	0.0E+00
Cs-131	3.4E-11	6.0E-11	NA	2.3E-12
Cs-132	4.5E-10	5.4E-10	NA	0.0E+00
Cs-134	3.7E-09	4.4E-09	NA	1.1E-10
Cs-134m +	4.0E-12	7.4E-12	NA	0.0E+00
Cs-135	3.4E-10	4.6E-10	NA	2.0E-14
Cs-136	2.4E-09	2.9E-09	NA	4.6E-11
Cs-137 +	2.3E-09	2.9E-09	NA	1.4E-10
Ba-131 +	1.8E-10	2.3E-09	NA	1.4E-11
Ba-133	2.5E-10	2.7E-09	NA	1.5E-11
Ba-133m	6.8E-11	4.0E-09	NA	ND
Ba-140 +	1.1E-09	2.3E-08	NA	4.9E-10
La-137	5.1E-12	3.9E-10	NA	ND
La-140	2.6E-10	1.3E-08	NA	3.2E-10
Ce-139	3.5E-11	1.6E-09	NA	5.1E-12

Radionuclides [a]	Ingestion			Contamination
	Red marrow	Colon	Thyroid	Derma of skin
	$AF_{2,IV}(\Delta)$ [b]	$AF_{4,IV}(\Delta)$ [c]	$AF_{5,IV}(\Delta)$ [d]	$AF_{6R,V}$ [e]
	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/(s×Bq/cm^2))
Ce-141	1.8E-11	5.5E-09	NA	5.6E-11
Ce-143 +	3.5E-11	8.4E-09	NA	4.5E-10
Ce-144 +	2.4E-11	4.2E-08	NA	4.3E-10
Pr-142 (*)	4.5E-12	1.0E-08	NA	3.6E-10
Pr-143	1.4E-12	9.4E-09	NA	2.0E-10
Nd-147 +	3.0E-11	8.3E-09	NA	1.3E-10
Nd-149 +	3.8E-12	5.5E-10	NA	5.1E-10
Pm-143	6.5E-11	9.9E-10	NA	ND
Pm-144	3.3E-10	3.7E-09	NA	ND
Pm-145	7.1E-12	6.4E-10	NA	ND
Pm-147	9.4E-13	2.0E-09	NA	2.1E-13
Pm-148m	4.1E-10	9.3E-09	NA	9.9E-11
Pm-149	2.1E-12	7.9E-09	NA	2.3E-10
Pm-151	3.7E-11	5.3E-09	NA	1.8E-10
Sm-145 +	1.5E-11	1.4E-09	NA	ND
Sm-147 (*)	6.8E-11	0.0E+00	NA	0.0E+00
Sm-151	3.0E-13	6.4E-10	NA	1.6E-14
Sm-153	9.5E-12	5.7E-09	NA	1.4E-10
Eu-147	9.8E-11	2.4E-09	NA	ND
Eu-148	4.4E-10	4.9E-09	NA	ND
Eu-149	1.4E-11	6.1E-10	NA	ND
Eu-150b	3.1E-10	4.4E-09	NA	ND
Eu-150a (*)	3.1E-12	2.8E-09	NA	ND
Eu-152	2.3E-10	6.7E-09	NA	6.9E-11
Eu-152m	1.5E-11	3.4E-09	NA	2.5E-10
Eu-154	2.5E-10	1.2E-08	NA	1.3E-10
Eu-155	1.5E-11	2.2E-09	NA	2.0E-12
Eu-156	2.3E-10	1.5E-08	NA	1.8E-10
Gd-146 +	4.4E-10	8.9E-09	NA	ND
Gd-148 (*)	9.7E-11	0.0E+00	NA	0.0E+00
Gd-153	2.5E-11	1.8E-09	NA	5.0E-12
Gd-159 (*)	4.6E-12	3.7E-09	NA	2.0E-10
Tb-157	7.0E-13	2.1E-10	NA	ND
Tb-158	1.6E-10	5.4E-09	NA	ND
Tb-160	2.2E-10	1.0E-08	NA	1.3E-10
Dy-159	1.1E-11	6.3E-10	NA	3.4E-12
Dy-165 (*)	3.5E-13	4.1E-10	NA	2.7E-10
Dy-166 +	1.2E-11	1.5E-08	NA	3.6E-10
Ho-166	3.3E-12	1.1E-08	NA	3.3E-10
Ho-166m	3.7E-10	7.7E-09	NA	2.9E-11
Er-169	8.4E-13	3.0E-09	NA	1.6E-11
Er-171	1.7E-11	2.3E-09	NA	2.4E-10
Tm-167	3.1E-11	4.1E-09	NA	2.0E-11
Tm-170	8.1E-12	1.1E-08	NA	2.1E-10
Tm-171	7.2E-13	8.2E-10	NA	5.2E-14
Yb-169	7.0E-11	4.7E-09	NA	1.2E-11
Yb-175	7.4E-12	3.4E-09	NA	4.7E-11
Lu-172	3.2E-10	6.5E-09	NA	ND
Lu-173	3.1E-11	1.6E-09	NA	ND

Radionuclides [a]	Ingestion			Contamination
	Red marrow	Colon	Thyroid	Derma of skin
	$AF_{2,IV}(\Delta)$ [b]	$AF_{4,IV}(\Delta)$ [c]	$AF_{5,IV}(\Delta)$ [d]	$AF_{6R,V}$ [e]
	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/(s×Bq/cm^2))
Lu-174	2.7E-11	1.7E-09	NA	ND
Lu-174m +	1.6E-11	4.0E-09	NA	ND
Lu-177 (*)	7.6E-12	4.2E-09	NA	5.2E-11
Hf-172 +	4.0E-10	1.1E-08	NA	ND
Hf-175	8.5E-11	2.3E-09	NA	3.4E-11
Hf-181	1.3E-10	7.5E-09	NA	6.3E-11
Hf-182 +	3.1E-10	1.3E-08	NA	6.6E-11
Ta-178a (*)	1.3E-11	2.3E-10	NA	ND
Ta-179	7.7E-12	4.1E-10	NA	ND
Ta-182	2.5E-10	9.3E-09	NA	6.2E-11
W-178	2.9E-11	1.4E-09	NA	ND
W-181	1.1E-11	4.4E-10	NA	3.0E-12
W-185	1.6E-11	3.4E-09	NA	4.0E-11
W-187 (*)	5.4E-11	4.9E-09	NA	1.7E-10
W-188 +	1.8E-10	1.9E-08	6.3E-09	3.7E-10
Re-184	2.9E-10	2.2E-09	1.6E-09	1.6E-11
Re-184m +	3.0E-10	3.7E-09	2.8E-09	1.6E-11
Re-186	9.9E-11	4.2E-09	4.8E-09	2.2E-10
Re-187	3.5E-13	1.3E-11	1.1E-11	0.0E+00
Re-188 (*)	8.0E-11	3.1E-09	6.6E-09	3.6E-10
Re-189	5.2E-11	1.9E-09	3.5E-09	ND
Os-185	1.6E-10	2.1E-09	NA	1.6E-11
Os-191	1.9E-11	4.3E-09	NA	5.2E-12
Os-191m +	1.1E-12	7.1E-10	NA	7.5E-12
Os-193	9.5E-12	6.2E-09	NA	2.2E-10
Os-194 +	4.4E-11	2.7E-08	NA	3.7E-10
Ir-189	1.8E-11	1.8E-09	NA	ND
Ir-190	2.9E-10	6.5E-09	NA	4.0E-11
Ir-192	1.9E-10	8.5E-09	NA	1.3E-10
Ir-194 (*)	8.9E-12	1.0E-08	NA	3.7E-10
Pt-188 +	2.3E-10	5.4E-09	NA	2.2E-11
Pt-191	5.0E-11	2.1E-09	NA	2.1E-11
Pt-193	1.2E-13	2.5E-10	NA	2.0E-12
Pt-193m	2.8E-12	3.6E-09	NA	4.5E-12
Pt-195m	1.4E-11	4.9E-09	NA	7.5E-12
Pt-197 (*)	2.4E-12	3.0E-09	NA	1.1E-10
Pt-197m +(*)	9.2E-13	4.1E-10	NA	3.4E-10
Au-193	1.5E-11	8.5E-10	NA	ND
Au-194	1.3E-10	1.9E-09	NA	1.4E-11
Au-195	2.4E-11	1.8E-09	NA	6.0E-12
Au-198	7.6E-11	7.3E-09	NA	2.1E-10
Au-199	2.1E-11	3.3E-09	NA	1.2E-11
Hg-194 +	2.1E-09	4.1E-09	NA	1.6E-11
Hg-195m +	1.4E-10	4.0E-09	NA	1.6E-11
Hg-197	5.9E-11	1.7E-09	NA	5.1E-12
Hg-197m +	7.8E-11	3.5E-09	NA	1.1E-11
Hg-203	7.3E-10	3.5E-09	NA	1.8E-11
Tl-200	1.5E-10	2.8E-10	NA	3.8E-11
Tl-201	5.6E-11	2.3E-10	NA	4.8E-12

Radionuclides [a]	Ingestion			Contamination
	Red marrow	Colon	Thyroid	Derma of skin
	$AF_{2,IV}(\Delta)$ [b]	$AF_{4,IV}(\Delta)$ [c]	$AF_{5,IV}(\Delta)$ [d]	$AF_{6R,V}$ [e]
	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/(s×Bq/cm^2))
Tl-202	3.5E-10	7.9E-10	NA	2.1E-11
Tl-204	5.9E-10	3.9E-09	NA	1.5E-10
Pb-201 +	4.7E-11	7.1E-10	NA	4.8E-12
Pb-202 +	5.4E-10	1.2E-09	NA	2.1E-11
Pb-203	6.8E-11	1.3E-09	NA	2.3E-11
Pb-205	1.9E-11	1.9E-10	NA	2.0E-12
Pb-210 +	2.5E-08	1.3E-08	NA	1.9E-10
Pb-212 +(*)	6.6E-09	1.9E-08	NA	6.1E-10
Bi-205	3.0E-10	3.7E-09	NA	2.8E-11
Bi-206	5.6E-10	8.8E-09	NA	9.8E-11
Bi-207	3.1E-10	6.5E-09	NA	7.0E-11
Bi-210 +	7.3E-10	1.0E-08	NA	1.9E-10
Bi-210m	1.7E-10	1.9E-08	NA	ND
Bi-212 +(*)	1.3E-12	0.0E+00	NA	5.7E-10
Po-210	2.3E-08	1.9E-14	NA	9.3E-17
At-211	1.1E-09	3.7E-12	NA	7.2E-11
Rn-222	0.0E+00	0.0E+00	NA	8.6E-15
Ra-223 +	2.9E-08	3.0E-08	NA	1.3E-11
Ra-224 +	1.9E-08	2.7E-08	NA	9.2E-13
Ra-225 +	2.7E-08	1.1E-08	NA	1.5E-11
Ra-226	7.7E-09	6.9E-09	NA	4.9E-10
Ra-228 +	2.7E-08	5.8E-08	NA	2.4E-10
Ac-225	1.1E-09	2.0E-08	NA	1.3E-12
Ac-227 +	2.9E-08	3.5E-08	NA	8.1E-12
Ac-228	3.3E-11	2.2E-09	NA	2.3E-10
Th-227 +	1.4E-08	1.6E-08	NA	2.1E-11
Th-228 +	2.4E-08	4.0E-08	NA	1.5E-12
Th-229 +	2.9E-08	2.9E-08	NA	2.2E-11
Th-230 +	2.5E-10	5.1E-10	NA	5.1E-13
Th-231	1.8E-12	2.6E-09	NA	9.0E-12
Th-232 +	1.9E-08	4.1E-08	NA	5.1E-13
Th-234 +	1.8E-11	2.7E-08	NA	1.2E-10
Pa-230 +	2.0E-10	3.3E-09	NA	2.5E-11
Pa-231 +	8.2E-09	1.2E-08	NA	6.5E-12
Pa-233	4.5E-11	6.5E-09	NA	4.4E-11
U-230 +	4.3E-09	1.4E-09	NA	7.3E-13
U-232 +	2.4E-08	3.8E-08	NA	1.3E-12
U-233	8.3E-10	2.1E-10	NA	7.0E-12
U-234 +	8.2E-10	4.3E-10	NA	1.1E-12
U-235 +	8.2E-10	7.3E-09	NA	1.3E-11
U-236	7.7E-10	3.7E-10	NA	1.1E-12
U-238 +	7.8E-10	2.9E-08	NA	1.4E-12
Depleted U	7.7E-10	1.5E-09	NA	7.1E-13
Np-235	6.4E-13	4.0E-10	NA	ND
Np-236b +	2.3E-11	1.3E-09	NA	ND
Np-236a	3.1E-11	7.1E-09	NA	ND
Np-237 +	2.1E-10	9.2E-09	NA	4.7E-11
Np-239	2.6E-11	6.0E-09	NA	5.2E-11
Pu-236	2.2E-10	4.5E-10	NA	ND

Radionuclides [a]	Ingestion			Contamination
	Red marrow	Colon	Thyroid	Derma of skin
	$AF_{2,IV}(\Delta)$ [b]	$AF_{4,IV}(\Delta)$ [c]	$AF_{5,IV}(\Delta)$ [d]	$AF_{6R,V}$ [e]
	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/Bq)	((Gy-Eq)/(s×Bq/cm^2))
Pu-237	1.1E-11	6.7E-10	NA	ND
Pu-238	2.1E-10	3.6E-10	NA	6.0E-13
Pu-239	2.0E-10	2.3E-10	NA	2.3E-13
Pu-240	2.0E-10	3.6E-10	NA	5.7E-13
Pu-241 +	1.6E-12	1.7E-10	NA	1.7E-14
Pu-242	1.9E-10	3.0E-10	NA	4.9E-13
Pu-244 +	2.7E-10	2.7E-08	NA	4.9E-12
Am-241	1.2E-10	1.9E-09	NA	3.7E-12
Am-242m +	1.1E-10	7.6E-09	NA	1.3E-12
Am-243 +	1.6E-10	9.7E-09	NA	3.9E-13
Am-244	4.3E-11	2.9E-09	NA	6.0E-11
Cm-240	9.2E-11	3.6E-10	NA	ND
Cm-241 +	1.1E-10	5.2E-09	NA	ND
Cm-242	1.2E-10	3.3E-10	NA	5.4E-13
Cm-243	1.5E-10	4.8E-09	NA	1.8E-11
Cm-244	1.2E-10	2.9E-10	NA	5.1E-13
Cm-245	1.3E-10	2.4E-09	NA	4.5E-12
Cm-246	1.1E-10	2.7E-10	NA	1.7E-12
Cm-247	1.8E-10	6.4E-09	NA	1.1E-11
Cm-248 (*)	6.9E-10	ND	NA	2.8E-10
Bk-247	2.7E-10	2.2E-09	NA	ND
Bk-249	7.3E-13	1.1E-09	NA	1.3E-11
Cf-248 +	2.7E-10	2.0E-10	NA	ND
Cf-249	3.3E-10	2.1E-09	NA	1.7E-11
Cf-250 [g]	2.7E-10	1.9E-10	NA	3.5E-12
Cf-251	2.9E-10	6.8E-09	NA	3.6E-11
Cf-252 (*)	6.4E-10	ND	NA	3.7E-10
Cf-253	7.7E-11	2.4E-09	NA	3.8E-12
Cf-254 (*)	2.8E-08	5.0E-07	NA	3.5E-09
^{239}Pu/^{9}Be [h]	2.0E-10	2.3E-10	NA	2.3E-13
^{241}Am/^{9}Be [h]	1.2E-10	1.9E-09	NA	3.7E-12

[a] In growth of radioactive progeny was taken into account when calculation the D values for all the radionuclides as described in Appendix VIII. A "+" indicates the radionuclides for which the progeny were significant sources of dose for the scenarios considered. The factors are based on data from Ref. [49] except where noted by a "*" indicating that they are based on data from [50].

[b] 30-day (Δ) committed RBE-weighted dose in the red marrow due to ingestion.

[c] 30-day (Δ) committed RBE-weighted dose in the colon due to ingestion.

[d] 365-day (Δ) committed RBE-weighted dose in the thyroid due to ingestion.

[e] RBE-weighted dose rate in the derma of the skin.

[f] "NA" means "not applicable". "ND" means "no data".

[g] The activity given is that of the alpha-emitting radionuclide, e.g., ^{239}Pu or ^{241}Am.

[h] The dose from neutrons was not considered as discussed in Section 5.

VI.2. SKIN CONTAMINATION

The risk approach used dose conversion factors, $AF_{6R,V}$, equal to the RBE-weighted dose rate in Tissue 6R (derma of skin) per unit surface activity of a radionuclide, delivered in accordance with Scenario V. Radionuclide-specific values of these dose conversion factors were calculated as a sum of

three terms as presented in Eq. (70). The first term on the right hand side of Eq. (70) is the contributions from discrete photons of energy $E_{\gamma,i}$, and yield Y_i^{γ}, per nuclear transformation. The second term is the contribution from conversion electrons of yield Y_j^e, and kinetic energy $E_{e,j}$, and the final term is the contribution from the beta spectrum with a maximum energy E_e^0:

$$AF_{6R,V} = \sum_i^n Y_i^{\gamma} \times d_{6R,V}^{\gamma}(E_{\gamma,i}) + \\ + \sum_j^m Y_j^e \times d_{6R,V}^e(E_{e,j}) + \int_0^{E_e^0} n_{\beta}(E_e, E_e^0)\, d_{6R,V}^e(E_e)\, dE_e. \quad (70)$$

where:

$AF_{6R,V}$ is the RBE-dose conversion factor for the skin derma (Tissue 6R) from uniformly distributed contamination on the skin surface as described in Scenario V, ((Gy-Eq)/(s×Bq/cm^2));

$n_{\beta}(E_e, E_e^0)\, dE_e$ is the average number of electrons with an energy from E_e to E_e+dE_e arising from beta-decay of a radionuclide with a maximum energy of beta decay E_e^0, (MeV), taken from Ref. [52];

$d_{6R,V}^{\gamma}(E_{\gamma})$ is the response function equal to the RBE-weighted dose of the skin derma at 40 mg×cm^{-2} (0.4 mm or 400 μm) under the skin surface from a source of photons with energy E_{γ}, uniformly distributed on the surface of the skin, ((Gy-Eq)×cm^2);

$d_{6R,V}^e(E_e)$ is the response function equal to the RBE-weighted dose of the skin derma from a source of electrons with energy E_e, uniformly distributed on the surface of the skin, ((Gy-Eq)×cm^2).

The sum of the first term on the right hand side of Eq. (70) is the RBE-weighted dose for irradiation of the skin derma from photons emitted by the radionuclide concerned. The values of this quantity, as reported by Rohloff and Heinzelmann [53], were used in calculating the dose conversion factors. The empirical equation developed by Faw [54] was used for calculating the response function of the RBE-weighted dose to the skin derma by a source of electrons with an energy E_e, uniformly distributed on the surface of the skin, ((Gy-Eq)×cm^2):

$$d_{6R,V}^e(E_e) = 1.602 \times 10^{-10} \frac{2.7767 + y(8.5167 + y(8.1517 + 2.3104y))}{1 + y(2.5806 + y(1.6233 - 0.2723y))}, \quad (1)$$

where: $y = \log_{10} E_e$ and E_e is the energy of the electrons, (MeV). This equation is valid for electrons with a minimum energy, E_{min}, of more than 0.18 MeV. For electrons with a minimum energy less than this, $d_{6R,V}^e(E_e)$ is equal to zero.

The dose at a depth of 300-500 μm should [15] be evaluated for the purposes of estimating severe deterministic effects such as moist desquamation. This was the method used by the risk approach where it was assumed that development of severe deterministic effects follows irradiation of more than 100 cm^2 of skin tissue [12] lying at a depth of 400 μm (40 mg×cm^{-2}).

Comparison of the calculated results with existing published data [54, 55, 56, 57, 58] shows good agreement. Values of the dose conversion factor $AF_{6R,V}$ are listed in Table 19.

VI.3. IMMERSION

The risk approach used dose conversion factors, $AF_{2,VI}$, equal to the RBE-weighted dose rate in Tissue 2 (red marrow) due to immersion in a radioactive noble gas. Semi-infinite cloud data from Ref. [40] that were used in the calculation of $AF_{2,VI}$ correctly approximate the situation of air immersion [40]. Use of these dose factors for external exposure to γ-radiation due to immersion in a 300 m^3 room (Scenario VI) provided conservative estimates for exposure, due to the size of the room compared to an infinite cloud. Values of the dose conversion factor $AF_{2,VI}$ are listed in Table 20.

TABLE 20. RBE-WEIGHTED DOSE CONVERSION FACTORS FOR IMMERSION IN A RADIOACTIVE GAS

Radionuclide	Red marrow	Radionuclide	Red marrow
	$AF_{2,VI}$		$AF_{2,VI}$
	(Gy-Eq)/(Bq×s/m^3)		(Gy-Eq)/(Bq×s/m^3)
N-13	4.60E-14	Kr-87	4.00E-14
Ar-37	0.00E+00	Xe-122	4.50E-14
Ar-39	6.60E-18	Xe-123	3.50E-14
Ar-41	6.30E-14	Xe-127	1.10E-14
Kr-81	2.40E-16	Xe-131m	2.30E-16
Kr-85	1.10E-16	Xe-133	1.10E-15
Kr-85m	6.40E-15	Xe-135	1.10E-14

APPENDIX VII
EVALUATION OF D-VALUES

This section provides a general characterization and evaluation of the recommended D-values given in Table 1.

VII.1. GENERAL CHARACTERIZATION OF THE RECOMMENDED D-VALUES

Table 21 shows the conditions that limit the D_1-values. In most cases (312 out of the 369 analysed), exposure to an adjacent source defines the dangerous activity for non-dispersed radioactive material. Exposure to a distant source is limiting for 13 radionuclides. As a rule, these radionuclides have very low specific activity and do not pass the "pocket" test because they could not be carried in a pocket. In 19 cases, the D_1-value is limited by criticality, and D_1-values are unlimited in 25 cases.

TABLE 21. CONDITIONS THAT LIMIT THE D_1-VALUES

Limited by developing severe deterministic effects in the organ or tissue:	Scenario	
	I	II
Soft tissue	312	
Red marrow		
AI region of respiratory tract		
Colon		
Thyroid		
Derma of skin		
Torso		13
Limited by criticality	19	
Unlimited	25	
Total	369	

Table 22 shows the conditions that limit the D_2-values. In most cases (314 out of the 369 analysed), inhalation and contact exposure of the skin derma define the dangerous activity of dispersed radioactive material. Red marrow, the alveolar region of the respiratory tract and the derma of skin are the critical organs which define the D_2-values. Table 22 also shows that ingestion intake associated with inadvertent ingestion or consumption of contaminated water is important only in the case of ^{14}C. In ten cases, the D_2-value is limited by criticality, and in 17 cases the D_2-values are unlimited.

TABLE 22. CONDITIONS THAT LIMIT THE D_2-VALUES

Limited by developing severe deterministic effects in the organ or tissue:	Scenario			
	IIIR	IV	V	VI
Soft tissue				
Red marrow	119	1		12
AI region of respiratory tract	76			
Colon	10	0		
Thyroid	28	0		
Derma of skin			96	
Torso				
Limited by criticality	10			
Unlimited	17			
Total	369			

Table 23 shows the conditions that limit the D-value (minimum of D_1 and D_2-values). In most cases (266 out of the 369 analysed), exposure to an adjacent source defines the dangerous quantity of radioactive material. Only in six cases (^{97m}Tc, ^{99}Tc, ^{125m}Te, ^{127m}Te, ^{125}I and ^{126}I), is the D-value limited by exposure of the thyroid to dispersed material containing thyroid-seeking radionuclides. For comparison, this effect limits the D_2-value in all cases of inhalation where the dispersed material contains thyroid-seeking radionuclides. In nine cases, the D-value is limited by criticality, and in 15 cases it is unlimited.

TABLE 23. CONDITIONS THAT LIMIT THE D-VALUES

Limited by developing severe deterministic effects in the organ or tissue:	Scenario					
	I	II	IIIR	IV	V	VI
Soft tissue	266					
Red marrow			27	1		0
AI region of respiratory tract			32			
Colon			0	0		
Thyroid			6	0		
Derma of skin					8	
Torso		5				
Limited by criticality	9					
Unlimited	15					
Total	369					

VII.2. VERIFICATION OF THE RECOMMENDED D-VALUES

The IAEA TECDOC-1432 "Development of extended framework for emergency response criteria" [15] recognizes that uncertainties cannot be avoided when performing dose assessments and provides guidance for establishing the generic reference levels for emergency response. There are considerable uncertainties in the development of the D-values, and it is estimated that based on data and assumptions, the results could easily vary by a factor of ten or more. Two comparisons were made in order to provide some validation of the recommended D-values given in Table 1. The first was to compare the values calculated using the expert approach with those calculated using the risk approach. The second was to see how the calculated D-values compared with sources that have been involved in radiological emergencies in order to determine if the values were consistent with actual experience. here.

Very different dosimetric data and criteria were used in the expert and the risk approaches for determining D_2-values. The D-values based on the risk approach were used as the base line because they were developed using the latest methods for the projection of the occurrence of deterministic effects contained in Ref. [15].

In comparing the D-values developed by means of the expert and the risk approaches, taking into account the uncertainties in dose factors, dose criteria and scenario parameters it seems appropriate that a difference between D-values of less than a factor of five should be regarded as negligible.

Table 24 presents the D-values calculated by the expert and risk approaches for the radionuclides addressed in the expert approach. Comparison of the D_1-values determined by means of the expert approach with those obtained by means of the verified risk approach shows that their difference is negligible. This demonstrates the adequacy of the dosimetry data and criteria used in these approaches. Data listed in Table 24 show that the expert approach systematically leads to lower (conservative) estimates of D_2-values. The mean value of the ratio ${}^{E}D_2/{}^{R}D_2$ is 1.1±0.3 (99 % confidence level). There are only three cases for which the D_2-values calculated by the expert approach are more that a factor of two smaller than those calculated by the risk approach, and none where it is more than a factor of five smaller. In addition the D values were compared with values calculated totally independently using rules-of-thumb and dose factors from other sources. These result were also found to be consistent with the D values calculated here.

TABLE 24 COMPARISON OF THE D-VALUES DERIVED ACCORDING TO THE EXPERT AND THE RISK APPROACHES

Radio-nuclide [a]	D-value			D_1-value			D_2-value		
	(TBq)		E/R [b]	(TBq)		E/R	(TBq)		E/R
	E [b]	R [b]		E	R		E	R	
H-3	2.E+3	1.E+3	2.	UL [c]	UL	1.	2.E+3 [e]	1.E+3	2.
C-14	5.E+1	9.E+2	0.06	2.E+5	1.E+5	2.	5.E+1	9.E+2	0.06
P-32	1.E+1	8.E+0	1.	1.E+1	1.E+1	1.	2.E+1	8.E+0	3.
S-35	6.E+1	9.E+1	0.7	4.E+4	4.E+4	1.	6.E+1	9.E+1	0.7
Cl-36	2.E+1	3.E+1	0.7	3.E+2	2.E+2	2.	2.E+1 [f]	3.E+1	0.7
Cr-51	2.E+0	2.E+0	1.	2.E+0	2.E+0	1.	5.E+3	1.E+3	5.
Fe-55	8.E+2	4.E+2	2.	UL	UL	1.	8.E+2	4.E+2	2.
Co-57	7.E-1	7.E-1	1.	7.E-1	7.E-1	1.	4.E+2	3.E+2	1.
Co-60	3.E-2	3.E-2	1.	3.E-2	3.E-2	1.	3.E+1	3.E+1	1.
Ni-63	6.E+1	5.E+2	0.1	UL	UL	1.	6.E+1	5.E+2	0.1

Radio-nuclide [a]	D-value			D_1-value			D_2-value		
	(TBq)		E/R [b]	(TBq)		E/R	(TBq)		E/R
	E [b]	R [b]		E	R		E	R	
Zn-65	1.E-1	1.E-1	1.	1.E-1	1.E-1	1.	3.E+2	1.E+2	3.
Ge-68+	7.E-2	7.E-2	1.	7.E-2	7.E-2	1.	2.E+1	1.E+1	2.
Se-75	2.E-1	2.E-1	1.	2.E-1	2.E-1	1.	2.E+2	9.E+1	2.
Kr-85	3.E+1	3.E+1	1.	3.E+1	3.E+1	1.	2.E+3	2.E+3	1.
Sr-89	2.E+1	1.E+1	2.	2.E+1	2.E+1	1.	2.E+1	1.E+1	2.
Sr-90+	1.E+0	5.E+0	0.2	4.E+0	5.E+0	0.8	1.E+0	5.E+0	0.2
Y-90	5.E+0	5.E+0	1.	5.E+0	5.E+0	1.	1.E+1	1.E+1	1.
Y-91	8.E+0	9.E+0	0.9	8.E+0	9.E+0	0.9	2.E+1	2.E+1	1.
Zr-95+	4.E-2	4.E-2	1.	4.E-2	4.E-2	1.	1.E+1	1.E+1	1.
Nb-95	9.E-2	9.E-2	1.	9.E-2	9.E-2	1.	6.E+1	9.E+1	0.7
Mo-99+	3.E-1	3.E-1	1.	3.E-1	3.E-1	1.	2.E+1	2.E+1	1.
Tc-99m	7.E-1	6.E-1	1.	7.E-1	6.E-1	1.	7.E+2	5.E+2	1.
Ru-103+	1.E-1	1.E-1	1.	1.E-1	1.E-1	1.	3.E+1	5.E+1	0.6
Ru-106+	3.E-1	3.E-1	1.	3.E-1	3.E-1	1.	1.E+1	5.E+0	2.
Pd-103+	9.E+1	9.E+1	1.	9.E+1	9.E+1	1.	1.E+2	2.E+2	0.5
Cd-109	2.E+1	2.E+1	1.	2.E+1	2.E+1	1.	3.E+1	8.E+1	0.4
Te-132+	3.E-2	3.E-2	1.	3.E-2	3.E-2	1.	8.E-1	3.E-1	3.
I-125	2.E-1	2.E-1	1.	1.E+1	1.E+1	1.	2.E-1	8.E-1	0.3
I-129	UL [c]	UL		UL	UL		UL	UL	
I-131	2.E-1	2.E-1	1.	2.E-1	2.E-1	1.	2.E-1	3.E-1	0.7
Cs-134	4.E-2	4.E-2	1.	4.E-2	4.E-2	1.	3.E+1	2.E+1	2.
Cs-137+	1.E-1	1.E-1	1.	1.E-1	1.E-1	1.	2.E+1	3.E+1	0.7
Ba-133	2.E-1	2.E-1	1.	2.E-1	2.E-1	1.	7.E+1	8.E+1	0.9
Ce-141	1.E+0	1.E+0	1.	1.E+0	1.E+0	1.	2.E+1	6.E+1	0.3
Ce-144+	9.E-1	9.E-1	1.	9.E-1	9.E-1	1.	9.E+0	6.E+0	2.
Pm-147	4.E+1	1.E+2	0.4	8.E+3	8.E+3	1.	4.E+1	1.E+2	0.4
Eu-152	6.E-2	6.E-2	1.	6.E-2	6.E-2	1.	3.E+1	4.E+1	0.8
Eu-154	6.E-2	6.E-2	1.	6.E-2	6.E-2	1.	2.E+1	3.E+1	0.7
Gd-153	1.E+0	1.E+0	1.	1.E+0	1.E+0	1.	8.E+1	5.E+1	2.
Tm-170	2.E+1	2.E+1	1.	2.E+1	2.E+1	1.	2.E+1	3.E+1	0.7
Yb-169	3.E-1	3.E-1	1.	3.E-1	3.E-1	1.	3.E+1	7.E+1	0.4
Re-188	1.E+0	1.E+0	1.	1.E+0	1.E+0	1.	3.E+1	7.E+0	4.
Ir-192	8.E-2	8.E-2	1.	8.E-2	8.E-2	1.	2.E+1	3.E+1	0.7
Au-198	2.E-1	2.E-1	1.	2.E-1	2.E-1	1.	3.E+1	3.E+1	1.
Hg-203	3.E-1	3.E-1	1.	3.E-1	3.E-1	1.	2.E+0	1.E+1	0.2
Tl-204	2.E+1	4.E+1	0.5	7.E+1	7.E+1	1.	2.E+1	4.E+1	0.5
Po-210	6.E-2	3.E-1	0.2	8.E+3	8.E+3	1.	6.E-2	3.E-1	0.2
Ra-226+	4.E-2	4.E-2	1.	4.E-2	4.E-2	1.	7.E-2	3.E-1	0.2
Th-230	7.E-2	1.E-1	0.7	9.E+2	7.E+2	1.	7.E-2	1.E-1	0.7
Th-232	UL [f]	UL	1.	UL	UL	1.	UL	UL	1.

Radio-nuclide [a]	D-value			D_1-value			D_2-value		
	(TBq)		E/R [b]	(TBq)		E/R	(TBq)		E/R
	E [b]	R [b]		E	R		E	R	
U-232	6.E-2	3.E-2	2.	7.E-2	7.E-2	1.	6.E-2[f]	3.E-2	2.
U-235+	8.E-5	8.E-5	1.	8.E-5	8.E-5	1.	8E-5	8.E-5	1.
U-238	UL	UL	1.	UL	UL	1.	UL	UL	1.
U Natural	UL	ND c	-	UL	ND	-	UL	ND	-
U Depleted	UL	ND	-	UL	ND	-	UL	ND	-
U Enriched > 20 %	8E-5	ND	-	8E-5 [g]	ND	-	8E-5	ND	-
U Enriched 10 % - 20%	8E-4	ND	-	8E-4 [g]	ND	-	8E-4	ND	-
Np-237+	7.E-2	2.E-1	0.4	3.E-1	3.E-1	1.	7.E-2	2.E-1	0.4
Pu-238	6.E-2	2.E-1	0.3	3.E+2	3.E+2	1.	6.E-2	2.E-1	0.3
Pu-239	6.E-2	2.E-1	0.3	1.E+0	1.E+0	1.	6.E-2	2.E-1	0.3
Pu-240	6.E-2	2.E-1	0.3	4.E+0	4.E+0	1.	6.E-2	2.E-1	0.3
Pu-241+	3.E+0	2.E+1	0.2	2.E+3	2.E+3	1.	3.E+0	2.E+1	0.2
Pu-242	7.E-2	7.E-2	1.	7.E-2	7.E-2	1.	7.E-2 [g]	7.E-2	1.
Am-241	6.E-2	2.E-1	0.3	8.E+0	8.E+0	1.	6.E-2	2.E-1	0.3
Cm-242	4.E-2	2.E-1	0.2	2.E+3	2.E+3	1.	4.E-2	2.E-1	0.2
Cm-244	5.E-2	2.E-1	0.3	1.E+4	3.E+3	3.	5.E-2	2.E-1	0.3
Cf-252	2.E-2	9.E-3	2.	2.E-2	9.E-3	2.	1.E-1	6.E-2	2.
^{239}Pu/^{9}Be [d]	6.E-2	2.E-1	0.3	1.E+0 [g]	1.E+0	1.	6.E-2	2.E-1	0.3
^{241}Am/^{9}Be [d]	6.E-2	2.E-1	0.3	1.E+0	5.E+0	0.2	6.E-2	2.E-1	0.3

[a] In growth of radioactive progeny was taken into account when calculation the D values for all the radionuclides as described in Appendix VIII. An "+" indicates the radionuclides for which the progeny were significant sources of dose for the scenarios considered.

[b] "E" and "R" indicate expert and risk approaches; "E/R" is the ratio of D-values calculated in accordance with the expert and risk approaches.

[c] "UL" – indicates "unlimited quantity" as defined in Appendix II. "ND" indicates "no data".

[d] Neutron generator. The activity given is that of the alpha-emitting radionuclide, e.g., ^{239}Pu or ^{241}Am.

VII.3. EMERGENCY EXPERIENCE

A summary of the key facts in published reports involving lost or stolen sources is provided in Table 25. The ratio of the activity involved and the radionuclide's D_1-value, A/D_1, is also shown. The table does not include an event that involved leaving a 0.13 TBq ^{192}Ir brachytherapy source in a patient for four days resulting in her death [59]. Possibly the smallest uncontrolled source to result in an injury that reduced the quality of life involved a father intentionally placing a ^{137}Cs source in the bed and ear phones of his son over a period of weeks to months. This resulted in injuries that required surgery and in functional castration [64]. The father was licensed to have 4 Ci (0.14 TBq) of ^{137}Cs; however, it is impossible to determine the exact amount of material used. The smallest source to cause accidentally severe injuries due to external exposure was a 0.12 to 0.16 TBq ^{137}Cs source [27]. This was just slightly larger than the D_1-value of 0.10 TBq for ^{137}Cs in Table 1. The smallest uncontrolled source that resulted in fatal exposure among the public was a 1.2 TBq ^{192}Ir source [60]. This was about ten times the D_1-value. The only death from intake was from the intake of 10^{-5} of the very dispersible material in a ^{137}Cs source [36]. This is the intake fraction assumed in the calculation of the D_2-values.

An examination of emergencies that involved deaths due to whole body exposure showed that the dose rate to red marrow from a distance of one metre ("room" scenario) was probably in the range of 10-50 mGy/h during the period of exposure. This was considered in the criteria used for this scenario (Scenario II). Therefore it appears that the criteria for defining dangerous sources are consistent with the operational experience and are about one tenth to one hundredth of the level at which lethal doses have been seen in real emergencies involving uncontrolled radioactive sources.

TABLE 25. SUMMARY OF LOST OR STOLEN SOURCE EMERGENCIES

Emergencies			D_1 [a], TBq	A/D_1	Health consequences
Emergency	Source	A [b], TBq			
Istanbul [61]	Co-60	23.5	0.03	783	Severe injury, life threatening exposure
Samut Prakarn [62]	Co-60	15	0.03	500	3 deaths
Goiânia [36]	Cs-137	50	0.1	500	4 deaths
Georgia RTGs [c]	Sr-90	1000	5	200	1 death, severe injury and life threatening exposure
Tammiku [63]	Cs-137	7.4	0.1	74	1 death
Yanango [26, 31]	Ir-192	1.37	0.08	17	Severe injury, life threatening exposure
Case 20 [60]	Ir-192	1.2	0.08	13.8	8 deaths [d]
China [64]	Co-60	0.37	0.03	12	2 deaths [e]
Algeria [64]	Ir-192	0.97	0.08	11	Life threatening exposure [f]
USA [64]	Ir-192	1	0.08	11	Severe injury
Algeria [64]	Ir-192	1	0.08	11	Severe injury
Case 43 [60]	Ir-192	0.3	0.08	3.8	Severe injury
Gilan [32]	Ir-192	0.185	0.08	2.3	Severe injury
Case 37 [60]	Ir-192	0.26	0.08	3.3	Severe injury
Japan [64]	Ir-192	0.19	0.08	2.3	Life threatening exposure [g]
Lilo [27]	Cs-137	0.12-0.16	0.1	1.2-1.6	Severe injury

[a] D_1 for the radionuclide involved from Table 1.
[b] Activity (TBq) involved in the emergency.
[c] Two people were exposed, one died 1.5 years after the exposure.
[d] The source may have been in the room for up to four months with a likely dose rate between 20-50 mSv/h at 1 metre from the source.
[e] The source was left in the room for two weeks resulting in a fatal exposure with a dose rate of about 50 mGy/h at 1 m from the source.
[f] The source was left in room for five weeks but this did not result in a fatality. The dose rate was about 10 mGy/h at 1 m from the source.
[g] The source was kept in the room for six days and handled.

APPENDIX VIII
CHARACTERISTICS OF RADIOACTIVE SOURCES

This Appendix describes the basic nuclear characteristics of the radionuclides considered. This includes radionuclide half-life, decay constants and specific activities, neutron production, nuclear parameters of radioactive emitters of neutrons, radioactive decay chains, criticality, criticality limit-values and chemical toxicity. This also contains a description of the approach used to consider radioactive decay and in-growth of progeny and criticality.

VIII.1. HALF-LIFE AND SPECIFIC ACTIVITY

The half-life ($T_{1/2}$) and specific activity (SA) for each of the radionuclides of concern are provided in Table 26. Values for the half-life were obtained from ICRP Publication 38 [38].

TABLE 26. RADIONUCLIDE HALF-LIFE, DECAY CONSTANTS AND SPECIFIC ACTIVITIES

Radio nuclide	$T_{1/2}$ [a]	$T_{1/2}$ (s)	SA (Bq/g)
H-3	12.3 a	3.88E+08	3.59E+14
Be-7	53.3 d	4.61E+06	1.29E+16
Be-10	1.60E+6 a	5.05E+13	8.27E+08
C-11	20.38 min	1.22E+03	3.10E+19
C-14	5.73E+3 a	1.81E+11	1.65E+11
N-13	9.965 min	5.98E+02	5.37E+19
F-18	109.77 min	6.59E+03	3.52E+18
Na-22	2.60 a	8.20E+07	2.31E+14
Na-24	15.00 h	5.40E+04	3.22E+17
Mg-28	20.91 h	7.53E+04	1.98E+17
Al-26	7.16E+5 a	2.26E+13	7.11E+08
Si-31	157.3 min	9.44E+03	1.43E+18
Si-32	4.50E+2 a	1.42E+10	9.19E+11
P-32	14.3 d	1.24E+06	1.06E+16
P-33	25.4 d	2.19E+06	5.76E+15
S-35	87.4 d	7.55E+06	1.58E+15
Cl-36	3.01E+5 a	9.49E+12	1.22E+09
Cl-38	37.21 min	2.23E+03	4.92E+18
Ar-37	35.02d	3.03E+06	3.73E+15
Ar-39	269 a	8.48E+09	1.26E+12
Ar-41	1.827 h	6.58E+03	1.55E+18
K-40	1.28E+9 a	4.04E+16	2.58E+05
K-42	12.36 h	4.45E+04	2.23E+17
K-43	22.6 h	8.14E+04	1.19E+17
Ca-41	1.40E+5 a	4.42E+12	2.31E+09
Ca-45	163 d	1.41E+07	6.58E+14
Ca-47	4.53 d	3.91E+05	2.27E+16
Sc-44	3.927 h	1.41E+04	6.71E+17
Sc-46	83.8 d	7.24E+06	1.25E+15
Sc-47	3.35 d	2.89E+05	3.07E+16
Sc-48	1.82 d	1.57E+05	5.53E+16

Radio nuclide	$T_{1/2}$ [a]	$T_{1/2}$ (s)	SA (Bq/g)
Ti-44	47.3 a	1.49E+09	6.36E+12
V-48	16.2 d	1.40E+06	6.21E+15
V-49	330 d	2.85E+07	2.99E+14
Cr-51	27.7 d	2.39E+06	3.42E+15
Mn-52	5.59 d	4.83E+05	1.66E+16
Mn-53	3.70E+6 a	1.17E+14	6.75E+07
Mn-54	312 d	2.70E+07	2.87E+14
Mn-56	2.5785 h	9.28E+03	8.03E+17
Fe-52	8.28 h	2.98E+04	2.69E+17
Fe-55	2.70 a	8.51E+07	8.91E+13
Fe-59	44.5 d	3.84E+06	1.84E+15
Fe-60	1.00E+5 a	3.15E+12	2.21E+09
Co-55	17.54 h	6.31E+04	1.20E+17
Co-56	78.7 d	6.80E+06	1.10E+15
Co-57	271 d	2.34E+07	3.13E+14
Co-58	70.8 d	6.12E+06	1.18E+15
Co-58m	9.15 h	3.29E+04	2.18E+17
Co-60	5.27 a	1.66E+08	4.18E+13
Ni-59	7.50E+4 a	2.37E+12	2.99E+09
Ni-63	96.0 a	3.03E+09	2.19E+12
Ni-65	2.520 h	9.07E+03	7.08E+17
Cu-64	12.701 h	4.57E+04	1.43E+17
Cu-67	2.58 d	2.23E+05	2.79E+16
Zn-65	244 d	2.11E+07	3.05E+14
Zn-69	57 min	3.42E+03	1.77E+18
Zn-69m	13.76 h	4.95E+04	1.22E+17
Ga-67	3.26 d	2.82E+05	2.21E+16
Ga-68	68.0 min	4.08E+03	1.50E+18
Ga-72	14.1 h	5.08E+04	1.14E+17
Ge-68	288 d	2.49E+07	2.47E+14
Ge-71	11.8 d	1.02E+06	5.76E+15
Ge-77	11.3 h	4.07E+04	1.33E+17
As-72	1.08 d	9.33E+04	6.21E+16
As-73	80.3 d	6.94E+06	8.24E+14
As-74	17.8 d	1.54E+06	3.67E+15
As-76	1.10 d	9.50E+04	5.78E+16
As-77	1.62 d	1.40E+05	3.87E+16
Se-75	120 d	1.04E+07	5.37E+14
Se-79	6.50E+4 a	2.05E+12	2.58E+09
Br-76	16.2 h	5.83E+04	9.41E+16
Br-77	2.33 d	2.01E+05	2.69E+16
Br-82	1.47 d	1.27E+05	4.01E+16
Kr-81	2.1E5 a	6.62E+12	7.78E+08
Kr-85	10.72 a	3.38E+08	1.45E+13
Kr-85m	4.48 h	1.61E+04	3.04E+17

Radio nuclide	$T_{1/2}$ [a]	$T_{1/2}$ (s)	SA (Bq/g)
Kr-87	76.3 min	4.58E+03	1.05E+18
Rb-81	4.58 h	1.65E+04	3.12E+17
Rb-83	86.2 d	7.45E+06	6.75E+14
Rb-84	32.8 d	2.83E+06	1.75E+15
Rb-86	18.6 d	1.61E+06	3.02E+15
Rb-87	4.7E+10 a	1.48E+18	3.24E+03
Sr-82	25.0 d	2.16E+06	2.36E+15
Sr-85	64.8 d	5.60E+06	8.77E+14
Sr-85m	1.16 h	4.18E+03	1.18E+18
Sr-87m	2.805 h	1.01E+04	4.75E+17
Sr-89	50.5 d	4.36E+06	1.07E+15
Sr-90	29.1 a	9.18E+08	5.05E+12
Sr-91	9.50 h	3.42E+04	1.34E+17
Sr-92	2.71 h	9.76E+03	4.65E+17
Y-87	3.35 d	2.89E+05	1.66E+16
Y-88	107 d	9.24E+06	5.13E+14
Y-90	2.67 d	2.31E+05	2.01E+16
Y-91	58.5 d	5.05E+06	9.07E+14
Y-91m	0.828 h	2.98E+03	1.54E+18
Y-92	3.54 h	1.27E+04	3.56E+17
Y-93	10.1 h	3.64E+04	1.23E+17
Zr-88	83.4 d	7.21E+06	6.58E+14
Zr-93	1.53E+6 a	4.83E+13	9.30E+07
Zr-95	64.0 d	5.53E+06	7.94E+14
Zr-97	16.90 h	6.08E+04	7.07E+16
Nb-93m	13.6 a	4.29E+08	1.05E+13
Nb-94	2.03E+4 a	6.40E+11	6.93E+09
Nb-95	35.1 d	3.03E+06	1.45E+15
Nb-97	72.1 min	4.33E+03	9.94E+17
Mo-93	3.50E+3 a	1.10E+11	4.07E+10
Mo-99	2.75 d	2.38E+05	1.77E+16
Tc-95m	61.0 d	5.27E+06	8.33E+14
Tc-96	4.28 d	3.70E+05	1.18E+16
Tc-96m	0.858 h	3.09E+03	1.41E+18
Tc-97	2.60E+6 a	8.20E+13	5.25E+07
Tc-97m	87.0 d	7.52E+06	5.72E+14
Tc-98	4.20E+6 a	1.32E+14	3.21E+07
Tc-99	2.13E+5 a	6.72E+12	6.27E+08
Tc-99m	6.02 h	2.17E+04	1.94E+17
Ru-97	2.90 d	2.51E+05	1.72E+16
Ru-103	39.3 d	3.40E+06	1.19E+15
Ru-105	4.44 h	1.60E+04	2.49E+17
Ru-106	1.01 a	3.19E+07	1.24E+14
Rh-99	16.0 d	1.38E+06	3.05E+15
Rh-101	3.20 a	1.01E+08	4.09E+13

Radio nuclide	$T_{1/2}$ [a]	$T_{1/2}$ (s)	SA (Bq/g)
Rh-102	2.90 a	9.15E+07	4.47E+13
Rh-102m	207 d	1.79E+07	2.29E+14
Rh-103m	56.12 min	3.37E+03	1.20E+18
Rh-105	1.47 d	1.27E+05	3.13E+16
Pd-103	17.0 d	1.47E+06	2.76E+15
Pd-107	6.50E+6 a	2.05E+14	1.90E+07
Pd-109	13.427 h	4.83E+04	7.92E+16
Ag-105	41.0 d	3.54E+06	1.12E+15
Ag-108m	1.27E+2 a	4.01E+09	9.65E+11
Ag-110m	250 d	2.16E+07	1.76E+14
Ag-111	7.45 d	6.44E+05	5.84E+15
Cd-109	1.27 a	4.01E+07	9.56E+13
Cd-113m	13.6 a	4.29E+08	8.61E+12
Cd-115	2.23 d	1.93E+05	1.88E+16
Cd-115m	44.6 d	3.85E+06	9.42E+14
In-111	2.83 d	2.45E+05	1.54E+16
In-113m	1.658 h	5.97E+03	6.19E+17
In-114m	49.5 d	4.28E+06	8.56E+14
In-115m	4.486 h	1.61E+04	2.25E+17
Sn-113	115 d	9.94E+06	3.72E+14
Sn-117m	13.6 d	1.18E+06	3.04E+15
Sn-119m	293 d	2.53E+07	1.39E+14
Sn-121m	55.0 a	1.73E+09	1.99E+12
Sn-123	129 d	1.11E+07	3.04E+14
Sn-125	9.64 d	8.33E+05	4.01E+15
Sn-126	1.00E+5 a	3.15E+12	1.05E+09
Sb-122	2.70 d	2.33E+05	1.47E+16
Sb-124	60.2 d	5.20E+06	6.47E+14
Sb-125	2.77 a	8.74E+07	3.82E+13
Sb-126	12.4 d	1.07E+06	3.09E+15
Te-121	17.0 d	1.47E+06	2.35E+15
Te-121m	154 d	1.33E+07	2.59E+14
Te-123m	120 d	1.04E+07	3.27E+14
Te-125m	58.0 d	5.01E+06	6.66E+14
Te-127	9.35 h	3.37E+04	9.76E+16
Te-127m	109 d	9.42E+06	3.49E+14
Te-129	69.6 min	4.18E+03	7.75E+17
Te-129m	33.6 d	2.90E+06	1.11E+15
Te-131m	1.25 d	1.08E+05	2.95E+16
Te-132	3.26 d	2.82E+05	1.12E+16
I-123	13.2 h	4.75E+04	7.14E+16
I-124	4.18 d	3.61E+05	9.32E+15
I-125	60.1 d	5.19E+06	6.43E+14
I-126	13.0 d	1.12E+06	2.95E+15

Radio nuclide	$T_{1/2}$ [a]	$T_{1/2}$ (s)	SA (Bq/g)
I-129	1.57E+7 a	4.95E+14	6.53E+06
I-131	8.04 d	6.95E+05	4.59E+15
I-132	2.30 h	8.28E+03	3.82E+17
I-133	20.8 h	7.49E+04	4.19E+16
I-134	52.6 min	3.16E+03	9.87E+17
I-135	6.61 h	2.38E+04	1.30E+17
Xe-122	20.1 h	7.24E+04	4.73E+16
Xe-123	2.08 h	7.49E+03	4.53E+17
Xe-127	36.41d	3.15E+06	1.04E+15
Xe-131m	11.9d	1.03E+06	3.10E+15
Xe-133	5.245d	4.53E+05	6.92E+15
Xe-135	9.09 h	3.27E+04	9.45E+16
Cs-129	1.34 d	1.16E+05	2.79E+16
Cs-131	9.69 d	8.37E+05	3.80E+15
Cs-132	6.48 d	5.60E+05	5.65E+15
Cs-134	2.06 a	6.50E+07	4.79E+13
Cs-134m	2.90 h	1.04E+04	2.98E+17
Cs-135	2.30E+6 a	7.25E+13	4.26E+07
Cs-136	13.1 d	1.13E+06	2.71E+15
Cs-137	30.0 a	9.46E+08	3.22E+12
Ba-131	11.8 d	1.02E+06	3.12E+15
Ba-133	10.7 a	3.37E+08	9.30E+12
Ba-133m	1.62 d	1.40E+05	2.24E+16
Ba-140	12.7 d	1.10E+06	2.72E+15
La-137	6.00E+4 a	1.89E+12	1.61E+09
La-140	1.68 d	1.45E+05	2.05E+16
Ce-139	138 d	1.19E+07	2.52E+14
Ce-141	32.5 d	2.81E+06	1.05E+15
Ce-143	1.38 d	1.19E+05	2.45E+16
Ce-144	284 d	2.45E+07	1.18E+14
Pr-142	19.13 h	6.89E+04	4.27E+16
Pr-143	13.6 d	1.18E+06	2.48E+15
Nd-147	11.0 d	9.50E+05	2.99E+15
Nd-149	1.73 h	6.23E+03	4.50E+17
Pm-143	265 d	2.29E+07	1.27E+14
Pm-144	363 d	3.14E+07	9.24E+13
Pm-145	17.7 a	5.58E+08	5.16E+12
Pm-147	2.62 a	8.26E+07	3.44E+13
Pm-148m	41.3 d	3.57E+06	7.90E+14
Pm-149	2.21 d	1.91E+05	1.47E+16
Pm-151	1.18 d	1.02E+05	2.71E+16
Sm-145	340 d	2.94E+07	9.80E+13
Sm-147	1.1E+11 a	3.34E+18	8.49E+02
Sm-151	90.0 a	2.84E+09	9.74E+11
Sm-153	1.95 d	1.68E+05	1.62E+16

Radio nuclide	$T_{1/2}$ [a]	$T_{1/2}$ (s)	SA (Bq/g)
Eu-147	24.0 d	2.07E+06	1.37E+15
Eu-148	54.5 d	4.71E+06	5.99E+14
Eu-149	93.1 d	8.04E+06	3.48E+14
Eu-150a	12.62 h	4.54E+04	6.12E+16
Eu-150b	34.2 a	1.08E+09	2.58E+12
Eu-152	13.3 a	4.19E+08	6.55E+12
Eu-152m	9.32 h	3.36E+04	8.18E+16
Eu-154	8.80 a	2.78E+08	9.76E+12
Eu-155	4.96 a	1.56E+08	1.72E+13
Eu-156	15.2 d	1.31E+06	2.04E+15
Gd-146	48.3 d	4.17E+06	6.85E+14
Gd-148	93.0 a	2.93E+09	9.61E+11
Gd-153	242 d	2.09E+07	1.30E+14
Gd-159	18.56 h	6.68E+04	3.93E+16
Tb-157	1.50E+2 a	4.73E+09	5.62E+11
Tb-158	1.50E+2 a	4.73E+09	5.58E+11
Tb-160	72.3 d	6.25E+06	4.17E+14
Dy-159	144 d	1.24E+07	2.11E+14
Dy-165	2.334 h	8.40E+03	3.01E+17
Dy-166	3.40 d	2.94E+05	8.56E+15
Ho-166	1.12 d	9.68E+04	2.60E+16
Ho-166m	1.20E+3 a	3.78E+10	6.64E+10
Er-169	9.30 d	8.04E+05	3.07E+15
Er-171	7.52 h	2.71E+04	9.01E+16
Tm-167	9.24 d	7.98E+05	3.13E+15
Tm-170	129 d	1.11E+07	2.20E+14
Tm-171	1.92 a	6.05E+07	4.03E+13
Yb-169	32.0 d	2.76E+06	8.93E+14
Yb-175	4.19 d	3.62E+05	6.59E+15
Lu-172	6.70 d	5.79E+05	4.19E+15
Lu-173	1.37 a	4.32E+07	5.58E+13
Lu-174	3.31 a	1.04E+08	2.30E+13
Lu-174m	142 d	1.23E+07	1.95E+14
Lu-177	6.71 d	5.80E+05	4.07E+15
Hf-172	1.87 a	5.90E+07	4.11E+13
Hf-175	70.0 d	6.05E+06	3.94E+14
Hf-181	42.4 d	3.66E+06	6.29E+14
Hf-182	9.00E+6 a	2.84E+14	8.08E+06
Ta-178b	2.2 h	7.92E+03	2.96E+17
Ta-179	1.82 a	5.74E+07	4.06E+13
Ta-182	115 d	9.94E+06	2.31E+14
W-178	21.7 d	1.87E+06	1.25E+15
W-181	121 d	1.05E+07	2.21E+14
W-185	75.1 d	6.49E+06	3.48E+14
W-187	23.9 h	8.60E+04	2.59E+16

Radio nuclide	$T_{1/2}$ [a]	$T_{1/2}$ (s)	SA (Bq/g)
W-188	69.4 d	6.00E+06	3.70E+14
Re-184	38.0 d	3.28E+06	6.91E+14
Re-184m	165 d	1.43E+07	1.59E+14
Re-186	3.78 d	3.27E+05	6.87E+15
Re-187	5.0E+10 a	1.58E+18	1.42E+03
Re-188	16.98 h	6.11E+04	3.63E+16
Re-189	1.01 d	8.73E+04	2.53E+16
Os-185	94.0 d	8.12E+06	2.78E+14
Os-191	15.4 d	1.33E+06	1.64E+15
Os-191m	13.0 h	4.68E+04	4.67E+16
Os-193	1.25 d	1.08E+05	2.00E+16
Os-194	6.00 a	1.89E+08	1.14E+13
Ir-189	13.3 d	1.15E+06	1.92E+15
Ir-190	12.1 d	1.05E+06	2.10E+15
Ir-192	74.0 d	6.39E+06	3.40E+14
Ir-194	19.15 h	6.89E+04	3.12E+16
Pt-188	10.2 d	8.81E+05	2.52E+15
Pt-191	2.80 d	2.42E+05	9.03E+15
Pt-193	50.0 a	1.58E+09	1.37E+12
Pt-193m	4.33 d	3.74E+05	5.78E+15
Pt-195m	4.02 d	3.47E+05	6.16E+15
Pt-197	18.3 h	6.59E+04	3.22E+16
Pt-197m	94.4 min	5.66E+03	3.74E+17
Au-193	17.6 h	6.34E+04	3.41E+16
Au-194	1.64 d	1.42E+05	1.52E+16
Au-195	183 d	1.58E+07	1.35E+14
Au-198	2.69 d	2.32E+05	9.07E+15
Au-199	3.14 d	2.71E+05	7.73E+15
Hg-194	2.60E+2 a	8.20E+09	2.62E+11
Hg-195m	1.73 d	1.49E+05	1.43E+16
Hg-197	2.67 d	2.31E+05	9.18E+15
Hg-197m	23.8 h	8.57E+04	2.47E+16
Hg-203	46.6 d	4.03E+06	5.11E+14
Tl-200	1.09 d	9.42E+04	2.22E+16
Tl-201	3.04 d	2.63E+05	7.90E+15
Tl-202	12.2 d	1.05E+06	1.96E+15
Tl-204	3.78 a	1.19E+08	1.72E+13
Pb-201	9.40 h	3.38E+04	6.13E+16
Pb-202	3.00E+5 a	9.46E+12	2.18E+08
Pb-203	2.17 d	1.87E+05	1.10E+16
Pb-205	1.43E+7 a	4.51E+14	4.51E+06
Pb-210	22.3 a	7.03E+08	2.83E+12
Pb-212	10.64 h	3.83E+04	5.14E+16
Bi-205	15.3 d	1.32E+06	1.54E+15
Bi-206	6.24 d	5.39E+05	3.76E+15

Radio nuclide	$T_{1/2}$ [a]	$T_{1/2}$ (s)	SA (Bq/g)
Bi-207	38.0 a	1.20E+09	1.68E+12
Bi-210	5.01 d	4.33E+05	4.59E+15
Bi-210m	3.00E+6 a	9.46E+13	2.10E+07
Bi-212	60.55 min	3.63E+03	5.42E+17
Po-210	138 d	1.19E+07	1.67E+14
At-211	7.21 h	2.60E+04	7.62E+16
Rn-222	3.8235d	3.30E+05	5.69E+15
Ra-223	11.4 d	9.85E+05	1.90E+15
Ra-224	3.66 d	3.16E+05	5.89E+15
Ra-225	14.8 d	1.28E+06	1.45E+15
Ra-226	1.60E+3 a	5.05E+10	3.66E+10
Ra-228	5.75 a	1.81E+08	1.01E+13
Ac-225	10.0 d	8.64E+05	2.15E+15
Ac-227	21.8 a	6.87E+08	2.67E+12
Ac-228	6.13 h	2.21E+04	8.29E+16
Th-227	18.7 d	1.62E+06	1.14E+15
Th-228	1.91 a	6.02E+07	3.04E+13
Th-229	7.34E+3 a	2.31E+11	7.87E+09
Th-230	7.70E+4 a	2.43E+12	7.47E+08
Th-231	1.06 d	9.16E+04	1.97E+16
Th-232	1.4E+10 a	4.42E+17	4.07E+03
Th-234	24.1 d	2.08E+06	8.56E+14
Pa-230	17.4 d	1.50E+06	1.21E+15
Pa-231	3.27E+4 a	1.03E+12	1.75E+09
Pa-233	27.0 d	2.33E+06	7.68E+14
U-230	20.8 d	1.80E+06	1.01E+15
U-232	72.0 a	2.27E+09	7.92E+11
U-233	1.58E+5 a	4.98E+12	3.59E+08
U-234	2.44E+5 a	7.69E+12	2.32E+08
U-235	7.04E+8 a	2.22E+16	8.00E+04
U-236	2.34E+7 a	7.38E+14	2.40E+06
U-238	4.47E+9 a	1.41E+17	1.24E+04
Np-235	1.08 a	3.41E+07	5.21E+13
Np-236b	1.15E+5 a	3.63E+12	4.88E+08
Np-236a	22.5 h	8.10E+04	2.18E+16
Np-237	2.14E+6 a	6.75E+13	2.61E+07
Np-239	2.36 d	2.04E+05	8.56E+15
Pu-236	2.85 a	8.99E+07	1.97E+13
Pu-237	45.3 d	3.91E+06	4.50E+14
Pu-238	87.7 a	2.77E+09	6.34E+11
Pu-239	2.41E+4 a	7.60E+11	2.30E+09
Pu-240	6.54E+3 a	2.06E+11	8.43E+09
Pu-241	14.4 a	4.54E+08	3.81E+12
Pu-242	3.76E+5 a	1.19E+13	1.45E+08
Pu-244	8.26E+7 a	2.60E+15	6.57E+05

Radio nuclide	$T_{1/2}$ [a]	$T_{1/2}$ (s)	SA (Bq/g)
Am-241	4.32E+2 a	1.36E+10	1.27E+11
Am-242m	1.52E+2 a	4.79E+09	3.60E+11
Am-243	7.38E+3 a	2.33E+11	7.38E+09
Am-244	10.1 h	3.64E+04	4.70E+16
Cm-240	27.0 d	2.33E+06	7.45E+14
Cm-241	32.8 d	2.83E+06	6.11E+14
Cm-242	163 d	1.41E+07	1.22E+14
Cm-243	28.5 a	8.99E+08	1.91E+12
Cm-244	18.1 a	5.71E+08	3.00E+12
Cm-245	8.50E+3 a	2.68E+11	6.35E+09
Cm-246	4.73E+3 a	1.49E+11	1.14E+10
Cm-247	1.56E+7 a	4.92E+14	3.43E+06
Cm-248	3.39E+5 a	1.07E+13	1.57E+08
Bk-247	1.38E+3 a	4.35E+10	3.88E+10
Bk-249	320 d	2.76E+07	6.06E+13
Cf-248	334 d	2.89E+07	5.83E+13
Cf-249	3.50E+2 a	1.10E+10	1.52E+11
Cf-250	13.1 a	4.13E+08	4.04E+12
Cf-251	8.98E+2 a	2.83E+10	5.87E+10
Cf-252	2.64 a	8.33E+07	1.99E+13
Cf-253	17.8 d	1.54E+06	1.07E+15
Cf-254	60.5 d	5.23E+06	3.14E+14

[a] years (a), days (d), hours (h) and minutes (min)

VIII.2. NEUTRON PRODUCTION

Typically, radioactive materials that emit neutrons do so as a result of either spontaneous fission or the (α, n) reaction. Neutron emitters could be both internal and external hazards. For the intake of dispersed material containing radionuclides that spontaneous fission, dose conversion factors from Ref. [49, 50] were used and the internal dose from prompt and delayed neutrons, photons, and beta particles arising from the fission were all considered. Neutron yields of (α, n) sources depend on their physical form and composition. The yield is highest for solid material and negligible for a dispersed source. Therefore after dispersion, such a source becomes a mixture of alpha-emitting grains with a negligible neutron yield. It then presents the same internal hazard as the dispersed alpha-emitting material part of the source. The expert and risk approaches both consider neutron-emitting radioactive materials as a special source of external exposure.

In the expert approach, the yield of neutrons for ^{239}Pu/^{9}Be and ^{241}Am/^{9}Be sources (neutrons arising from the (α, n) reaction) was assumed to be 6.0×10^{-5} neutron/(Bq×s) [47] and dose conversion factors were calculated as described in Appendix IV. For ^{252}Cf (spontaneous fission), the external dose rate conversion factor from Ref. [46] was used.

Table 27 contains the neutron source yields that were used in the risk approach. Spontaneously fissioning radionuclides of ^{248}Cm, ^{250}Cf, ^{252}Cf, and ^{254}Cf were considered in this approach. Different nuclei have different fission neutron energy spectra, but for ^{248}Cm, ^{250}Cf, ^{252}Cf, and ^{254}Cf these differences are small enough not to lead to significant differences in the dose conversion factors. Therefore, the unmodified energy spectrum of neutrons from ^{252}Cf fission from Ref. [48] was used for estimating the dose conversion factors for all spontaneously fissioning radionuclides. Prompt and

delayed photons as well as beta particles are also emitted following spontaneous fission, as described in Ref. [65]. These radiations carry a significant portion of the energy of spontaneous fission and are also an external hazard. ^{239}Pu/^{9}Be and ^{241}Am/^{9}Be sources emit neutrons arising from the (α, n) reaction with beryllium. This reaction in ^{9}Be leads to the emission of 4.4 MeV photons with a photon to neutron ratio of about 0.6 to 1 [66]. The energy spectrum of neutrons produced in an (α, n) reaction depends on the energy of the interactive alpha particle. However, differences in the energy of the alpha particles of ^{239}Pu (E_α = 5.15 MeV) and ^{241}Am (E_α = 5.45 MeV) are small enough to lead to only small differences in the neutron spectra of ^{239}Pu/^{9}Be and ^{241}Am/^{9}Be sources. Therefore, the unmodified energy spectrum of neutrons from an ^{241}Am/^{9}Be source given in Ref. [48] was used for estimating the dose conversion factors for both sources.

TABLE 27. NUCLEAR PARAMETERS OF RADIOACTIVE EMITTERS OF NEUTRONS

Source of neutrons	Origin of neutrons	Nuclear parameter	
		Yield of neutrons	Yield of photon energy [a]
		(neutron/(Bq×s))	(MeV/(Bq×s))
^{248}Cm	SF [b]	2.6E-01 [38]	1.3E+00 [38, 65]
^{250}Cf	SF	2.7E-03 [38]	1.1E-02 [38, 65]
^{252}Cf	SF	1.1E-01 [38]	4.7E-01 [38, 65]
^{254}Cf	SF	3.9E+00 [38]	1.7E+01 [38, 65]
^{239}Pu/^{9}Be [c]	(α,n) reaction	6.0E-05 [67]	9.4E-04 [38, 66]
^{241}Am/^{9}Be [c]	(α,n) reaction	7.5E-05 [67]	3.2E-02 [38, 66]

[a] This parameter includes photons arising from alpha and beta decay as well as from spontaneous fission or the (α,n) reaction.

[b] Spontaneous fission

[c] The activity given is that of the alpha-emitting radionuclide, e.g., ^{239}Pu or ^{241}Am.

VIII.3. RADIOACTIVE DECAY CHAINS

All D-values are given in terms of the activity of a source at the time of its manufacture. This is referred to as the initial activity of the parent radionuclide in the source, or in brief, the initial activity of the source. To take into account changes in the radiological properties of the radionuclides in a source with time, D-values were calculated for the most dangerous mixture of parent and progeny radionuclides for a source up to the cut-off age of 10 years.

VIII.3.1.The expert approach

The expert approach addresses decay and in-growth by a simple and conservative approach where it was assumed that all daughters were in equilibrium with the initial activity of their parent at the time of the emergency human exposure. The exception was the ^{241}Pu - ^{241}Am decay chain. For ^{241}Pu, the in-growth of ^{241}Am over 10 years was simply added to the initial quantity of ^{241}Pu. Therefore, when calculating the D-values it was assumed that for each becquerel of ^{241}Pu, 0.02 Bq of ^{241}Am was also present at the start of the exposure.

VIII.3.2.The risk approach

The risk approach takes decay and in-growth into account by the use of an adjusted dose conversion factor as described below. The value of the adjusted dose conversion factor was attributed to the initial activity and took into account decay of the parent radionuclide, the in-growth of progeny and their nuclear properties. It was assumed that the exposure from the source would occur when it contained the most dangerous mixture of radionuclides produced by decay of the parent radionuclide. For

instance, a ^{225}Ra source has the highest adjusted dose conversion factor for irradiating the alveolar region of the respiratory tract (Tissue 3R) after nine days and for irradiating the red marrow (Tissue 2) after 16 days. Plutonium-241 is most dangerous at ten years when it is assumed that for each becquerel of initial activity of ^{241}Pu, there are 0.62 Bq of ^{241}Pu and 0.012 Bq of ^{241}Am present. The risk approach method of accounting for decay chains is further detailed below.

During radioactive decay, a parent radionuclide produces progeny. If the progeny are radioactive, they, together with the parent radionuclide form a radioactive decay chain. This chain may be expressed as follows:

$$P \xrightarrow{\lambda_P} D \xrightarrow{\lambda_D} \dots, \tag{72}$$

where:

"P" and "D" are the parent and daughter (progeny) nuclei;

λ_P and λ_D are the decay constants of the parent and daughter radionuclide, s^{-1}.

Decay of the initial (parent) radionuclide starts at t = 0, when the source is manufactured and the number of daughter nuclei is equal to zero, $N_D(0) = 0$. At age t>0, the source contains a mixture of decay chain nuclei. The activities of the parent and daughter radionuclide in the source are a function of time:

$$A_P(t) = A_P(0) \times \exp(-\lambda_P t), \tag{73}$$

$$A_D(t) = A_P(0) \frac{\lambda_D}{\lambda_D - \lambda_P} \left[\exp(-\lambda_P t) - \exp(-\lambda_D t)\right], \tag{74}$$

where:

$A_P(t)$ is the activity of the parent radionuclide at time t, Bq;

$A_D(t)$ is the activity of the daughter radionuclide at time t, Bq;

$A_P(0)$ is the initial activity of the parent radionuclide at t = 0, Bq;

λ_P and λ_D are the decay constants of the parent and daughter radionuclide respectively, s^{-1}.

At age t>0, the source causes an exposure resulting in a dose D(t) depending on the radioactivity of the chain radionuclides:

$$D(t) = \left[A_P(t) \times CF_P + A_D(t) \times CF_D\right] \times F, \tag{75}$$

where:

CF_P and CF_D are dose conversion factors for the parent and daughter radionuclide (dose conversion factors for absorbed dose, RBE-weighted dose, etc.);

F is a product of exposure factors taking into account the given scenario; and,

λ_P and λ_D are the decay constants of the parent and daughter radionuclides respectively, s^{-1}.

If the dose D(t) is normalized by the initial activity of a source, $A_P(0)$, it can be expressed as

$$D(t) = A_P(0) \times CF_{P+D}(t) \times F, \tag{76}$$

where:

$A_P(0)$ is the initial activity of the parent radionuclide at t = 0, Bq;

F is a product of exposure factors taking into account the given scenario;

$CF_{P+D}(t)$ is an adjusted dose conversion factor for an initial unit activity of a parent radionuclide at age t (when the source became uncontrolled). Taking into account Eq. (73), (74), (75), and (76), this can be written as:

$$CF_{P+D}(t) = CF_P \times \exp(-\lambda_P t) + CF_D \frac{\lambda_D}{\lambda_D - \lambda_P}\left[\exp(-\lambda_P t) - \exp(-\lambda_D t)\right]. \quad (77)$$

The value of D(t) has a maximum at $t = t_{max}$, when $CF_{P+D}(t)$ has a maximum also. The value of t_{max} depends upon the properties of the chain radionuclides and is limited by the cut-off maximum age of a source of 10 years:

$$t_{max} = \begin{cases} 0, \text{ if } \tau \le 0; \\ \tau, \text{ if } 0 < \tau < 10 \text{ years}; \\ 10 \text{ years, if } 10 \text{ years} < \tau, \end{cases} \quad (78)$$

and

$$\tau = \begin{cases} 0, \quad \text{if } CF_D\lambda_D \le CF_P\lambda_P; \\ \dfrac{1}{\lambda_P - \lambda_D} \ln\left[\left(\dfrac{CF_P}{CF_D} + 1\right)\dfrac{\lambda_P}{\lambda_D} - \dfrac{CF_P}{CF_D}\left(\dfrac{\lambda_P}{\lambda_D}\right)^2\right], \quad \text{if } CF_D\lambda_D > CF_P\lambda_P. \end{cases} \quad (79)$$

The maximum value of the adjusted dose conversion factor for the initial activity of a parent radionuclide in a source, CF_{P+}, is given by:

$$CF_{P+} = \max_{t>0} CF_{P+D}(t) = \begin{cases} CF_P, \text{ if } CF_D\lambda_D \le CF_P\lambda_P; \\ CF_{P+D}(t_{max}), \text{ if } CF_D\lambda_D > CF_P\lambda_P, \end{cases} \quad (80)$$

where $CF_{P+D}(t_{max})$ is given by (77) for $t = t_{max}$ given by (78).

Some radionuclides from Table 26 have more than one progeny. The algorithm described above for one segment of a simple radioactive chain is also applicable for the more general situation as given by:

$$A_n(t) = A_P(0)\frac{\lambda_n}{\lambda_P}\sum_{i=0}^{n} q_{n,i} \exp(-\lambda_i t), \; n = 0, 1,. \quad (81)$$

where:

$q_{n,i}$ are coefficients connected by a recurrent formula

$$q_{n,i} = -\frac{\lambda_{n-1}}{\lambda_i - \lambda_n} q_{n-1,i}, \; i = 0,., n\text{-}1, \text{ and } q_{0,0} = 1; \quad (82)$$

$$q_{n,n} = -\sum_{i=0}^{n-1} q_{n,i}; \quad (83)$$

λ_i is the decay constant of progeny number i in the chain where the parent radionuclide has an index 0.

The extended algorithm was used for evaluating dose conversion factors for ^{131m}Te, ^{224}Ra, ^{225}Ra, ^{228}Ra, ^{227}Ac, ^{227}Th, ^{228}Th, ^{229}Th, ^{232}Th, ^{230}Pa, ^{231}Pa, ^{232}U, ^{234}U, ^{238}U, and ^{242m}Am.

VIII.4. CRITICALITY

In establishing D-values, the mass of the initial activity considered dangerous for various exposure scenarios was also evaluated against a criterion to ensure criticality is not a concern. This was accomplished by establishing a criticality activity limit (A_c). Many radionuclides with an atomic number (Z) greater than 87 are capable of supporting a fission chain reaction. Refs. [68, 69, 70] provide limits, in terms of a sub-critical mass, at which isotopes can be used safely without the risk of a criticality. Table 28 lists these as well as the criticality limit converted to activity, A_c. In addition, plutonium and highly enriched uranium could be used in the construction of a nuclear explosive device by a technically competent group. In recognition of this possibility, INFCIRC/225/Rev.4 "The Physical Protection of Nuclear Material and Nuclear Facilities", [71] provides recommendations for the physical protection of nuclear material against unauthorized removal and for protection of nuclear material or facilities against sabotage. This IAEA publication [71] has established guidance for three categories of nuclear materials. Each category has an associated recommended level of physical protection measures based on the potential risk of these materials being used for a nuclear explosive. "Nuclear Material Category II", according to Ref. [71], is the lowest level that warrants robust security measures and warrants an immediate response to promptly regain control over lost or stolen material. The criteria for "Nuclear Material Category II" are also shown in Table 28.

When establishing the A_C-values, priority was given to criteria approved by the international community in Ref. [71]. As can be seen from Table 28, except for ^{241}Pu, the criteria for inclusion in "Nuclear Material Category II" were less than the criticality limits given in Refs. [68, 69]. For ^{241}Pu the criticality limit in Ref. [69] was for an aqueous solution, which would only be applicable in determining the D_2-value (dispersible material). The critically limit for the solid form, used to define a dangerous quantity of a non-dispersed material (D_1-values), would be expected to be a factor of five or more above that for an aqueous solution. This would place it above the criteria for inclusion in "Nuclear Material Category II". Therefore for plutonium, highly enriched uranium, or ^{235}U, the criteria for inclusion in "Nuclear Material Category II" were used in establishing the D-values. For radionuclides that were not addressed by INFCIRC/225/Rev.4, the minimum values from Refs. [68, 69, 70] were used as the criteria for the criticality hazard. Any amount of the radionuclides with an atomic number $Z < 87$ listed in Table 26 was assumed as unlimited for the criticality hazard except ^{222}Rn, for which the A_C-value is given in Table 28.

TABLE 28. CRITICALITY LIMIT-VALUES

Radio-nuclide	Estimates of criticality limit			NMC-II criteria [71] [a]	Criticality criteria used in D-values	
	Ref. [68]	Ref. [69]	Ref. [70]		M_C	A_C
	(g)	(g)	(g)	(g)	(g)	(TBq)
Rn-222			1.5E+01		1.5E+01	8.5E+04
Ra-223			1.5E+01		1.5E+01	2.9E+04
Ra-224			1.5E+01		1.5E+01	8.8E+04
Ra-225			1.5E+01		1.5E+01	2.2E+04
Ra-226			Unlimited		Unlimited	Unlimited
Ra-228			1.5E+01 [b]		1.5E+01	1.5E+02
Ac-227			Unlimited		Unlimited	Unlimited
Ac-225			1.5E+01		1.5E+01	4.0E+01
Ac-228			1.5E+01 [b]		1.5E+01	1.2E+06
Th-227			1.5E+01 [b]		1.5E+01	1.7E+04
Th-228			Unlimited		Unlimited	Unlimited
Th-229			Unlimited		Unlimited	Unlimited
Th-230			Unlimited		Unlimited	Unlimited
Th-231			1.5E+01 [b]		1.5E+01	3.0E+05
Th-232			Unlimited		Unlimited	Unlimited

Radio-nuclide	Estimates of criticality limit			NMC-II criteria [71] [a]	Criticality criteria used in D-values	
	Ref. [68]	Ref. [69]	Ref. [70]		M_C	A_C
	(g)	(g)	(g)	(g)	(g)	(TBq)
Th-234			1.5E+01 [b]		1.5E+01	1.3E+04
Pa-230			1.5E+01 [b]		1.5E+01	1.8E+04
Pa-231			1.0E+04		1.0E+04	1.8E+01
Pa-233			1.5E+01 [b]		1.5E+01	1.2E+04
U-230			1.5E+01 [b]		1.5E+01	1.5E+04
U-232			5.0E+02		5.0E+02	4.0E+02
U-233	5.5E+02 [c] 6.7E+02 [d]		1.95E+02		2.0E+02	7.0E-02
U-234			5.0E+02		5.0E+02	1.2E-01
U-235	7.6E+02 [c] 2.0E+04 [d]		2.9E+02	1.E+03	1.E+03	8.0E-05
^{235}U > 20%				1.E+03	1.E+03	8.0E-05 [e]
^{235}U 10% - 20%				1.E+04	1.E+04	8.0E-04 [e]
U-236			Unlimited		Unlimited	Unlimited
U-238			Unlimited		Unlimited	Unlimited
Np-235			5.0E+02		5.0E+02	2.6E+04
Np-236b			1.5E+01 [b]		1.5E+01	7.3E-03
Np-236a			1.5E+01 [b]		1.5E+01	3.3E+05
Np-237		2.0E+04 [f] 3.0E+04 [g]	1.0E+04		1.0E+04	2.6E-01
Np-239			Unlimited		Unlimited	Unlimited
Pu-236			5.0E+02	5.E+02	5.0E+02	9.9E+03
Pu-237			1.5E+01 [b]	5.E+02	1.5E+01	6.8E+03
Pu-238		3.0E+03 [f] 4.0E+03 [g]	1.0E+03	5.E+02	5.E+02	3.0E+02
Pu-239	5.1E+02 [c] 5.0E+03 [d]	4.5E+02 [h]	1.45E+02	5.E+02	5.E+02	1.0E+00
Pu-240		1.5E+04 [f] 2.0E+04 [g]	1.0E+04	5.E+02	5.E+02	4.0E+00
Pu-241		2.0E+02 [h]	6.0E+01	5.E+02	5.E+02	2.0E+03
Pu-242		4.0E+04 [f] 6.0E+04 [g]	1.8E+04	5.E+02	5.E+02	7.0E-02
Pu-244			5.0E+02	5.E+02	5.0E+02	3.3E-04
Am-241		1.6E+04 [f] 2.4E+04 [g]	1.0E+04		1.0E+04	1.3E+03
Am-242m		1.3E+01 [h]	4.0E+00		4.0E+00	1.4E+00
Am-243		2.5E+04 [f] 3.5E+04 [g]	1.0E+04		1.0E+04	7.4E+01
Am-244			2.0E+00 [i]		2.0E+00	9.4E+04
Cm-240			2.0E+00 [i]		2.0E+00	1.5E+03
Cm-241			2.0E+00 [i]		2.0E+00	1.2E+03
Cm-242			5.0E+02		5.0E+02	6.1E+04
Cm-243		9.0E+01 [h]	3.5E+01		3.5E+01	6.7E+01
Cm-244		3.0E+03 [f] 5.0E+03 [g]	1.0E+03		1.0E+03	3.0E+03
Cm-245		3.0E+01 [h]	1.4E+01		1.4E+01	8.9E-02
Cm-246			5.0E+02		5.0E+02	5.7E+00
Cm-247		9.0E+02 [h]	3.0E+02		3.0E+02	1.0E-03

Radio-nuclide	Estimates of criticality limit			NMC-II criteria [71] [a]	Criticality criteria used in D-values	
	Ref. [68]	Ref. [69]	Ref. [70]		M_C	A_C
	(g)	(g)	(g)	(g)	(g)	(TBq)
Cm-248			5.0E+02		5.0E+02	7.9E-02
Bk-247			2.0E+00 [i]		2.0E+00	7.8E-02
Bk-249			5.0E+02		5.0E+02	3.0E+04
Cf-248			2.0E+00 [i]		2.0E+00	1.2E+02
Cf-249		1.0E+01 [h]	4.0E+00		4.0E+00	6.1E-01
Cf-251		5.0E+00 [h]	2.0E+00		2.0E+00	8.1E+00
Cf-250			5.0E+02		5.0E+02	2.9E+01
Cf-252			5.0E+02		5.0E+02	1.0E+04
Cf-253			2.0E+00 [i]		2.0E+00	2.1E+03
Cf-254			2.0E+00 [i]		2.0E+00	6.3E+02

[a] Nuclear Material Category II.
[b] Default-value for isotopes with an atomic number $88 \leq Z < 95$.
[c] Data for aqueous solutions given in Table 1 of Ref. [68].
[d] Data for metal given in Table 2 of Ref. [68].
[e] A_C expressed in terms of activity of ^{235}U. The total activity per unit mass of enriched uranium includes ^{234}U, which is concentrated during the enrichment process, as well as the activity of the ^{238}U, as described in Ref. [35].
[f] Data for metal given in Table 1 of Ref. [69].
[g] Data for aqueous solutions of non-fissile actinide nuclides given in Table 1 of Ref. [69].
[h] Data for aqueous solutions of fissile actinide nuclides given in Table 2 of Ref. [69].
[i] Default-value for isotopes with an atomic number $95 \leq Z < 99$.

VIII.5. CHEMICAL TOXICITY

The chemical toxicity of dispersed sources was examined by comparing the Immediate Dangerous to Life or Heath (IDLHs) concentrations [72] with the airborne concentration resulting from a release of the material with a mass equivalent to the D_2-value into a room, as given by:

$$C = \frac{D_2 \times RRF}{SA \times V}, \tag{84}$$

where:

C is an airborne concentration of the dispersed material, g/m^3;

D_2 is the D_2-value, Bq, and is given in Table 1;

SA is the specific activity of the radionuclide, (Bq/g), and is given in Table 26;

V is the volume of the room where the material was released, 1000 m^3;

RRF is the respirable release fraction of the initial activity in a source, and is equal to 0.1 as described in Scenario III (Appendix II).

The IDLH (or NIOSH IDLH) is considered the limit beyond which an individual will not be capable of escaping death or permanent injury without help in less than thirty minutes. Where an IDLH could not be found in Ref. [72], it was assumed the IDLH was 10 mg/m^3, which was representative of the lower bound for IDLHs. It was found that for virtually all of the radionuclides, the airborne concentrations C derived from the D_2-values as described by Eq. (84) were a factor of 10 below the IDLH and in most cases a factor of 1000 or more below the IDLH. For uranium (and possibly thorium) radionuclides, which have unlimited D_2-values, the chemical toxicity from dispersal could be of concern. For those radionuclides where the airborne concentration calculated by Eq (84)

approached or exceeded the IDLH, or 10 mg/m^3 (where appropriate), precautionary notes were added to the list of D-values in Table 1.

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DEFINITIONS

absorbed dose, D. The fundamental dosimetric quantity D, defined as:

$$D = \frac{d\bar{\varepsilon}}{dm}$$

where $d\bar{\varepsilon}$ is the mean energy imparted by ionizing radiation to matter in a volume element, and dm is the mass of matter in the volume element. The unit of absorbed dose is J/kg, termed the gray (Gy).

acute exposure. Exposure received within a short period.

(a) Normally used to refer to exposure of sufficiently short duration that the resulting doses can be treated as instantaneous (e.g. less than an hour).

acute intake. An intake occurring within a time short enough that it can be treated as instantaneous for the purposes of assessing the resulting committed dose.

committed absorbed dose, $D_T(\Delta)$. The quantity $D_T(\Delta)$ is characteristic of internal exposure and is defined as:

$$D_T^R(\Delta) = \int_{t_0}^{t_0+\Delta} \dot{D}_T^R(t)\, dt\,;$$

where t_0 is the time of intake, $\dot{D}_T(t)$ is the organ dose rate at time t, in an organ or tissue T, and Δ is the time elapsed after an intake of the radioactive material.

(a) For an intake of radioactive material, a committed absorbed dose causes internal irradiation of the organs and tissues of an individual according to its distribution in the body of reference man, which would occur after the same intake.

committed RBE-weighted dose, $AD_T(\Delta)$. The quantity $AD_T(\Delta)$ is characteristic of internal exposure and is defined as:

$$AD_T(\Delta) = \int_{t_0}^{t_0+\Delta} \dot{AD}_T(t)\, dt\,;$$

where t_0 is the time of intake, $\dot{AD}_T(t)$ is the RBE-weighted dose rate at time t, in an organ or tissue T, and Δ is the time elapsed after an intake of the radioactive material.

(a) For an intake of radioactive material, a committed RBE-weighted dose causes internal irradiation of the organs and tissues of an individual according to the quality of radiation and to its distribution in the body of reference man, which would occur after the same intake.

D-value. The quantity of radioactive material which, if uncontrolled, could result in the death of an exposed individual or a permanent injury which decreases that person's quality of life. For the purposes of determining D-values, the exposure scenarios that were used fall into two groups;

one for material has not been dispersed and one for which the material that has been dispersed. Different D-values are provided for each of these groups:

(a) The D_1-value is the activity[24] of a radionuclide in a source that if uncontrolled, but not dispersed (i.e. it remains encapsulated), might result in an emergency that could reasonably be expected to cause severe deterministic health effects;
(b) The D_2-value is the activity[24] of a radionuclide in a source that if uncontrolled and dispersed might result in an emergency that could reasonably be expected to cause severe deterministic health effects;
(c) The D-value is the lowest-value of the D_1- and D_2-values for a radionuclide.

dangerous source. A source that could, if not under control, give rise to exposure sufficient to cause severe deterministic effects. This designation is used for determining the need for emergency response arrangements and is not to be confused with categorization of sources for other purposes.

deterministic effect. A health effect of radiation for which, generally, a threshold level of dose exists above which the severity of the effect is greater for a higher dose. Such an effect is described as a 'severe deterministic effect' if it is fatal or life threatening or results in a permanent injury that reduces the quality of life.

dose. (1) A measure of the energy deposited by radiation in a target. (2) A general term used to designate such quantities as: absorbed dose, RBE-weighted dose, radiation weighted dose and effective dose.

exposure. The act or condition of being subject to irradiation. Exposure can be either external exposure (due to a source outside the body), or internal exposure (due to radioactive material within the body).

exposure pathway. A route, by which radiation or radionuclides can reach humans and cause exposure. An exposure pathway may be very simple, e.g. external exposure from airborne radionuclides, or more complex, e.g. internal exposure from drinking milk from cows that ate grass contaminated with deposited radionuclides.

gray-equivalent, Gy-Eq. Name for the unit of RBE-weighted absorbed dose.

intake. (1) The ingestion or inhalation of a radioactive material. (2) The amount of radioactive material (activity, Bq) taken into the body by inhalation, ingestion, absorption through the skin, injection, or via a wound.

internal exposure. Exposure due to a source within the body (because of deposition of radionuclides in body tissue).

nuclear or radiological emergency. An emergency in which there is, or is perceived to be, a hazard due to:

(a) the energy resulting from a nuclear chain reaction or from the decay of the products of a chain reaction; or
(b) radiation exposure.

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[24] Allowances are made for the fact that sources may be more hazardous later in life (up to 10 years) due to the in-growth of progeny; however, D-values are expressed in terms of the activity of the parent radionuclides before decay, i.e. at the time of manufacture as described in Appendix VIII.

organ dose, D_T^R**.** The mean absorbed dose in a specified organ or tissue T, of the human body. It is given by:

$$D_T^R = \frac{\Delta\varepsilon_R}{m_T};$$

where m_T is the mass of the organ or tissue T, and $\Delta\varepsilon_R$ is the energy of the ionizing radiation R, imparted to the mass of the given organ or tissue. The quality of the radiation is not taken into account in evaluating the organ absorbed dose.

RBE-weighted dose, $\mathbf{AD_T}$. A product of the absorbed dose in an organ or tissue and the RBE of the radiation imparting the dose:

$$AD_T = \sum_R D_T^R \times RBE_T^R;$$

where D_T^R is the organ dose from radiation R, in tissue T, and RBE_T^R is the relative biological effectiveness of radiation R, in producing a specific effect in a particular organ or tissue T. The unit of RBE-weighted absorbed dose is $J \times kg^{-1}$, termed the gray-equivalent (Gy-Eq).

(a) The RBE-weighted absorbed dose is intended to account for differences in biological effectiveness in producing deterministic health effects in organs or tissues of reference man due to the quality of the radiation.

RDD. Radiological Dispersal Devices

reference man. An adult human with the anatomical and physiological characteristics defined in the report of the ICRP Task Group on Reference Man [73].

reference worker. An adult worker with the anatomical and physiological characteristics defined in the report of the ICRP Task Group on Reference Man [73].

relative biological effectiveness, RBE_T^R. For a particular organ or tissue T, the RBE_T^R is the ratio of the absorbed dose from a reference radiation that produces a specified biological effect relative to the absorbed dose from the radiation of interest (R) that produces the same biological effect. In general, the value of RBE_T^R for biological effects of radiation depends on such factors as the quality of the radiation, the irradiated organ or tissue, the committed effect, and the dose rate. Values of RBE_T^R for severe deterministic health effects used in this manual are the given in Table 8 and Table 9.

severe deterministic effect. A health effect of radiation that is fatal or life threatening or results in a permanent injury that decreases the quality of life.

stochastic effect (of radiation). A radiation induced health effect, the probability of occurrence of which is greater for a higher radiation dose and the severity of which (if it occurs) is independent of dose. Stochastic effects may be somatic effects or hereditary effects, and generally occur without a threshold level of dose. Examples include thyroid cancer and leukaemia.

ANNEXES

ANNEX I
SYMBOLS AND INDICES FORMAT

Generally, the symbols for the dosimetric quantities used in the expert and risk approaches may have up to four indices as shown in Fig. 11.

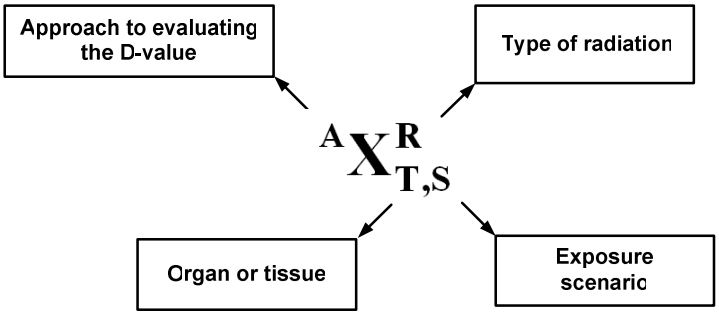

FIG. 11. Indexing of the dosimetric quantities.

The indexes are:

"A" denotes the approach used:
- (a) "E" - expert approach; and
- (b) "R" - risk approach.

"R" denotes the radiation type:
- (a) "L" - low LET radiation;
- (b) "H" - high LET radiation;
- (c) "L+H - any radiation; and
- (d) "S" may be included to indicate a compound with lung absorption type s.

"S" denotes the exposure scenario:
- (a) "I" - "pocket" scenario;
- (b) "II" - "room" scenario;
- (c) "III' - "inhalation" scenario;
- (d) "IV" - "ingestion" scenario;
- (e) "V" - "skin contamination" scenario; and
- (f) "IV - "immersion" scenario.

"T" denotes an organ or tissue as given in the table below:

Organ or tissue	Exposure pathway	Tissue reference number	
		Expert approach	Risk approach
Soft tissue	External adjacent source	1	1
Red marrow	Internal	2	2
Lung regions	Internal	3E	3R
Colon or small intestine	Internal	4	4
Thyroid	Internal	5	5
Skin regions	Skin contact	6E	6R
Torso	External distant source	7	7

ANNEX II
SPECIFIC SYMBOLS

The general rule for indexing dosimetric quantities used in this report is given in Figure 10.

Symbol	Unit	Description
A_C	Bq	The activity limit of a given radionuclide based on criticality considerations.
AD_T	Gy-Eq	The RBE-weighted (absorbed) dose in an organ or tissue T.
$AD_T(\Delta)$	Gy-Eq	The RBE-weighted dose in an organ or tissue T, committed over time interval Δ after intake of a radionuclide.
$AF_{T,S}$	(Gy-Eq)/(Bq×s)	A dose conversion factor equal to the RBE-weighted dose rate delivered in accordance with scenario S, to tissue T, from 1 Bq of a radionuclide.
$AF_{T,S}(\Delta)$	(Gy-Eq)/Bq	A dose conversion factor equal to the RBE-weighted dose in organ or tissue T, committed in accordance with scenario S, for time interval Δ after intake of 1 Bq of a radionuclide.
$AF_{1,I}$	(Gy-Eq)/(Bq×s)	A dose conversion factor equal to the RBE-weighted dose rate delivered in accordance with Scenario I, in Tissue 1 (soft tissue), from 1 Bq of a radionuclide.
$AF_{7,II}$	(Gy-Eq)/(Bq×s)	A dose conversion factor equal to the RBE-weighted dose rate delivered in accordance with Scenario II, in Tissue 7 (torso), from 1 Bq of a radionuclide.
$AF_{2,IIIR}(\Delta)$	(Gy-Eq)/Bq	A dose conversion factor equal to the 30-day committed RBE-weighted dose delivered in accordance with Scenario IIIR, in Tissue 2 (red marrow), due to an inhalation intake of 1 Bq of a radionuclide.
$AF_{3R,IIIR}(\Delta)$	(Gy-Eq)/Bq	A dose conversion factor equal to the 30-day committed RBE-weighted dose delivered in accordance with Scenario IIIR, in Tissue 3R (alveolar region of respiratory tract), due to an inhalation intake of 1 Bq of a radionuclide.
$AF_{4,IIIR}(\Delta)$	(Gy-Eq)/Bq	A dose conversion factor equal to the 30-day committed RBE-weighted dose delivered in accordance with Scenario IIIR, in Tissue 4 (colon), due to an inhalation intake of 1 Bq of a radionuclide.
$AF_{5,IIIR}(\Delta)$	(Gy-Eq)/Bq	A dose conversion factor equal to the 365-day committed RBE-weighted dose delivered in accordance with Scenario IIIR, in Tissue 5 (thyroid), due to an inhalation intake of 1 Bq of a radionuclide.
$AF_{2,IV}(\Delta)$	(Gy-Eq)/Bq	A dose conversion factor equal to the 30-day committed RBE-weighted dose delivered in accordance with Scenario IV, in Tissue 2 (red marrow), due to an ingestion intake of 1 Bq of a radionuclide.
$AF_{4,IV}(\Delta)$	(Gy-Eq)/Bq	A dose conversion factor equal to the 30-day committed RBE-weighted dose delivered in accordance with Scenario IV, in Tissue 4 (colon), due to an ingestion intake of 1 Bq of a radionuclide.
$AF_{5,IV}(\Delta)$	(Gy-Eq)/Bq	A dose conversion factor equal to the 365-day committed RBE-weighted dose delivered in accordance with Scenario IV, in Tissue 5 (thyroid), due to an ingestion intake of 1 Bq of a radionuclide.
$AF_{6R,V}$	(Gy-Eq)/(Bq×s/cm^2)	A dose conversion factor equal to the RBE-weighted dose rate in Tissue 6R (derma of skin), delivered in accordance with Scenario V, due to unit surface activity of a radionuclide.
$AF_{2,VI}$	(Gy-Eq)/(Bq×s/m^3)	A dose conversion factor equal to the RBE-weighted dose rate in Tissue 2 (red marrow), delivered in accordance with Scenario VI, due to immersion in a radioactive noble gas of unit concentration.

Symbol	Unit	Description
${}^{E}A_{I}$	Bq	The initial activity of a radionuclide in a non-dispersed source which, in accordance with the expert approach, is regarded a dangerous if it exposes an individual in accordance with Scenario I.
${}^{E}A_{II}$	Bq	The initial activity of a radionuclide in a non-dispersed source which, in accordance with the expert approach, is regarded a dangerous if it exposes an individual in accordance with Scenario II.
${}^{E}A_{7,VI}$	Bq	The particular initial activity of a radioactive noble gas in a dispersed source which, in accordance with the expert approach, is thought to cause severe deterministic health effects in Tissue 7 (torso) if exposes an individual in accordance with Scenario VI.
${}^{E}A_{IIIE}$	Bq	The initial activity of a radionuclide in a dispersed source which, in accordance with the expert approach, is regarded a dangerous if it exposes an individual in accordance with Scenario IIIE.
${}^{E}A_{2,IIIE}$	Bq	The particular initial activity of a radionuclide in a dispersed source which, in accordance with the expert approach, is thought to cause severe deterministic health effects in Tissue 2 (red marrow) if exposes an individual in accordance with Scenario IIIE.
${}^{E}A_{3E,IIIE}$	Bq	The particular initial activity of a radionuclide in a dispersed source which, in accordance with the expert approach, is thought to cause severe deterministic health effects in Tissue 3E (thoracic region of the respiratory tract) if it exposes an individual in accordance with Scenario IIIE.
${}^{E}A_{5,IIIE}$	Bq	The particular initial activity of a radionuclide in a dispersed source which, in accordance with the expert approach, is thought to cause severe deterministic health effects in Tissue 5 (thyroid) if it exposes an individual in accordance with Scenario IIIE.
${}^{E}A_{6E,V}$	Bq	The particular initial activity of a radionuclide in a dispersed source which, in accordance with the expert approach, is thought to cause severe deterministic health effects in Tissue 6E (basal membrane of skin) if it exposes an individual in accordance with Scenario V.
${}^{R}A_{I}$	Bq	The initial activity of a radionuclide in a non-dispersed source which, in accordance with the risk approach, is regarded a dangerous if it exposes an individual in accordance with Scenario I.
${}^{R}A_{II}$	Bq	The initial activity of a radionuclide in a non-dispersed source which, in accordance with the risk approach, is regarded a dangerous if it exposes an individual in accordance with Scenario II.
${}^{R}A_{IIIR}$	Bq	The initial activity of a radionuclide in a dispersed source which, in accordance with the risk approach, is regarded a dangerous if it exposes an individual in accordance with Scenario IIIR.
${}^{R}A_{T,IIIR}$	Bq	The particular initial activity of a radionuclide in a dispersed source which, in accordance with the risk approach, is thought to cause severe deterministic health effects in tissue T, if it exposes an individual in accordance with Scenario IIIR.
${}^{R}A_{IV}$	Bq	The initial activity of a radionuclide in a dispersed source which, in accordance with the risk approach, is regarded a dangerous if it exposes an individual in accordance with Scenario IV.
${}^{R}A_{T,IV}$	Bq	The particular initial activity of a radionuclide in a dispersed source which, in accordance with the risk approach, is thought to cause severe deterministic health effects in tissue T, if it exposes an individual in accordance with Scenario IV.

Symbol	Unit	Description
${}^{R}A_{V}$	Bq	The initial activity of a radionuclide in a dispersed source which, in accordance with the risk approach, is regarded a dangerous if it exposes an individual in accordance with Scenario V.
${}^{R}A_{6R,V}$	Bq	The particular initial activity of a radionuclide in a dispersed source which, in accordance with the risk approach, is thought to cause severe deterministic health effects in Tissue 6R (derma of skin) if it exposes an individual in accordance with Scenario V.
${}^{R}A_{VI}$	Bq	The initial activity of a radioactive noble gas in a dispersed source which, in accordance with the risk approach, is regarded a dangerous if it exposes an individual in accordance with Scenario VI.
${}^{R}A_{7,VI}$	Bq	The particular initial activity of a radioactive noble gas in a dispersed source which, in accordance with the risk approach, is thought to cause severe deterministic health effects in Tissue 7 (torso) if it exposes an individual in accordance with Scenario VI.
AMAD	μm	The diameter, in an aerodynamic particle size distribution, for which the total activity above and below this size are equal. A lognormal distribution of particle sizes is usually assumed. Fifty per cent of the activity in the aerosol is associated with particles of aerodynamic diameter greater than the AMAD (Activity Median Aerodynamic Diameter).
D_T^R	Gy	The absorbed dose from radiation R, in an organ or tissue T.
$D_T^R(\Delta)$	Gy	The absorbed dose from radiation R, in organ or tissue T, committed over a period of time Δ after intake of 1 Bq of a radionuclide.
Δ	d	The duration of the integration time after intake of radioactive material used for calculating a committed absorbed dose, committed RBE-weighted dose, and committed radiation weighted dose.
$DF_{T,S}^R$	Gy/(Bq×s)	A dose conversion factor equal to the absorbed dose rate of radiation R, delivered in accordance with scenario S, in tissue T, from 1 Bq of a radionuclide.
$DF_{1,I}^{L+H}$	Gy/(Bq×s)	A dose conversion factor equal to the absorbed dose rate from any combination of low LET and high LET radiation.
$DF_{2,II}^{L+H}$	Gy/(Bq×s)	A dose conversion factor equal to the absorbed dose rate from any combination of low LET and high LET radiation delivered in accordance with Scenario II, in Tissue 2 (red marrow), from 1 Bq of a radionuclide.
$DF_{T,S}^R(\Delta)$	Gy/Bq	A dose conversion factor equal to the absorbed dose from radiation R, in organ or tissue T, committed in accordance with scenario S, for time interval Δ after intake of 1 Bq of a radionuclide.
$DF_{2,IIIE}^{L+H}(\Delta)$	Gy/Bq	A dose conversion factor equal to the 2-day committed absorbed dose from any combination of low LET and high LET radiation, delivered in accordance with Scenario IIIE, in organ or Tissue 2 (red marrow), due to an inhalation intake of 1 Bq of a radionuclide.
$DF_{3E,IIIE}^{HS}(\Delta)$	Gy/Bq	A dose conversion factor equal to the 365-day committed absorbed dose from high LET radiation delivered in accordance with Scenario IIIE, in organ or Tissue 3E (thoracic region of the respiratory tract), due to an intake of 1 Bq of an aerosol of a long-lived radionuclide assigned to inhalation Type S.

Symbol	Unit	Description
$DF^{L}_{3E,IIIE}(\Delta)$	Gy/Bq	A dose conversion factor equal to the 2-day committed absorbed dose from low LET radiation delivered in accordance with Scenario IIIE, in Tissue 3E (thoracic region of the respiratory tract), due to an intake of 1 Bq of an aerosol of a radionuclide which could not be assigned to inhalation Type S.
$DF^{LS}_{3E,IIIE}(\Delta)$	Gy/Bq	A dose conversion factor equal to the 365-day committed absorbed dose from low LET radiation delivered in accordance with Scenario IIIE, in Tissue 3E (thoracic region of the respiratory tract), due to an intake of 1 Bq of a non-soluble aerosol of a long-lived radionuclide.
$DF^{L}_{5,IIIE}(\Delta)$	Gy/Bq	A dose conversion factor equal to the 365-day committed absorbed dose from low LET radiation delivered in accordance with Scenario IIIE, in Tissue 5 (thyroid), due to an intake of 1 Bq of a thyroid seeking radionuclide.
$DF^{L}_{6E,V}$	Gy/(Bq×s/cm^2)	A dose conversion factor equal to the absorbed dose rate from low LET radiation, in Tissue 6E (basal membrane of skin), delivered in accordance with Scenario V, due to unit surface contamination of a radionuclide.
$DF^{L}_{2,VI}$	Gy/(Bq×s/m^3)	A dose conversion factor equal to the absorbed dose rate from low LET radiation, in Tissue 2 (red marrow), delivered in accordance with Scenario VI, due to immersion in a radioactive noble gas of unit concentration.
$DF^{R}_{T,S}(\Delta)$	Gy/Bq	A dose conversion factor equal to the committed absorbed dose from radiation R, in organ or tissue T, in accordance with scenario S, for an intake of 1 Bq of a radionuclide.
${}^{E}D_1$	Bq	The D_1-value of a radionuclide calculated using the expert approach.
${}^{E}D_2$	Bq	The D_2-value of a radionuclide calculated using the expert approach.
${}^{R}D_1$	Bq	The D_1-value of a radionuclide calculated using risk approach.
${}^{R}D_2$	Bq	The D_2-value of a radionuclide calculated using risk approach.
E	Sv	The effective dose.
F_{III}		The inhaled fraction of dispersed radioactive material in accordance with Scenario III.
F_{IV}		The ingested fraction of dispersed radioactive material in accordance with Scenario IV.
F_V		The dispersed fraction of radioactive material in accordance with Scenario V.
F_{VI}		The dispersed fraction of radioactive material in accordance with Scenario VI.
H_T	Sv	The radiation weighted (absorbed) dose in an organ or tissue.
$H_T(\tau)$	Sv	The committed radiation weighted dose in an organ or tissue T after intake of a radionuclide.
I	Bq	The quantity of intake of a radionuclide.
LET	keV/μm	The total average linear energy transfer of ionizing radiation in liquid water.
M_S	g	A limit for the mass of radioactive material in Scenario S. If the mass of material with a particular activity exceeded this limit, the radionuclide was considered unlimited.
R_V		The ratio of skin contamination and the primary contamination of an object or surface, in accordance with Scenario V.

Symbol	Unit	Description
RBE_T^R	(Gy-Eq)/Gy	The coefficient of relative biological effectiveness. It is the ratio of the absorbed dose from a reference radiation that produces a specified biological effect in a given organ or tissue T, relative to the absorbed dose from the radiation of interest (R) producing the same biological effect.
RD_1^{L+H}	Gy	A reference level of absorbed dose of any radiation in Tissue 1 (soft tissue) for developing severe deterministic health effects from external local exposure.
RD_7^{L+H}	Gy	A reference level of absorbed dose from any radiation in Tissue 7 (torso) for developing severe deterministic health effects from external total body exposure to distant source.
$RD_2^{L+H}(\Delta)$	Gy	A reference level of the 2-day committed absorbed dose from any radiation in Tissue 2 (red marrow) for developing severe deterministic health effects from internal exposure.
$RD_{3E}^{HS}(\Delta)$	Gy	A reference level of committed absorbed dose in Tissue 3E (thoracic region of the respiratory tract), for developing severe deterministic health effects from inhalation intake of a long-lived radionuclide, emitting high LET radiation, that has slow clearance from the lung.
$RD_{3E}^{L}(\Delta)$	Gy	A reference level of the 2-day committed absorbed dose in Tissue 3E (thoracic region of the respiratory tract) for developing severe deterministic health effects from inhalation intake of a radionuclide emitting low LET radiation that could not be assigned to the slow clearance group.
$RD_{3E}^{LS}(\Delta)$	Gy	A reference level of the 365-day committed absorbed dose in Tissue 3E (thoracic region of the respiratory tract) for developing severe deterministic health effects from inhalation intake of a long-lived radionuclide, emitting low LET radiation, that has slow clearance from the lung.
$RD_5^{L}(\Delta)$	Gy	A reference level of the 365-day committed absorbed dose in Tissue 5 (thyroid) for developing severe deterministic health effects from inhalation intake of a thyroid seeking radionuclide, emitting low LET radiation.
RD_{6E}^{L}	Gy	A reference level of absorbed dose from low LET radiation in Tissue 6E (basal membrane of skin) for developing severe deterministic health effects from skin contamination.
S_V	m^2	The area of the primary contamination due to dispersion of radioactive material in accordance with Scenario V.
TD_1	Gy-Eq	A threshold level of the RBE-weighted dose in Tissue 1 (soft tissue) for developing severe deterministic health effects from external local exposure of soft tissue.
TD_7	Gy-Eq	A threshold level of the RBE-weighted dose in Tissue 7 (torso) for developing severe deterministic health effects from external total body exposure to a distant source.
$TD_2(\Delta)$	Gy-Eq	A threshold level of the 30-day committed RBE-weighted dose in Tissue 2 (red marrow) for developing severe deterministic health effects from an intake of a radionuclide.
$TD_{3R}(\Delta)$	Gy-Eq	A threshold level of the 30-day committed RBE-weighted dose in Tissue 3R (alveolar region of a respiratory tract) for developing severe deterministic health effects from an intake of a radionuclide.
$TD_4(\Delta)$	Gy-Eq	A threshold level of the 30-day committed RBE-weighted dose in Tissue 4 (colon) for developing severe deterministic health effects from an intake of a radionuclide.

Symbol	Unit	Description
$TD_5(\Delta)$	Gy-Eq	A threshold level of the 365-day committed RBE-weighted dose in Tissue 5 (thyroid) for developing severe deterministic health effects from an intake of a radionuclide.
TD_{6R}	Gy-Eq	A threshold level of the RBE-weighted dose in Tissue 6R (derma of skin) for developing severe deterministic health effects from contact exposure to skin contamination.
T_S	s	An exposure time equal to the period of irradiation defined by exposure scenario S.
V_{VI}	m^3	The volume of a room where the radioactive noble gas is released in accordance with Scenario VI.
w_R	Sv/Gy	The radiation weighting factor.

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